ELECTRIC POWER
RESEARCH INSTITUTE

POWERING DECARBONIZATION

Strategies for Net-Zero CO_2 Emissions

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Introduction

Many stakeholders—including cities and states, utilities and large corporations, and now federal policymakers—are setting targets for deep reductions in greenhouse gas emissions to accelerate the transition to a more sustainable energy system. Although the long-run goal is framed in terms of reducing or eliminating economy-wide emissions, the most immediate focus has been on decarbonization in the electric sector. There are several promising or already mature low-carbon technologies available for reducing electric sector emissions at relatively low cost, including wind, solar, battery and other types of energy storage, carbon capture and storage (CCS), and advanced nuclear. At the same time, electrification at the end use is a primary option for reducing direct emissions outside the electric sector, particularly in transportation but also in buildings and industry. Combining clean electric power and electrification can help bring about cost-effective decarbonization throughout the economy, although reaching economy-wide net-zero targets will likely require additional technologies such as hydrogen and biofuels. Moreover, flexibility in terms of technologies and timing is critical to maximize the value of the transition to low-carbon electricity.

In a new analysis, EPRI explores scenarios for achieving net-zero emissions targets in the U.S. electric sector in the context of deep economy-wide decarbonization, considering the implications of how the target is defined, the timing of the target, the costs of the transformation, and interactions with the end-use sectors. This research addresses several key questions:

- What does "net-zero" mean, and what are the implications of alternative definitions?
- What are the roles and potential value of different low-carbon technologies?
- What pace of investment is required?
- What are the economic impacts on electricity prices and energy service costs?
- How does electric sector decarbonization enable economy-wide decarbonization?

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This white paper was prepared by EPRI.

Key Findings

Impacts of Net-Zero Targets on Electric Generation Technology Choices

- Reducing electric sector emissions up to roughly 80% below 2005 levels can be cost-effectively achieved with a combination of currently available technologies: existing nuclear, existing and new conventional natural gas, a rapid expansion of wind and solar, and battery storage, along with the retirement of existing coal.
- Achieving electric sector targets beyond 80% requires deployment of emerging low-carbon technologies, including natural gas or bioenergy with CCS, advanced nuclear, and long-duration storage such as hydrogen produced from electrolysis. The optimal combination of these technologies for achieving 100% reductions—and the associated costs—depends strongly on how the target is defined.
- If negative emissions technologies (that is, technologies that remove CO_2 from the atmosphere) are allowed, a net-zero electric sector can be configured with a mix of negative and positive emissions, retaining a role for natural gas both with and without CCS and avoiding a sharp increase in electricity prices. Without negative emissions technologies, the costs of reductions near 100% rise sharply, especially if the target is met with only renewables and storage. The analysis considers three definitions of *zero emissions targets*:
  - **Net-Zero Target**: This scenario allows some negative emissions to offset a positive emissions component, allowing the most flexibility and lowest incremental cost. This analysis includes bioenergy with CCS (BECCS) as a representative negative emissions technology, which deploys at a scale of around 37 GW nationally—creating a negative flow of around 250 $MtCO_2$ annually or about 20% of projected 2035 reference emissions. This negative flow enables around 490 GW of natural gas–fired capacity (93 GW with CCS), similar in scale to reference levels of conventional gas, to remain on the grid

providing firm capacity for balancing for wind and solar, which constitute around 45% of generation and around 570 GW of new capacity (including both utility-scale and distributed solar) by 2035.

– **Carbon-Free Target**: This scenario requires that all sources of generation must be zero-emitting, thus the potential flexibility and cost savings from negative emissions technologies are excluded. No CCS technologies can contribute in this scenario because of their small residual emissions, nor any conventional natural gas. Wind and solar additions reach nearly 900 GW of new capacity and provide around 65% of generation by 2035. Firm capacity to balance renewables is provided by existing hydro, 160 GW of nuclear (roughly half existing and half new), plus around 280 GW of hydrogen-fired capacity (fueled by 130 GW of electrolysis).

– **100% Renewables Target**: This scenario allows only renewable technologies such as wind, solar, hydro, and geothermal as generation sources so that existing and new nuclear are also excluded, further increasing costs. In this case, all existing thermal capacity is retired. Wind and solar capacity investments total nearly 1,500 GW, contributing over 90% of generation by 2035. Hydrogen capacity fueled by electrolysis and over 200 GW of battery storage are the only resources providing firm capacity.

Impacts of Net-Zero Targets on Electricity Prices, Investment, and Transmission

- Reaching zero electric sector emissions by 2035 requires a significant and immediate scale-up of investment in low-carbon technologies, with a corresponding increase in the electricity price. This scale-up and price impact are much larger with a restricted technology set. Compared to a projected national average generation price (expressed in real 2015 dollars) of around \$60/MWh in 2035 in the Reference (that is, without federal carbon policy), the price in the Net-Zero scenario is around \$80/MWh, while in the Carbon-Free and 100% Renewables scenarios the price rises to around \$110/MWh and \$130/MWh, respectively. When the target is set for 2050 (with an 80% reduction by 2035), the transition and corresponding price increases are more gradual, resulting in lower costs but also higher cumulative emissions.
- Electricity price impacts vary significantly by region, especially in scenarios that rely more heavily on renewables. Regions in the East and South United States, with poorer quality renewable resources, see larger price spikes than in the Midwest and West, even allowing some increase in transmission between regions. Much larger investments in inter-regional transmission corridors can reduce these price disparities by allowing broader use of higher quality renewables, but experience in recent decades suggests that these investments may be difficult to site. Further exploration of the trade-offs between transmission and renewable resources is a key modeling need.

Impacts of Net-Zero Targets on Economy-Wide Energy Use, Emissions, and Costs

- Electrification and efficiency improvements play a crucial role in reducing economy-wide CO_2 emissions. Their impact is observed in all scenarios, including the Reference case. Under an economy-wide carbon policy, the incentives for both electrification and efficiency are modestly strengthened. However, with higher electricity prices projected for the more restrictive target definitions, electrification is reduced and efficiency increased—resulting in lower overall electricity demand. Beneficial electrification and efficiency can reduce total energy service costs and lower economy-wide emissions, and they should always be a complement to electric sector targets to reach economy-wide goals.
- Negative emissions technologies, or other flexibility mechanisms, significantly reduce the total expenditure on energy services under net-zero targets in the electric sector. When an economy-wide carbon tax is applied with negative emissions, electric sector emissions become net-negative and allow economy-wide emissions to fall to 80% below 2005 levels.

The remainder of this paper briefly reviews other related studies and describes the details of the EPRI analysis, starting with an overview of the US-REGEN model, followed by a discussion of emissions trajectories and targets, followed by scenario definitions, then a presentation of modeling results—including electric generation and capacity, electricity prices, and economy-wide emissions and energy use and expenditures on energy services. The paper concludes with a discussion of implications of the key findings from the analysis and plans for follow-on research.

Review of Recent Net-Zero Studies

Modeling studies have demonstrated that low- or zero-carbon electricity systems are an essential enabler of low-emissions energy systems because of the direct reduction of electricity emissions through many lower cost mitigation options in the power sector and through the use of electrification to reduce emissions in other sectors of the economy (for example, Williams et al., 2021; EPRI, 2018; Rogelj et al., 2015). Many multi-model comparison studies and single-model analyses have explored deep carbon reductions in the electric power sector but have not typically considered "net-zero" goals (for example, Huntington, et al., 2020; Bistline and Young, 2019; Bistline et al., 2018).

The modeling studies that have examined "net-zero" electricity sector goals do not typically examine policy cost-effectiveness, capture interactions across sectors, or include a wide range of technological options (for example, Phadke et al., 2020; Jenkins et al., 2018; Sepulveda et al., 2018). Further, some models that look at country-level or global net-zero targets do not have technological, spatial, or temporal detail to evaluate high-renewable power sector pathways. For instance, global integrated assessment models are often used to examine pathways to meet climate goals, but these models do not resolve electric sector investments and operations with enough detail to capture key dynamics (Blanford et al., 2018; Santen et al., 2017). Recent studies on U.S. net-zero economy-wide targets have greater sectoral and geographical detail and investigate trade-offs with technological availability, but these analyses do not examine timing flexibility for power sector decarbonization and often focus on 2050 targets rather than earlier ones (Williams et al., 2021; Larson et al., 2020; SDSN 2020).

A few robust findings emerge from the literature on electric sector deep decarbonization:

- Advanced technology and broader technological portfolios lower the cost of decarbonization; cost is especially sensitive to the availability of firm low-carbon resources and carbon removal technologies (Bistline and Blanford, 2020a and 2020b; Sepulveda et al., 2018).
- Flexibility about when, where, and how emissions reductions occur lowers costs of achieving policy targets (Bistline and de la Chesnaye, 2017).
- Marginal abatement costs increase sharply near 100% decarbonization, especially without carbon removal (Jayadev et al., 2020; Bistline and Blanford, 2020a; Bistline et al., 2018).

The analysis presented in this paper confirms these insights while expanding on the earlier work by examining pathways to zero or net-negative electric sector emissions with a detailed electric sector-model, exploring the implications of a 2035 target year versus 2050, and estimating the ability of clean electricity to reduce emissions throughout the economy via electrification.

US-REGEN Model Overview

This analysis uses EPRI's U.S. Regional Economy, Greenhouse Gas, and Energy (US-REGEN) model, a detailed capacity expansion and dispatch model of the U.S. electric sector combined with an economic model of the nonelectric sectors representing technology trade-offs at the end use. US-REGEN solves for a least-cost combination of technology deployment to meet energy service demands subject to a constraint (or a price) on CO_2 emissions or similar policy targets. The electric model balances load and resources at the hourly level, while the load profile changes to reflect the evolving end-use mix over time. In this study, the model aggregates states into 16 regions (Figure 1), with additional spatial resolution characterizing wind and solar resources as well as climate zones for space heating and cooling. Additional information about US-REGEN is provided in the appendix. Full model documentation and other analyses are available at https://esca.epri.com.

Scenario Design

The Reference scenario for this analysis projects continued coal retirements replaced with new gas and renewables in the electric sector, with accelerated electrification (especially light-duty vehicles) and continued efficiency improvements in end-use sectors. In this scenario, electric sector CO_2 emissions decline by 50% relative to 2005 by 2035, and by 66% by 2050 (see Figure 2). Economy-wide CO_2 emissions decline by 40% relative to 2005 by 2035, and by 50% by 2050.[1] The Reference scenario includes existing state-level policies as well as a small carbon price of \$10/tCO_2 beginning in 2030, rising at 4% per year thereafter, to reflect emerging preferences for lower carbon energy sources—particularly CO_2 reduction commitments by the electric sector. In all cases, fuel prices and energy service demands follow the Annual Energy Outlook (AEO) 2020 Reference case. We do not include any potential COVID-19 impacts in the analysis (for example, see Liu et al., 2020).

[1] In this study, economy-wide CO_2 emissions are mainly those from fossil fuel combustion, which today accounts for about 93% of total CO_2 emissions and 75% of total U.S. greenhouse gas (GHG) emissions.

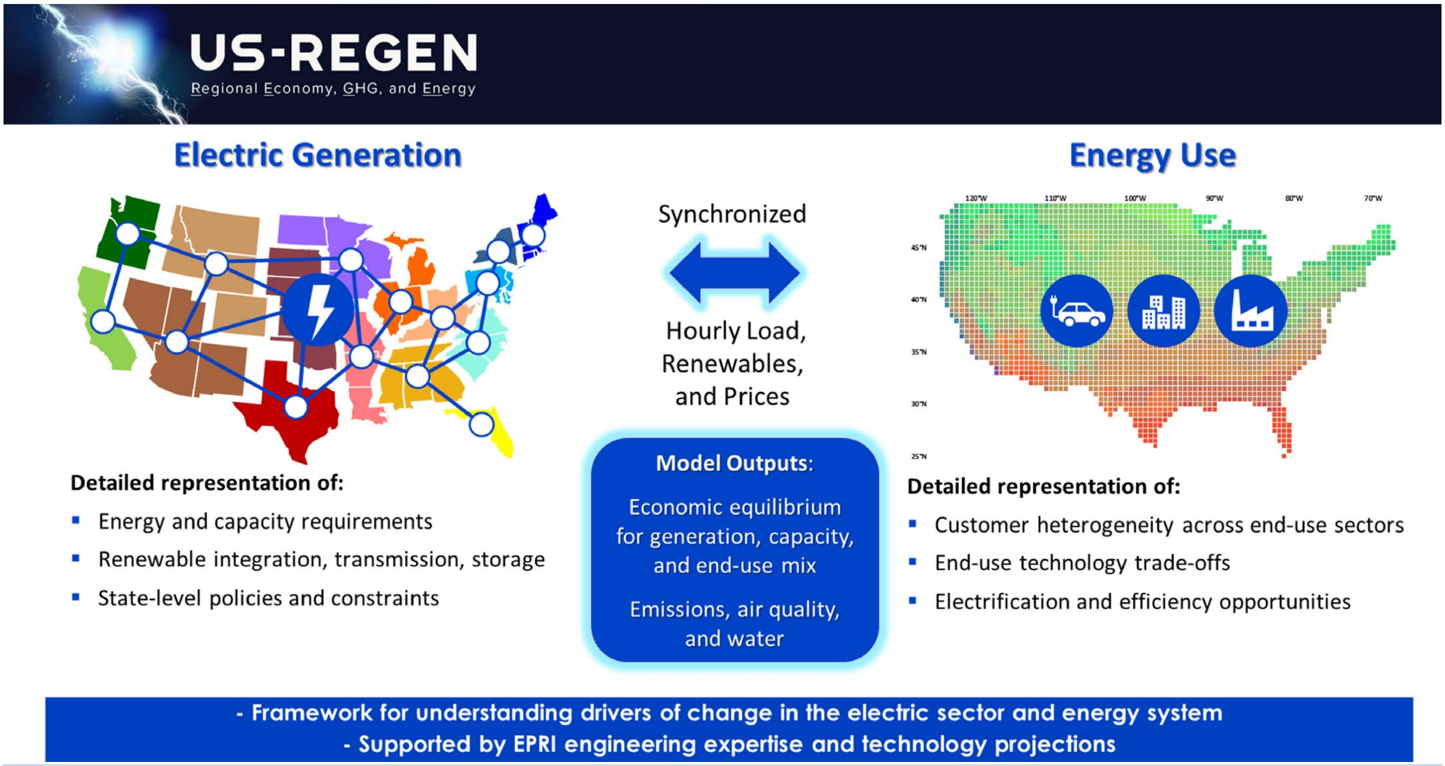

Figure 1. Overview of US-REGEN Model

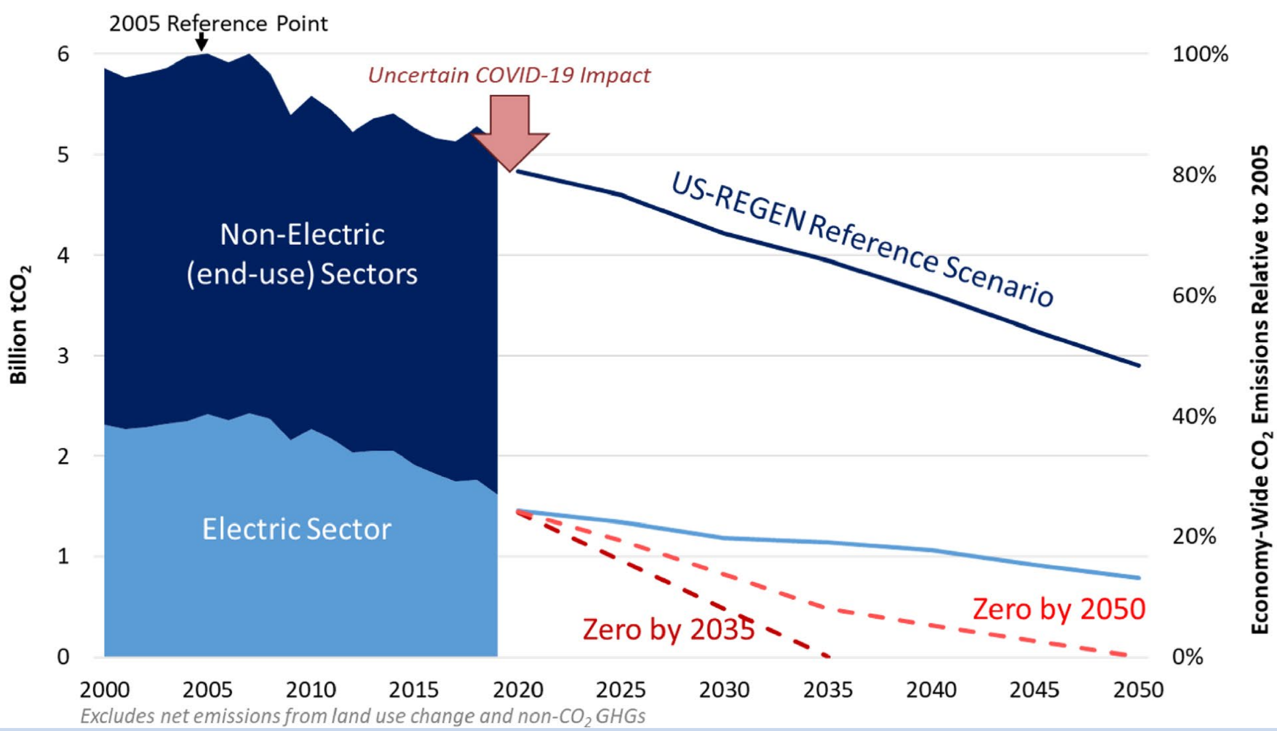

Figure 2. U.S. Economy-Wide CO_2 Emissions in Reference Scenario plus Electric Sector Targets

In addition to the Reference scenario, the analysis examines several alternative formulations for electric sector decarbonization targets, specifically varying the timing of the target for achieving decarbonization and the definition of *zero emissions.*

We consider two alternative target time paths for electric sector CO_2 emissions (see Figure 2):

- Zero Emissions by 2035
- Zero Emissions by 2050 (80% below 2005 by 2035)

For each time path, we consider three alternative definitions of *zero emissions* (see Figure 3):

- Net-Zero, which allows negative emissions to offset a positive component
- Carbon-Free, which allows only carbon-free sources, that is, excluding fossil and CCS
- 100% Renewables, which allows only wind, solar, hydro, geothermal, and storage

With a net-zero formulation—the most flexible interpretation of a zero-emissions target—several potential technological or nature-based options could be considered to either offset emissions or produce negative emissions (that is, net carbon removal from the atmosphere). These could include deployment of negative emissions technologies such as bioenergy with CCS (BECCS) or direct air capture (DAC) or offsets in the traditional sense, that is, certified reductions from non-covered sectors such as forestry or agriculture. For this analysis, we include BECCS (with the assumption of carbon neutral crediting of the bioenergy feedstock) as the representative negative emissions option for the electric sector. Conditional on the availability of suitable feedstocks, BECCS is one of the lowest cost options for negative emissions because it produces power alongside the atmospheric removal of CO_2. DAC technologies represent another potential negative emissions option, but they are likely to be more expensive than BECCS initially and were excluded from this analysis.[2] In the Carbon-Free formulation, bioenergy is not regarded as carbon neutral—eliminating it as a zero-emissions option and, more crucially, the negative emissions potential from BECCS. By extension, without the flexibility from negative emissions, no fossil or CCS technology is eligible because of the small residual emissions associated with incomplete capture (this analysis does not include a 100% capture technology option). In the 100% Renewables formulation—the most restrictive interpretation—the electric sector

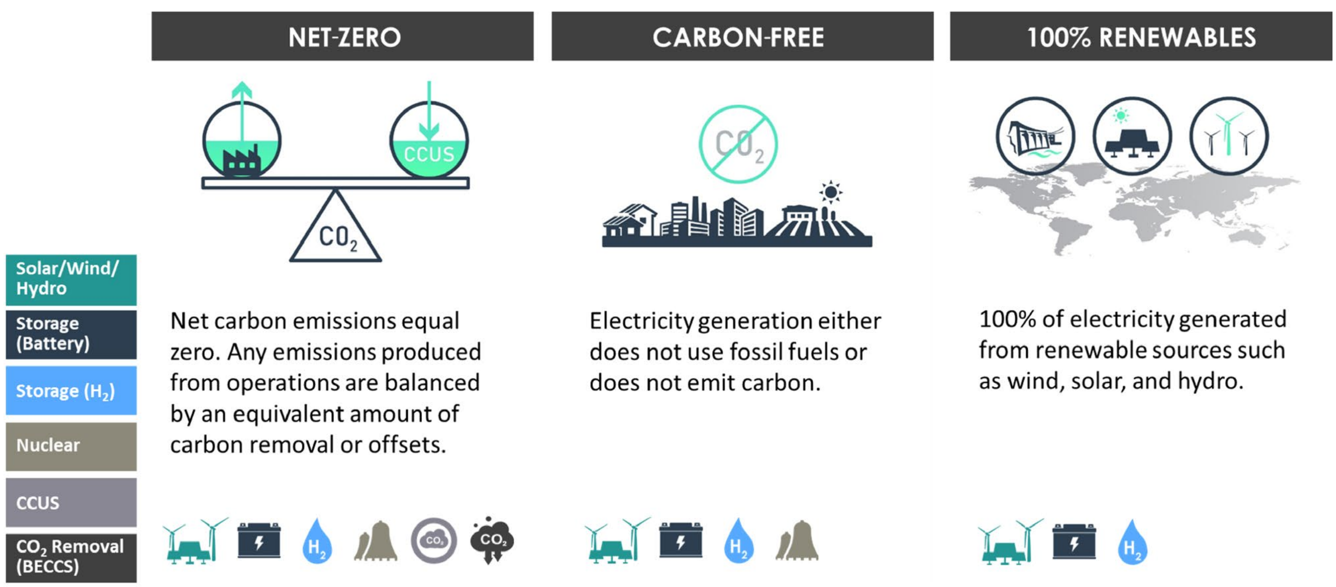

Figure 3. Alternative Definitions of Electric Sector Zero-Emissions Target

[2] Bistline and Blanford (2020a) use the US-REGEN model to examine electric sector net-zero CO_2 targets and vary the availability of BECCS and DAC. Costs and investment outcomes are similar when both technologies are available and only one is available, but DAC could play a larger role under economy-wide net-zero targets.

must achieve zero emissions with a restricted set of technologies that excludes not only CCS, but also both existing and new nuclear.

In addition to varying the definition of the target, we also vary the year in which the target is enforced. The more aggressive timing scenario requires zero emissions by 2035. We also consider a scenario in which the target in 2035 is 80% below 2005, with the zero-emissions target achieved by 2050 (see Figure 2). These alternative timing scenarios are applied to all three target definitions. For the scenario targeting 100% Renewables in 2050, the interim 2035 target is defined as an 80% renewable share of generation.

All scenarios (other than Reference) include a carbon price in the end-use sectors driving incentives for additional electrification and efficiency improvements ($50/t$CO_2$ starting in 2025, rising at the model's discount rate of 7% per year). To contrast the scenarios that mandate zero emissions for the electric sector with an efficient economy-wide allocation of emissions reductions, we also include two scenarios in which this carbon price trajectory is also applied in the electric sector in lieu of the quantity-based emissions target. In one case, we assume that negative emissions through BECCS are available; in the second case, we assume that they are not. When negative emissions are available, the economy-wide carbon price leads to net-negative emissions from the electric sector and thus lower economy-wide emissions. In this scenario, economy-wide CO_2 emissions reach 80% below 2005 by 2050.

Additional sensitivity cases were conducted but are not discussed at length here, including banking of emissions credits under the declining zero-emissions paths over time, variation in the timing of the zero-emissions target between 2035 and 2050, sensitivities around constraints on new transmission, and sensitivities around projected cost declines for key technologies. See Blanford (2020) and forthcoming EPRI research for further discussion of these important dimensions.

Model Results

Model Results: Definition of the Target

To achieve zero emissions in the electric sector, fundamental changes to the generation and capacity mix are required relative to the current system. Figures 4(a) and 4(b) depict three very different technology mixes that result from the three different interpretations of zero emissions in the electric sector, displaying capacity and generation, respectively, for the 2035 target scenarios. These results are compared to the projected mix in 2035 in both the Reference scenario and the Net-Zero by 2050 scenario with an intermediate goal of 80% in 2035.[3]

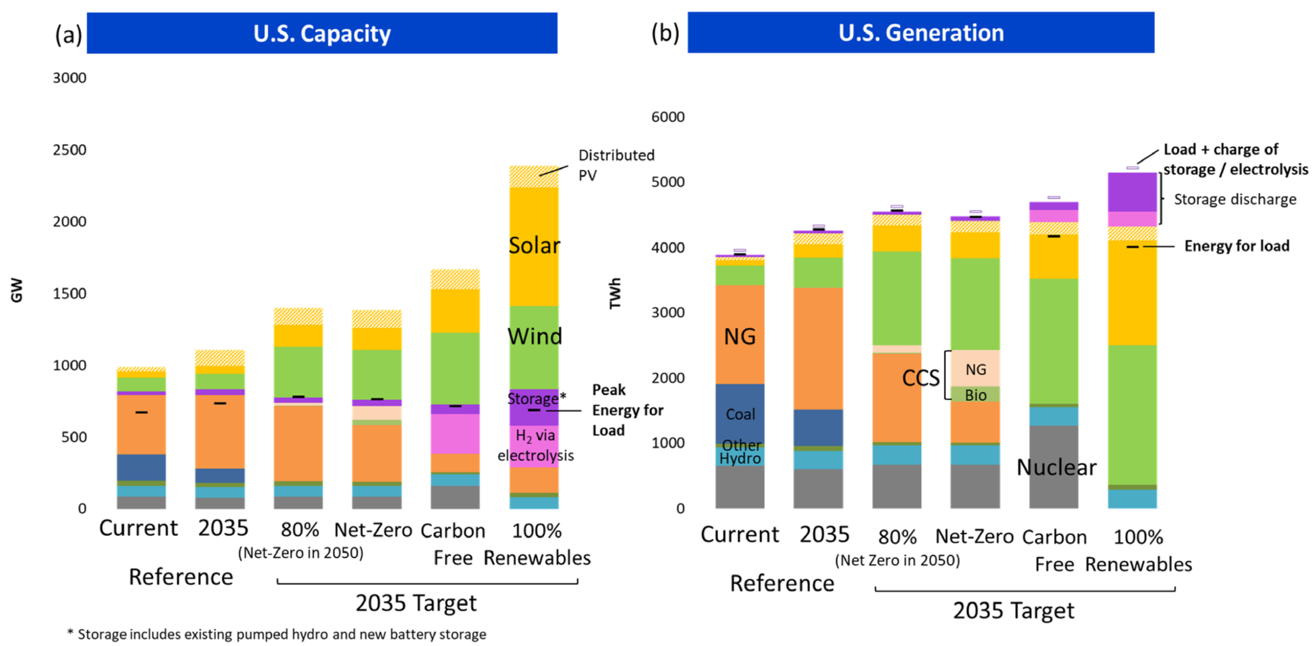

Figure 4. U.S. Capacity (a) and Generation (b) in 2035 Zero-Emissions Target Scenarios

[3] See Figure A-2 for additional scenario results and a full list of generation technology options.

In the Net-Zero by 2035 scenario, wind and solar increase to around 45% of energy—complemented by firm capacity from existing hydro and nuclear, both existing and new conventional natural gas, and new natural gas with CCS and BECCS. Negative emissions from BECCS offset the positive emissions from gas with and without CCS. Because biomass is much more carbon intensive than natural gas on an energy basis, its negative emissions per MWh are roughly three times as large as the positive emissions from a conventional natural gas–combined cycle (NGCC) unit and around 30 times the residual emissions from gas with CCS (assuming 90% capture). In this way, a comparatively small amount of BECCS generation (around 230 TWh) offsets emissions from a much larger amount of generation from natural gas and gas with CCS (around 600 TWh each).[4] The annual negative flow of emissions in this scenario is roughly 250 $MtCO_2$, or about 20% of 2035 emissions in the Reference scenario.[5]

The average capacity factor, or percent of the year generating at nominal capacity, varies widely across resources. The intermittent profiles of wind and solar cause dispatchable resources to operate at lower capacity factors, while the implicit price on carbon from the reduction target means that resources with lower emissions intensity are dispatched preferentially, resulting in higher capacity factors. Because of the high value of carbon removal, BECCS operates at its maximum allowable capacity factor of around 70%, limited only by seasonal availability. Natural gas with CCS also operates at a high capacity factor of around 70%, while conventional gas units operate much less frequently: 28% for NGCC and 2% for gas-fired combustion turbines (CTs). Thus the net-zero system includes nearly 400 GW of conventional natural gas capacity along with 93 GW of gas with CCS, similar to the scale of conventional gas capacity in the Reference scenario, albeit operated at a lower average capacity factor. As discussed next, this configuration keeps the cost of meeting the target comparatively low.

In the Carbon-Free case, the use of natural gas and bioenergy, with or without CCS, as well as any other potential offset option, is disallowed by assumption. This more restrictive definition means that the electric sector relies only on zero-carbon generation from renewables and nuclear. Wind and solar provide around 65% of energy, and there is a rapid expansion of nuclear generation—roughly doubling the size of the fleet by 2035. There is also much greater deployment of storage for renewable balancing, in particular, hydrogen for seasonal storage. This seasonal storage pathway uses around 130 GW of electrolysis capacity to produce hydrogen, operating at around a 40% average capacity factor (although this varies significantly across regions), and around 280 GW of hydrogen turbine capacity, operating at around a 7% average capacity factor. Some conventional natural gas CT capacity remains to satisfy local reserve requirements, but it does not operate because hydrogen turbines must effectively play the role of conventional gas CTs in providing carbon-free firm energy during high-load, low-renewable periods. The implied carbon price in this case is very high because the marginal cost curve for emissions reductions is very steep approaching "absolute zero" (see Figure 10 below).

In the 100% Renewables case, the most restrictive interpretation of a zero-emissions target for the electric sector, new and existing nuclear is also excluded, which leaves 92% of energy to be provided by wind and solar (hydro and geothermal supply the rest). Accordingly, there is a much larger deployment of storage to provide firm capacity. Because of the saturation of higher quality wind resources, most incremental renewable generation in this scenario is solar, which is complemented by substantial expansion of battery storage—around 210 GW of output capacity and 1,300 GWh energy reservoir capacity.[6] Seasonal storage capacity with electrolysis and hydrogen is similar to the Carbon-Free case, although there is more electrolysis capacity—around 180 GW—operating at a slightly lower capacity factor of around 37%. This scenario is even more costly than the Carbon-Free case. As the target definition becomes more restrictive, the price of electricity increases and customer load declines (see Figure 4 and Figure 8 below). Yet because of losses

[4] The use of biomass as a generation fuel for BECCS in the Net-Zero scenario is around 3.3 quad Btu, compared to about 0.5 quad Btu of biomass used currently as a generation fuel in the U.S. electric sector and about 5 quad Btu used total across the economy. The incremental supply comes from a combination of agriculture and forestry residues and energy crops produced on marginal pastureland. See full model documentation for more details.

[5] Note that other options could serve as a negative offset, such as afforestation or DAC, but these options were not included in this analysis.

[6] In US-REGEN, the ratio between output (power) capacity and reservoir (energy) capacity is endogenous with separate costs for each component so that the average battery duration is an outcome of the scenario optimization. In the 100% Renewables scenario, average battery duration is around 6 hours. In the other scenarios in which battery deployment is smaller, average duration is closer to 4 hours.

inherent in power storage—primarily from the production, storage, and use of electrolytic hydrogen—total generation (including storage discharge) increases despite this lower load.

Figure 5 shows the U.S. average price of electricity generation for the three zero-emissions target scenarios compared to the Reference case. The reported price reflects generation and new bulk transmission but excludes intra-region transmission and distribution costs associated with delivery from wholesale markets to retail customers.[7] Particularly for the more restrictive targets, there is a sharp increase in the generation price up to 2035 when the target binds, driven by the need for a rapid scale-up of new low-carbon capacity. In the 100% Renewables case, the price more than doubles relative to the Reference case, while in the Net-Zero case, the increase is only about 30%, or about 2 cents per kWh. Another factor driving the price increase in the 100% Renewables case is the forced retirement of around 80 GW of existing nuclear capacity, which must be replaced by almost 300 GW of additional renewables and storage.

There is a strong regional dimension to the decarbonization strategy for the U.S. electric sector. The Net-Zero target is less expensive in all regions, but the additional costs of the more restrictive targets are primarily realized in the South and East regions (see Figure 6). In the Midwest and West, where there is an abundance of high-quality renewables, the more restrictive targets are less impactful because the optimal share of renewables is higher. Conversely, the value of nuclear and CCS as alternatives to renewables is highest in the South and East where renewable resources are more limited. An important constraint in these scenarios is an upper bound on total new inter-regional transmission investments limiting the increase to roughly 20% of the current system, reflecting historical barriers (for example, exclusion areas, public acceptance, and financing) to new additions. In sensitivity cases in which this constraint is relaxed, the optimal investment portfolio includes much larger transmission capacity additions, which can reduce price disparities between regions by allowing more energy to flow from higher quality renewable resource regions to other parts of the country. Further exploration of the trade-offs between transmission and renewable resources is a key modeling need.

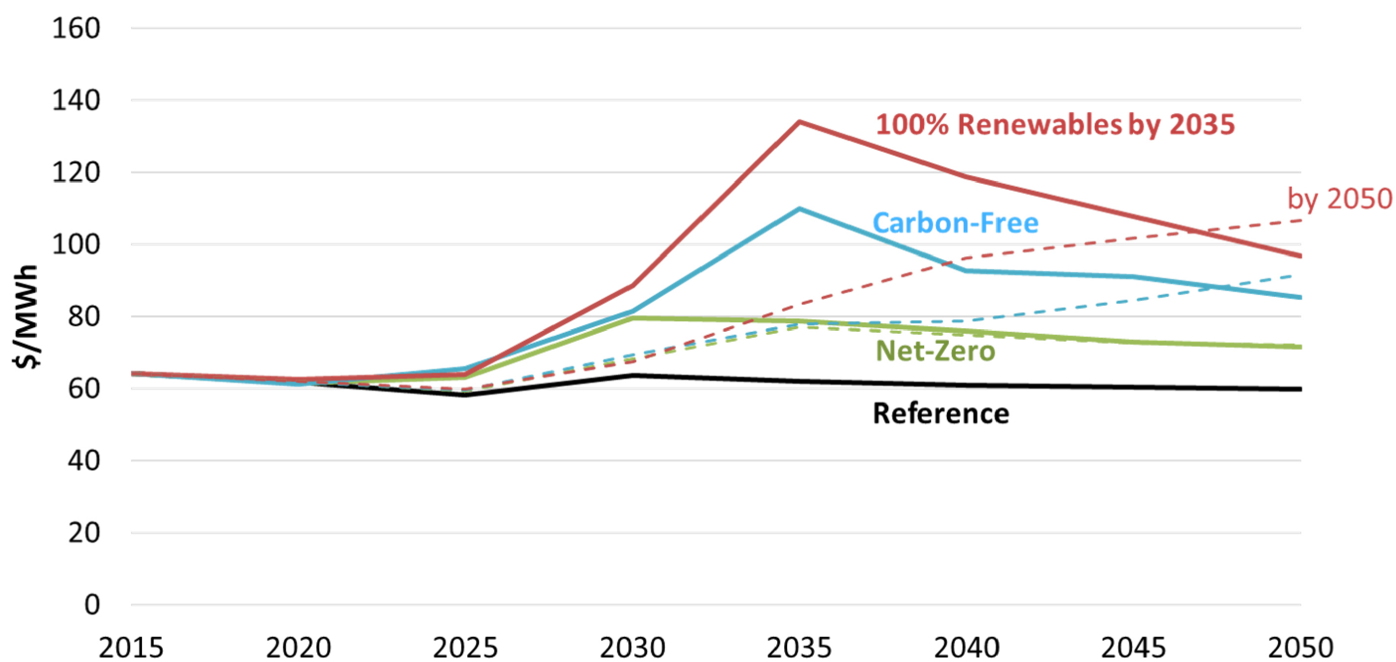

Figure 5. U.S. Average Electricity Generation Price in 2035 and 2050 Zero-Emissions Target Scenarios

[7] See the section below on Economy-Wide Energy Service Costs for a full accounting of electricity costs as well as expenditures on non-electric fuels and energy-using equipment.

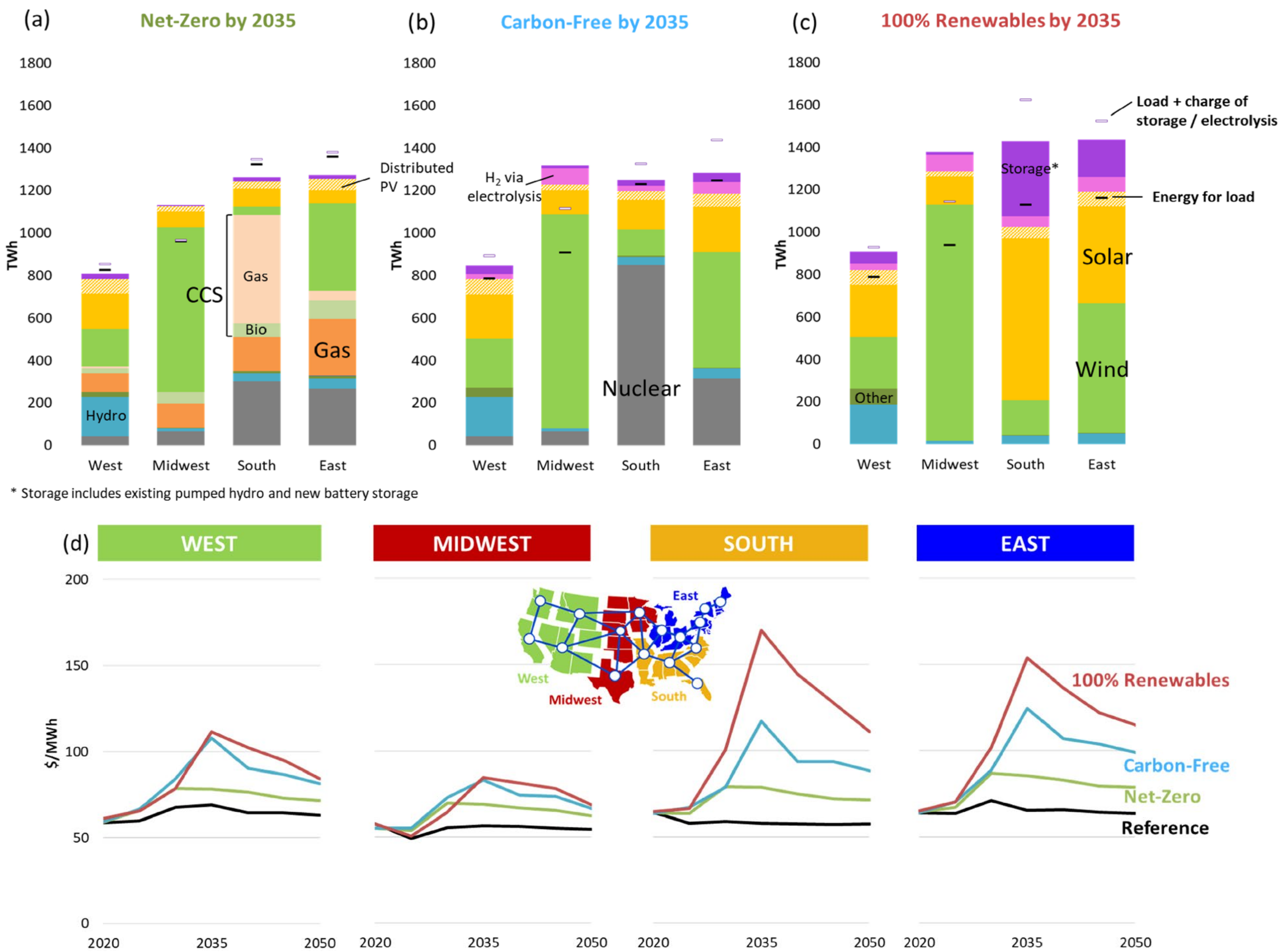

Figure 6. Regional Generation (a), (b), and (c) and Average Electricity Generation Price (d) in 2035 Zero-Emissions Target Scenarios

Model Results: Timing of the Target

The results presented so far have illustrated the impacts of a zero-emissions target enforced in 2035. What if the target for 2035 were an 80% reduction instead, with a zero-emissions target in 2050? In this case, there is a similar increase in wind and solar and retirement of coal by 2035, but NGCC continues to provide the majority of balancing energy with only a small deployment of CCS (see Figure 4). There is a more gradual introduction of emerging technologies (for example, CCS, advanced nuclear, and clean hydrogen), and the sharp increase in electricity prices is avoided (see Figure 5). Moreover, the ultimate price impact of reaching the target is lower because technology costs are assumed to continue to decline over time. The generation mix in 2050 is similar for each target definition to the mix in 2035 under the earlier target, though total generation is larger, reflecting further increases in customer load driven by electrification over time (Figure A-2).

To illustrate the scale of the challenge of reaching zero-emissions targets in the electric sector by 2035, Figure 7 shows cumulative capacity investments over the next 15 years, compared to recent history. Over the past 15 years, the U.S. electric sector has experienced significant growth in wind, solar, and natural gas with many coal plant retirements. In the Reference scenario, those trends are accelerated. But the pace of investment in the target scenarios is much higher still. In all target scenarios, all remaining coal is retired by 2035, and over 500 GW of new wind and solar is added. In the 80% and Net-Zero scenarios, around 180 GW of new natural gas is built as well, roughly half outfitted with CCS in the Net-Zero case. In the Carbon-Free case, there is nearly 900 GW of new wind and solar plus 78 GW of new nuclear, large investments in storage and hydrogen, and retirement of all existing fossil capacity (natural gas as well as coal) in the next 15 years. For the 100% Renewables case, nearly 1,500 GW of wind and solar is built and all existing nuclear and fossil capacity is retired. Clearly, emerging technologies play a critical role in all the scenarios that reach zero by 2035. Even the Net-Zero case requires a major scaling up of CCS (over 100 GW), which brings with it a wide array of engineering challenges and regulatory, permitting, and legal issues.

Figure 7 also shows total investments in both generation capacity and new transmission capacity for inter-regional links and connection of renewables between 2020 and 2035. These scenarios assume that a transformation on this scale is feasible, but in reality there could be significant barriers to transforming the system so quickly. These include research, development, and demonstration (RD&D) of emerging technologies; siting and construction of both transmission and generation; disruptions associated with plant closures; permitting (especially for CCS); and market and regulatory reforms, particularly around ensuring resource adequacy, reliability, and resilience of future systems with unprecedented levels of renewables, increased reliance on electricity, and changing stressors driven by climate change and manmade threats (for example, cyber security, electromagnetic pulses, and so on). We return to these challenges in the Discussion section below.

Model Results: Economy-Wide Energy Use and Emissions

How does decarbonization in the electric sector contribute to economy-wide decarbonization? The Reference scenario for the analysis reflects continued declines in CO_2 emissions resulting from increased shares of renewables, replacement of coal generation with gas, continued end-use efficiency improvements, and significant electrification—particularly for light-duty vehicles—which is beneficial even without a strong carbon policy signal. Figure 8 shows the change in final energy use relative to today, across the Reference and target scenarios by 2050, highlighting the effects of efficiency and electrification. Final energy declines in all cases as increased service demand is offset by efficiency improvements and the substitution of electricity for fossil fuels at the end use, which in many cases is much more efficient on a final energy basis.[8] Note that most efficiency and electrification measures deploy cost-effectively

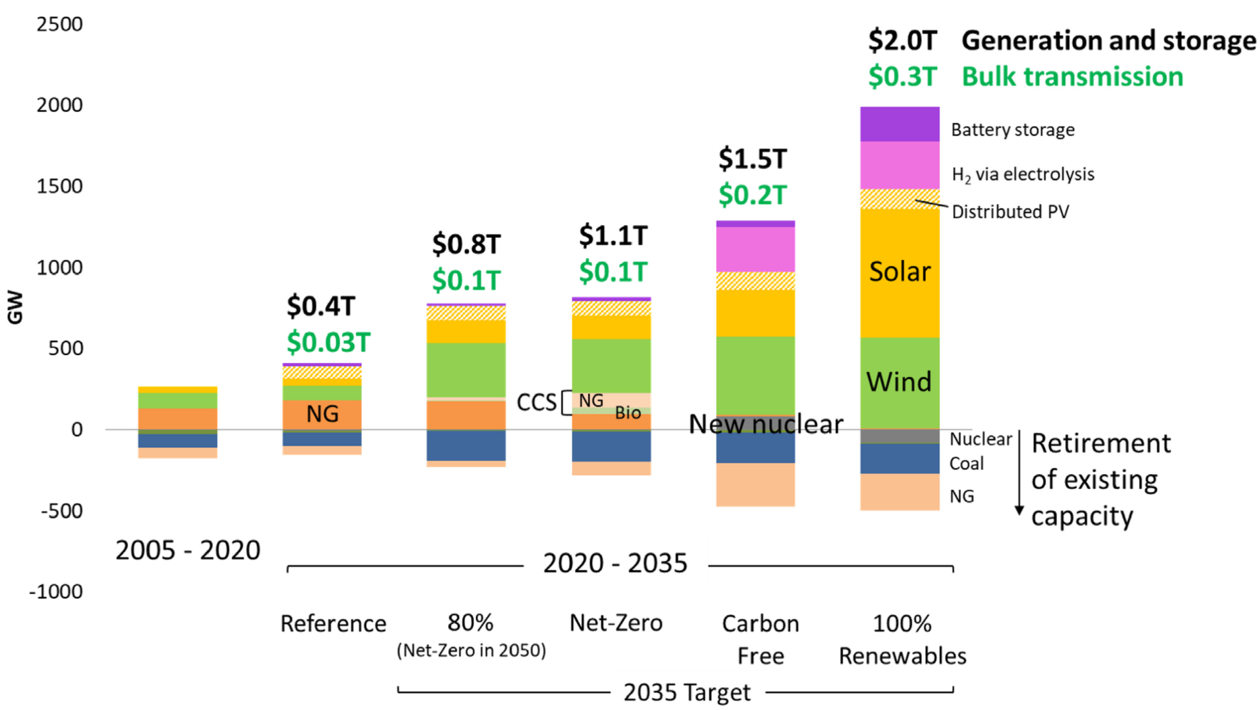

Figure 7. Cumulative Capacity Investments 2020–2035

[8] See EPRI's U.S. National Electrification Assessment (EPRI, 2018) for more details on efficient electrification.

in the model's Reference scenario, although in reality they may face behavioral barriers to adoption. The combination of these trends drives emissions down to around 50% below 2005 by midcentury in the Reference scenario (Figure 9a).

In the target scenarios, emissions from the electric sector are reduced to zero (albeit in different ways and at different costs, depending on the target definition). At the same time, the carbon price in the end-use sectors drives additional electrification beyond what is adopted in the Reference case.[9] The higher electricity prices projected for the more restrictive target definitions lead to more efficiency and less additional electrification (Figure 8). In the Net-Zero by 2035 scenario, decarbonization of electric generation combines with additional electrification to reduce energy system emissions to roughly 70% below 2005 by 2050 (Figure 9b).

In the scenarios described so far, the electric sector was subject to a constraint on emissions while the end-use sectors were subject to a price on emissions. The implied shadow price on emissions in the electric sector depends on, among other things, the definition of the target, with the more restrictive target definition leading to higher carbon prices (Figure 10). In the Net-Zero scenario, the shadow carbon price in the electric sector is lower than the carbon price assumed in the end-use sectors, while in the Carbon-Free case, the shadow price on emissions becomes very high—essentially reaching an asymptote at the margin as emissions are forced to "absolute zero," that is, a zero-emissions target with no flexibility.[10] This mismatch in carbon prices between the electric and end-use sectors implies that a more economically efficient allocation of emissions reductions is available, that is, one with a harmonized economy-wide carbon price.

When the same carbon price is applied economy-wide and negative emissions are not available, as in the Carbon-Free case, it is cost-effective for electric sector emissions to avoid going all the way to zero—resulting in emissions that are about 90% below 2005 in 2035 and 97% below 2005 in 2050 (Figure 9c, d; Figure A-2). If negative emissions technologies are available, as in the Net-Zero case, net electric sector CO_2 emissions reach zero by 2035. After this year, the carbon price continues to rise, making it cost-effective for the electric sector to expand its deployment of BECCS so that emissions become net-negative, or about 120% below 2005 by 2050 (Figure 9e, f; Figure A-2). Thus by allowing all sectors to respond to

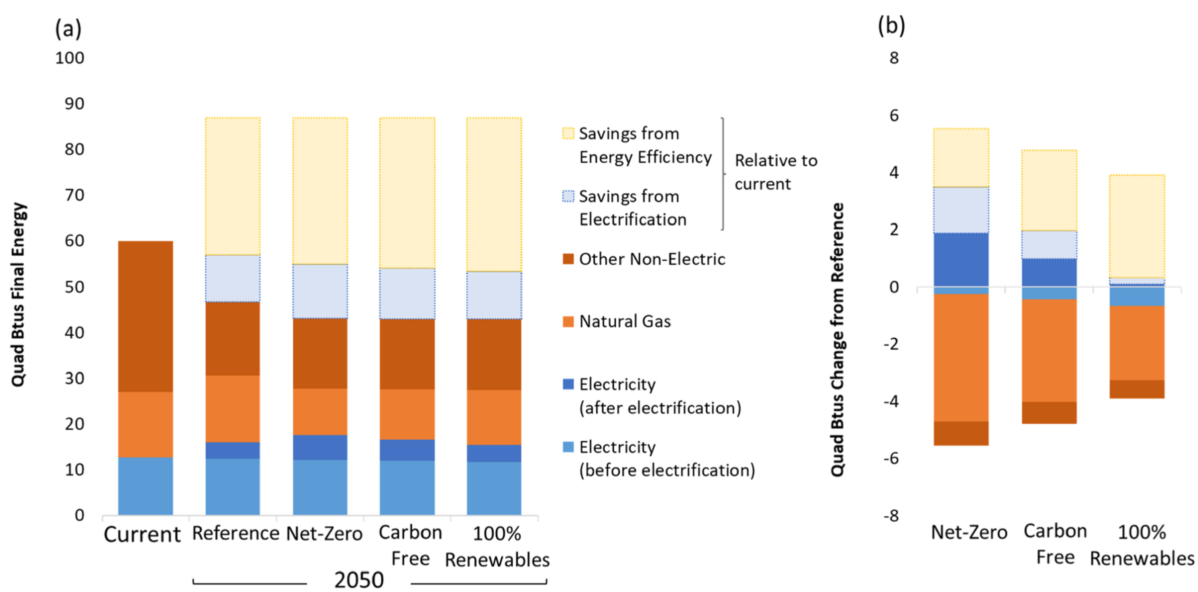

Figure 8. Total Final Energy in 2050 (a) and Change Relative to Reference (b)

[9] See EPRI (2020) and EPRI (2021) for more details on how economy-wide carbon prices impact electrification.

[10] The 100% Renewables scenario does not have a price on carbon per se because it is formulated as a constraint on the share of qualified generation rather than emissions. See Bistline and Blanford (2020a) for further information.

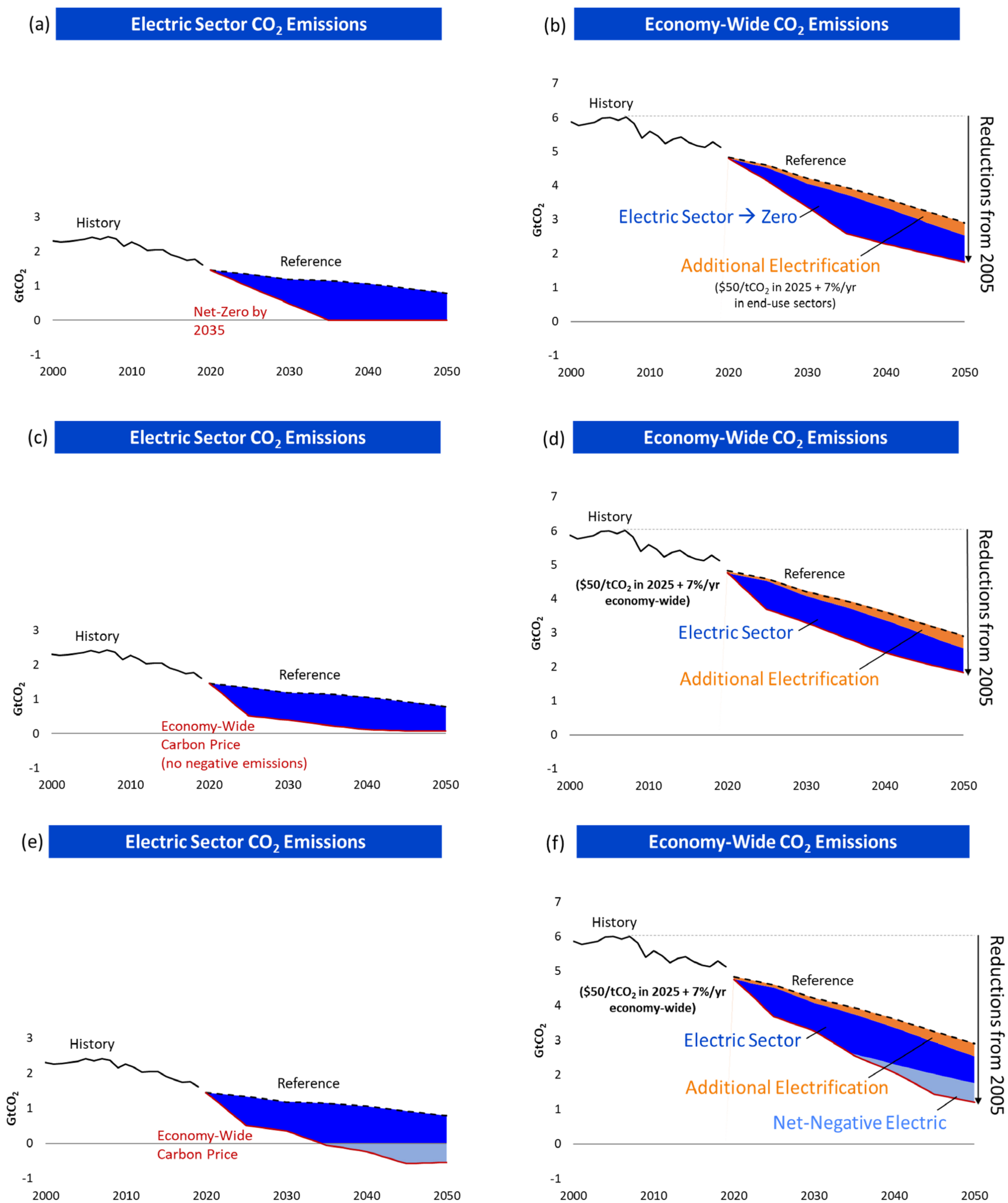

Figure 9. Electric Sector and Economy-Wide Emissions for Net-Zero by 2035 (a, b), Economy-Wide Carbon Price without negative emissions (c, d), and with negative emissions (e, f)

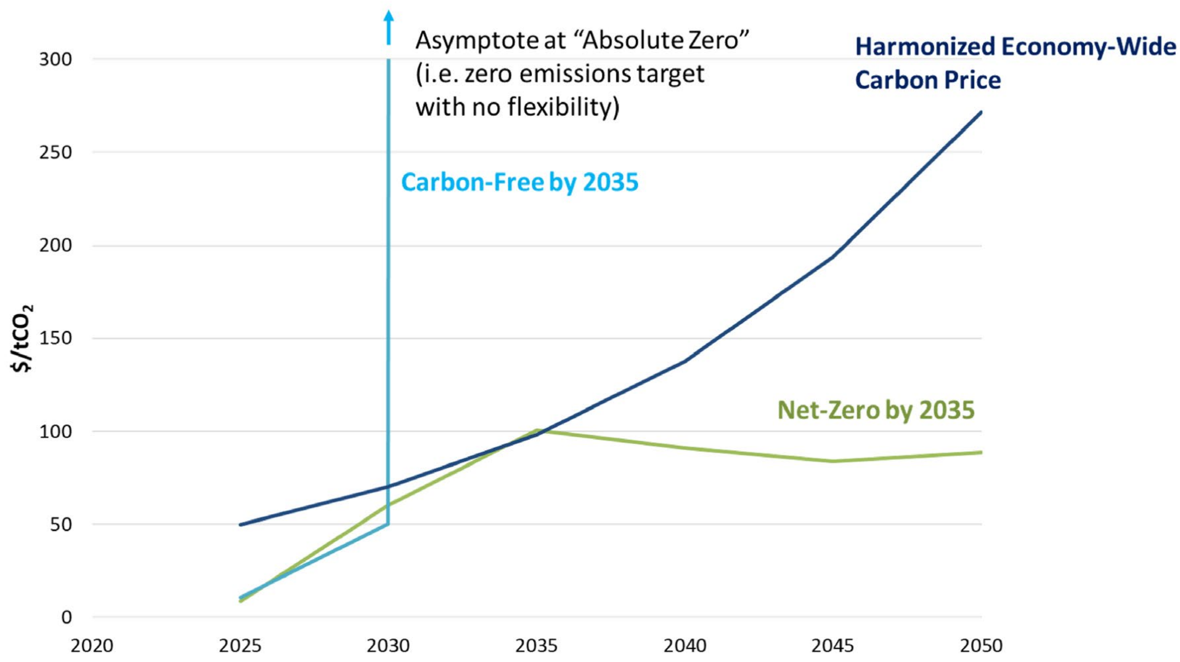

Figure 10. Carbon Price Across Scenarios

the same carbon price, the potential for negative emissions can be further leveraged to drive economy-wide emissions to 80% below 2005 by 2050. To achieve economy-wide net-zero, additional technologies and potentially additional policies are needed in the end-use sectors. These include low-carbon fuels derived from hydrogen and bioenergy as well as CCS in industrial applications, which are the subject of EPRI's forthcoming research effort under the Low-Carbon Resource Initiative (LCRI).[11]

Model Results: Economy-Wide Energy Service Costs

The results presented previously focused on the impact of alternative target definitions and timing for electric sector decarbonization on electricity prices, measured by the average generation cost per MWh. Although these costs reflect increased expenditures associated with decarbonizing electricity supply, they are only one component of total expenditures on energy and more broadly on energy services (for example, space conditioning, lighting, mobility, and process heat) from an economy-wide perspective. These include the costs of delivering electricity to retail customers (including transmission and distribution), the costs of nonelectric end-use fuels such as natural gas and petroleum products (for example, gasoline and heating oil), and costs of buying and maintaining energy-using equipment (such as vehicles and appliances). Trade-offs among these costs are critical to driving investments by more than 100 million homes and businesses that will be needed to decarbonize the nonelectric sectors of the economy.

Figure 11 shows how the electric generation costs shown previously stack up in relation to other energy and non-energy costs associated with providing energy services. Focusing first on the leftmost column, consumers today spend about $1 trillion annually on energy but around another $2 trillion on the purchase, operation, and maintenance of energy-using equipment. Only about $230 billion of that $3 trillion total, or less than 10%, goes toward the generation of electricity. The largest single component of the non-energy total is vehicles in the transportation sector (for example, cars, trucks, and planes), but it also includes appliances in buildings and industrial equipment such as boilers. The other columns in Figure 11 provide a snapshot of how annual expenditures are projected to change by 2050, when energy service demands (for example, vehicle miles traveled, heated floorspace, and so on) have increased as projected in AEO 2020—by roughly 45% when aggregated by current final energy use.

In the Reference scenario, total annual expenditures on electricity (that is, electricity consumption at retail prices) are higher in 2050

[11] See www.epri.com/lcri for more information.

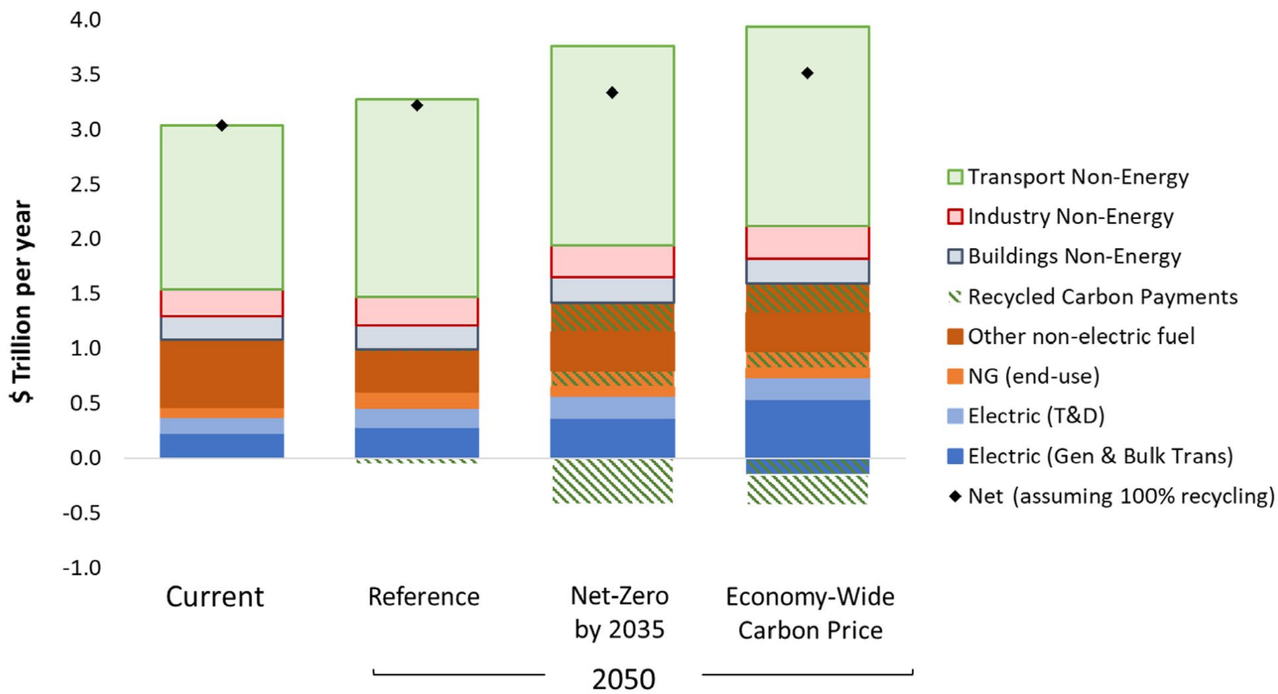

Figure 11. Total Economy-Wide Energy Service Costs

relative to today because of increased demand, which is primarily driven by electrification. However, with efficiency improvements and electrification displacing spending on nonelectric fuels, total energy expenditures actually fall over time in the Reference case. Consumers spend more on electricity and natural gas but much less on petroleum, especially gasoline and diesel in the transportation sector. On the other hand, with increased electrification and efficiency improvements, consumer expenditures on non-energy costs increase—especially in transportation, where the non-energy costs also include charging infrastructure associated with increased adoption of electric vehicles. Total expenditure on energy services increases slightly from today to 2050 but by much less than the projected growth in services demanded. Electrification and efficiency reduce consumers' total costs relative to continuing to use today's technologies, allowing energy service costs to stay relatively flat as services themselves grow.

In the Net-Zero by 2035 scenario, electricity expenditures increase further because of both the higher price of electricity (Figure 7) and additional demand through electrification (Figure 6). Relative to today, electricity use is 39% higher while electricity expenditures have increased by 57%. In the target scenarios, nonelectric fossil fuels are subject to a carbon price, shown in the hatched area in Figure 11. That carbon price is passed through to the end user's fuel price, which drives lower demand for nonelectric fuels, but expenditures (including the carbon price) increase. However, depending on how the carbon policy is implemented, there could be recycling or a rebate of some portion of those carbon payments back to households (shown as a negative flow in hatched green in the figure). In the Economy-Wide Carbon Price scenario, there are increased expenditures on the expanded deployment of BECCS to create additional negative emissions, which effectively results in the redistribution of some recycled carbon payments to BECCS producers, increasing net economy-wide costs. Finally, there is a slight increase in non-energy costs in the Net-Zero and Economy-Wide Carbon Price scenarios relative to the Reference because of additional electrification, but the main impacts of the carbon policy are reflected by the increase in energy expenditures—resulting in a 4–9% increase in total annual energy service costs (after recycling of carbon payments). Although this represents a relatively small increase, there are some important caveats:

- If carbon payments are not rebated to customers, total costs rise 15–21%, so policy design clearly makes a difference.
- Distributional impacts are important. Affordability of energy services for low-income households is a major issue for many parts of the country. The distribution of these costs will be another critical consideration for policy design.

- The total energy service cost metric does not capture potential macroeconomic impacts of the carbon price, nor any potential revenue recycling scheme, which could be non-negligible depending on the policy design.
- The electric sector results show how disruptive decarbonization will be from a technology perspective. The cost of addressing changing threats to the electric system (manmade and natural) have not been explicitly included.

Still, considering impacts on total energy service costs helps add perspective that energy costs per se are a relatively small part of the total economic picture.

Model Results: Economy-Wide Energy Service Costs versus Cumulative CO_2 Emissions

A final important distinction across the scenarios considered is the impact on cumulative CO_2 emissions. Because of the long-term nature of climate change, cumulative carbon emissions—rather than annual emissions at a target date—are the most relevant indicator for a scenario's contribution to global environmental impact.

Figure 12 plots results for each scenario in terms of cumulative emissions reductions and the net present value of incremental energy services costs, both measured relative to the Reference case. This chart allows a comparison of cost-effectiveness normalized by environmental performance. The Net-Zero targets achieve emissions reductions at lower cost than the more restrictive target definitions, while relaxing the target to 2050 lowers costs but also achieves fewer emissions reductions. The more restrictive target definitions for the electric sector not only increase costs, but also result in slightly higher emissions pathways because their higher prices discourage electrification. The economy-wide carbon price scenario without negative emissions from BECCS has slightly lower emissions than the Carbon-Free scenario, despite slightly higher emissions in the electric sector, but it has much lower costs because of the more efficient allocation between electric and nonelectric sectors. The economy-wide carbon price scenario including negative emissions achieves the lowest overall emissions, and although it is more costly than the Net-Zero by 2035 scenario, it falls on roughly the same efficient frontier.

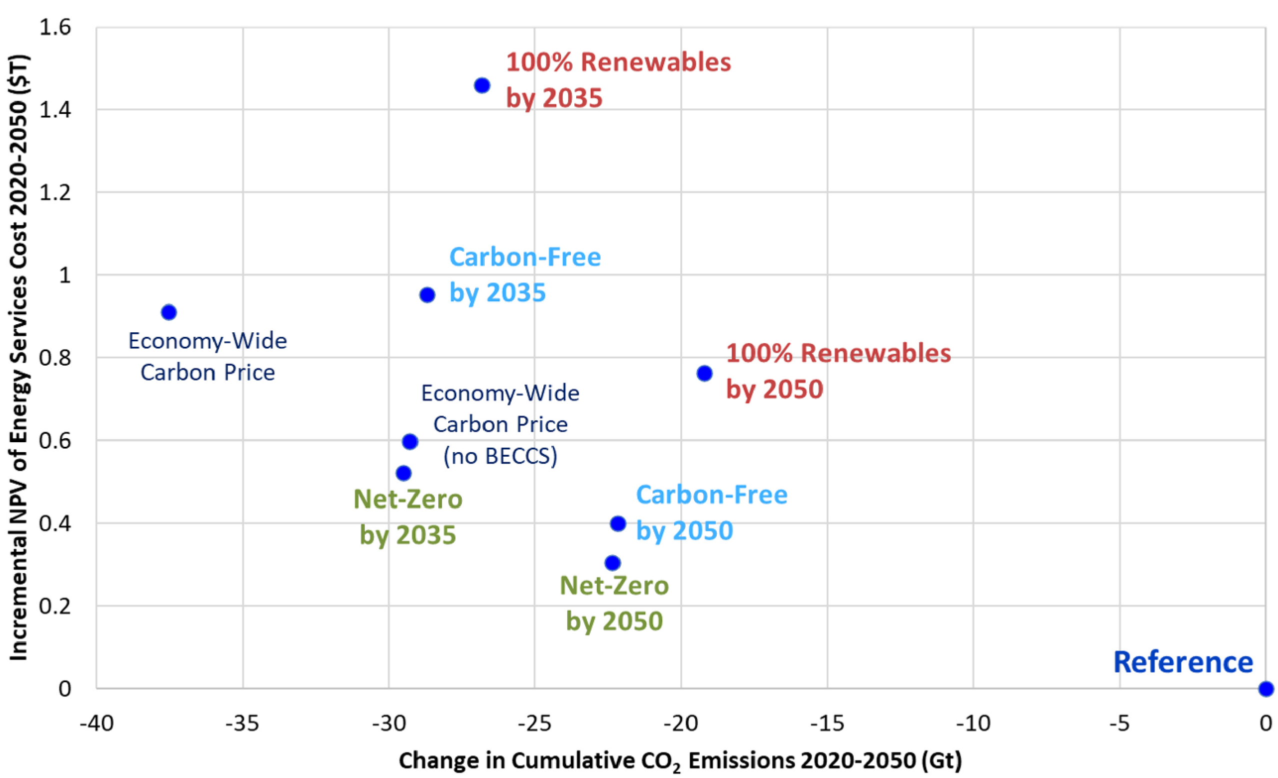

Figure 12. Incremental Net Present Value (NPV) of Energy Service Costs (net of recycled carbon payments) vs. Change in Cumulative Economy-Wide CO_2 Emissions Relative to Reference

Discussion

This analysis has illuminated the technologies and scale of change required to meet several commonly stated definitions of zero-emissions targets for the electric sector. Key insights from the analysis and some of their immediate implications include the following:

- **Target definition and timing matter.** The generation mix, cost, reliance on emerging technologies, and pace of change vary widely, depending on the definition of the target: Net-Zero, Carbon-Free, or 100% Renewables.
- **Solar and wind expand rapidly in all decarbonization scenarios, becoming the largest source of electricity generation by 2035.** With annual contributions to generation ranging from 45% to over 90% by 2035 versus 10% today, hourly contributions will frequently be much higher. Actions needed to allow this type of system to operate reliably include rapid grid expansion and modernization, new definitions for reliability, electricity market redesign, new communications and controls for integrating distributed energy resources (DER), and cyber security advances as system control becomes more distributed and automated and attacks become more sophisticated.
- **Immediate need for advanced low-carbon, firm capacity to balance solar and wind.** 130–380 GW of these technologies—CCS, BECCS, advanced nuclear, and/or clean hydrogen technologies (depending on the scenario)—are used to balance the system by 2035. Currently, these technologies are in operation at a scale of less than 1 GW. Moreover, deployment of negative emissions technologies allows conventional natural gas capacity to play a cost-effective balancing role.
- **Managing unprecedented pace of change.** "Zero" emission requires replacing or retrofitting 2/3 of today's electric generation and the wires to connect it, far exceeding the historical pace of change, whether accomplished over 15 or 30 years. Accelerated technology design, development, and field testing; streamlined permitting and siting coupled with increased public acceptance; support for communities with plant closures (280–500 GW of retired capacity by 2035 across scenarios); and development of the workforce for new manufacturing and construction (800–1900 GW of new generation and storage capacity by 2035 across scenarios) are key.
- **Efficiency and electrification essential.** Decarbonization will ultimately be driven by the energy and efficiency investments of more than 100 million households and businesses of widely varying means. Government standards, utility programs to overcome barriers to adoption where it makes sense, and efforts to support a just transition will be key factors.
- **Low-carbon fuels and carbon dioxide removal needed.** Even assuming zero electric sector emissions and aggressive electrification, a substantial portion of economy-wide emissions remains. Some combination of low-carbon resources, such as clean hydrogen and derivative synthetic fuels as well as bioenergy, potentially including carbon dioxide removal from the atmosphere (by nature-based or engineered solutions), will be essential to achieve net-zero emissions economy-wide.

Next Steps

EPRI will release a follow-up report examining the implications of this and other recent decarbonization studies, discussing in more detail the actions needed to implement the paths outlined here. As noted previously, quickly retooling the electric system will require technology, regulatory, market, and institutional advances.

Modeling efforts will advance in three directions:

- **Much more detailed analyses to explore planning, operational reliability, and resiliency in an electric grid with high deployments of solar and wind.** Although the US-REGEN modeling matched hourly supplies and demands, it was not able to evaluate the reliability of the future systems modeled—an essential step for guiding change.
- **Assessment of policy approaches.** The current analysis is largely policy-agnostic. Policies will be required to achieve zero emissions, and the forms of those policies will impact both total cost and distribution of costs.
- **Broader analyses that explore pathways to net zero for the economy.** More in-depth examination of emission reduction opportunities across the economy is essential to understand the roles of the sectors and the timing of reductions that minimize cost, maintain reliability, and achieve the ultimate national goal (rather than just a sectoral target).

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Appendix

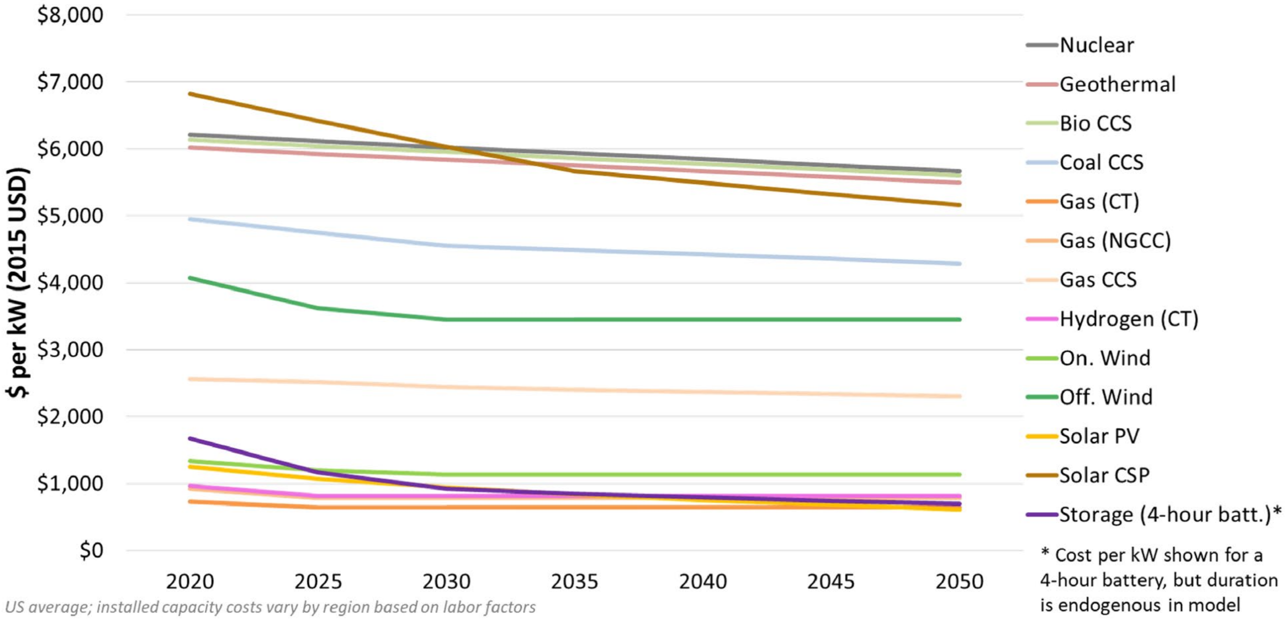

Figure A-1. US-REGEN Capital Cost Assumptions for Electric Technologies

Table A-1. Scenario Abbreviations

Current	Model Base Year (approximately 2020)
Reference	Reference (no federal carbon policy)
NZ 2050	Net-Zero by 2050 (80% below 2005 by 2035)
CF 2050	Carbon-Free by 2050 (80% below 2005 by 2035, no negative emissions)
100R 2050	100% Renewables by 2050 (80% Renewables by 2035)
NZ 2035	Net-Zero by 2035 (and thereafter)
CF 2035	Carbon-Free by 2035 (and thereafter)
100R 2035	100% Renewables by 2035 (and thereafter)
Econ Carb (No Neg)	Economy-Wide Carbon Price (no negative emissions)
Econ Carb	Economy-Wide Carbon Price (negative emissions allowed)

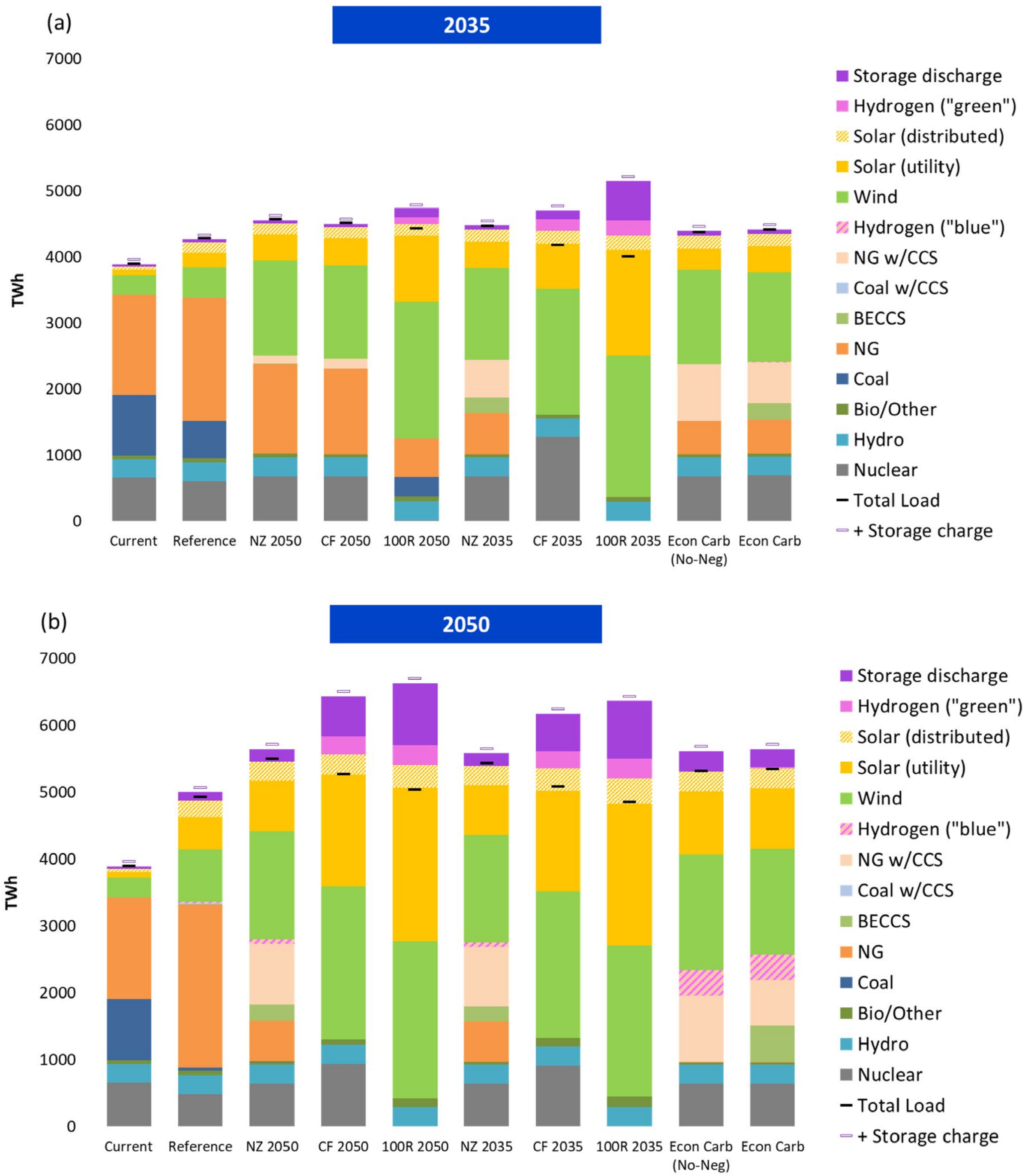

Figure A-2. U.S. Electric Generation in 2035 (a) and 2050 (b) Across All Scenarios

In Figure A-2, note the distinction between hydrogen ("blue"), which denotes generation from hydrogen produced from natural gas with CCS, and hydrogen ("green"), which denotes generation from hydrogen produced from electrolysis. The former use of hydrogen is similar to gas with CCS and does not appear in 2035. The latter represents the power-gas-power storage pathway described in the report.

EPRI RESOURCES

Geoffrey Blanford, *Senior Technical Executive*
650.855.2126, gblanford@epri.com

Tom Wilson, *Principal Technical Executive*
650.855.7928, twilson@epri.com

John Bistline, *Principal Project Manager*
650.855.8517, jbistline@epri.com

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Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com