Strategies and Actions for Achieving a 50% Reduction in U.S. Greenhouse Gas Emissions by 2030

EXECUTIVE SUMMARY

This white paper explores strategies to achieve the U.S. greenhouse gas (GHG) economy-wide emissions target of a 50–52% reduction from 2005 levels by 2030, identifying least-cost emission reduction actions across the electric sector, transport, buildings, and industry. Successfully implementing these strategies will require substantial policy changes coupled with accelerated deployment of electric end-use technologies and of electric sector technologies (including expedited financing, siting, permitting, and integration). While the analysis focuses on the U.S., many key findings provide insights that are valuable for nations with similar goals and rates of change.

The analysis focuses on three core scenarios:

- **Reference.** Assumes on-the-books federal and state policies and incentives [1]
- **50x30.** Achieves a 50% reduction in 2030 GHG emissions relative to 2005, assuming electrification economics and technology improvements consistent with earlier EPRI studies [2]
- **50x30 E+.** Assumes additional technology and policy drivers that accelerate electrification by lowering the cost of electricity-using technologies, reducing customers' reticence to shift technologies, and accelerating the turnover of end-use equipment

Outcomes are evaluated using EPRI's REGEN energy-economy model,[3] which integrates detailed representations of electric and end-use sectors and includes hourly simulations to capture the variability of renewables and load. The analysis was conducted with an eye to the future, recognizing that investments made today to meet 2030 targets are interim steps in a desired transition to net-zero. [4]

Results highlight that energy efficiency, cleaner electricity, and rapid electrification are the central strategies to achieve the 2030 target. Emerging technologies—carbon capture, utilization, and storage (CCUS); advanced nuclear; clean hydrogen—while important for driving future reductions, are unlikely to provide large reductions this decade given the stringency of the target and lead times for deploying these technologies at scale. Instead, the challenges in driving 2030 reductions are primarily in execution, with a 50% reduction requiring large changes in how energy is produced, delivered, used, and governed while maintaining reliability and affordability every step of the way. In parallel, technological advances and deployment incentives will be needed to facilitate more stringent 2035 and mid-century emission goals.

The rapid pace and extensive scale of change that this study (and other published analyses) project as necessary to meet these 50x30 scenarios highlight the need for additional efforts to understand key issues that are not fully addressed in this paper. EPRI has developed several companion studies that begin to identify and investigate some of these issues which are fundamental to a successful transition:[5]

- **Reliability.** Enhancing Grid Reliability and Resiliency in a Net-Zero Economy (http://mydocs.epri.com/docs/public/EPRI-Report-EnhancingEnergySystemReliability-20210804.pdf)
- **Grid Modernization and Decentralization.** Maximizing Distributed Energy Resource Value Through Grid Modernization (http://mydocs.epri.com/docs/public/EPRI-Report-MaximizingDistributedEnergyResourceValue-20210804.pdf)
- **Leveraging Existing Nuclear, Hydro, and Transmission.** Leveraging Existing Energy Infrastructure to Help Meet 2030 Greenhouse Gas Reduction Goals (http://mydocs.epri.com/docs/public/EPRI-Report-LeveragingExistingInfrastructure-20210804.pdf)
- **Climate Policy Choices.** Analyzing Federal Clean Energy Standards: Policy Design Choices and Future Electric Power Sector Outcomes (https://www.epri.com/research/products/000000003002020121)

[1] Tax subsidies for clean energy are assumed to expire per legislated schedules. Efficiency standards are assumed to remain in force (not weakened by future regulatory or legislative changes). State-level legislative and regulatory requirements are assumed to be met.

[2] EPRI (2018). "U.S. National Electrification Assessment," EPRI Report 3002013582.

[3] REGEN has been used extensively to explore energy system issues and potential policies. Full documentation and recent studies are available at: https://esca.epri.com/usregen

[4] A perspective on technology needs to achieve net-zero electric sector emissions is provided by: EPRI (2021). "Powering Decarbonization: Strategies for Net-Zero CO_2 Emissions," EPRI Report 3002020700.

[5] Additional papers are in development to address workforce and supply chain needs, siting/permitting/regulatory/codes/standards timelines, and the pace of innovation. Also, a companion analysis that examines economy-wide pathways to net-zero by mid-century is planned for late 2021.

EXECUTIVE SUMMARY | KEY FINDINGS

1. *Halving GHG emissions by 2030 will involve significant efforts beyond business-as-usual trends.*

- **Reductions triple their historic pace, enabled by accelerated electrification.** Electric sector CO_2 emissions reach 66–80% below their 2005 levels. End-use sectors (transport, buildings, and industry), which together have reduced their emissions by only 2% since 2005, electrify rapidly to reduce emissions by 23–33%. Accelerated end-use electrification avoids more costly electric sector reductions while still achieving the economy-wide 50% reduction target. The marginal cost of CO_2 reductions in 2030 required to reach the emission goal is projected to be \$86/t-CO_2 in the 50x30 scenario and \$50/t-CO_2 in 50x30 E+.
- **Achieving the 2030 interim emission goal will depend on strong policies.** The Reference case (i.e., no new policies) projects continued electric sector reductions combined with significant transport reductions, as consumers increasingly choose electric vehicle options and efficiency standards drive improvements across the fleet. However, emissions in this Reference scenario only achieve a 27% reduction in energy CO_2 by 2030 (from 2005 levels), around halfway to the target.
- **Emission reductions bring near- and long-term costs and benefits.** Power prices are projected to increase by 20-30%, with the increase varying across regions of the country. Total energy services spending[6] is projected to increase by 4–9% relative to Reference levels, which is an increase of \$115–275 billion annually (\$320–760 per person per year). Both 50x30 scenarios entail much lower non-CO_2 emissions relative to today and to the Reference scenario. The accelerated electrification scenario has lower NOx, CO, VOC, and $PM_{2.5}$ emissions than the 50x30 case (and the same CO_2 emissions), providing additional, immediate benefits for air quality and human health. Long-term GHG reduction benefits also would be substantial but may take decades to be realized.[7]

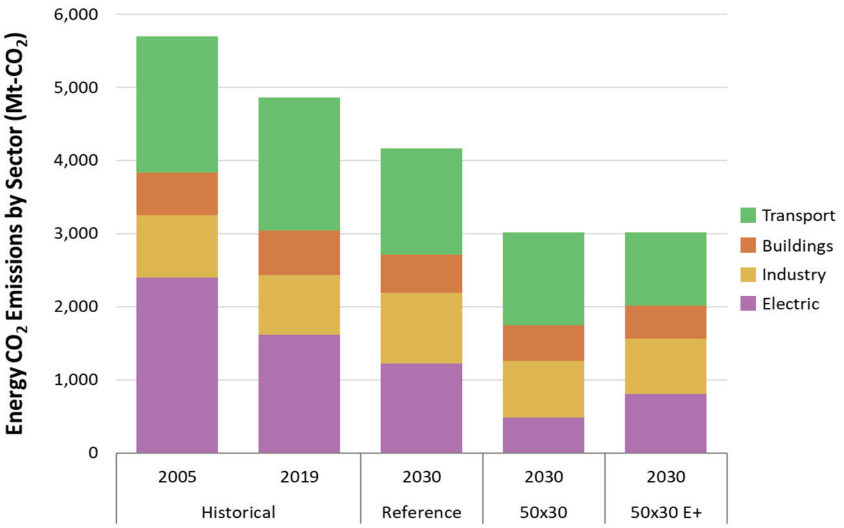

Figure 1. *U.S. historical energy CO_2 emissions by sector and 2030 scenarios. Historical emissions are based on U.S. EPA's "Inventory of U.S. Greenhouse Gas Emissions and Sinks."*

[6] Total energy services spending by households and businesses includes retail energy costs plus expenditures for purchase and maintenance of energy-using equipment (e.g., cars, HVAC, lighting). This study is agnostic to the specific form of policy and who will bear these costs (e.g., energy consumers or taxpayers).

[7] Intergovernmental Panel on Climate Change. Climate Change 2021: The Physical Science Basis (link).

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2. Reaching implied decarbonization targets for the power sector involves accelerated and sustained change.

- **Projected capacity additions in the 2020s total around half the capacity of the current U.S. grid in both 50x30 scenarios.** Annual wind and solar capacity additions would be two to three times their historical rates. Capacity additions—including renewables, storage, and natural gas—would exceed on average the historical maximum annual deployment in each year through 2030. In most instances, local transmission additions are needed to connect these new resources to the grid. In addition, inter-regional transmission is projected increase by 20% relative to current levels to help balance hourly supplies with demands economically. Deployment of this generation and grid equipment depends critically upon rapidly expanded equipment and labor supply.
- **Coal assets retire with attendant community, jobs, and financial impacts.** The transition from coal calls for thoughtful consideration of regional reliability, affordability, and environmental justice. Plant closure and repurposing decisions will have significant community impacts in many locations. They can also have rate and financial implications resulting from plants that are not fully depreciated when retired.
- **Firm capacity is a key asset for system balancing.** New natural-gas-fired capacity helps offset coal retirements, providing firm capacity to aid in balancing variable renewables, ensuring that supply can meet growing demand in every hour, minimizing electricity cost increases, and reducing system operational changes. Over time, these gas units operate less frequently, providing essential capacity, but less energy and emissions (and post-2030 they are converted for zero-emissions or their emissions are offset to reach net-zero). Although not pictured as system additions, continued operation of existing clean, firm capacity from nuclear and hydropower facilities helps balance the system. Continued coal use and more expensive options for providing new, firm capacity are deployed when gas capacity additions are limited.
- **New carbon-capture-equipped capacity can provide low-carbon, firm capacity.** Carbon capture, utilization, and storage (CCUS) is projected to be a critical technological enabler of a low-carbon future.[8] However, there are many challenges in bringing this capacity online by 2030, given that none are currently in operation in the U.S. If large-scale CCUS technology is available and viable, equipping existing fossil plants with CCUS could serve as an economic alternative to retiring certain fossil units and building new renewable generation in its place by 2030. Based on future technology deployment and economic assumptions, natural gas capacity with carbon capture totals 40 GW nationally in the 50x30 scenario, supporting an 80% reduction in electric sector emissions. Only a few units are economic in the 50x30 E+ scenario (where the electric sector reduces its emissions by 66%), providing a more measured ramp up of this technology. Given timelines for permitting, siting, and construction, many of the CCUS plants needed to meet post-2030 goals may need to begin development before 2030.

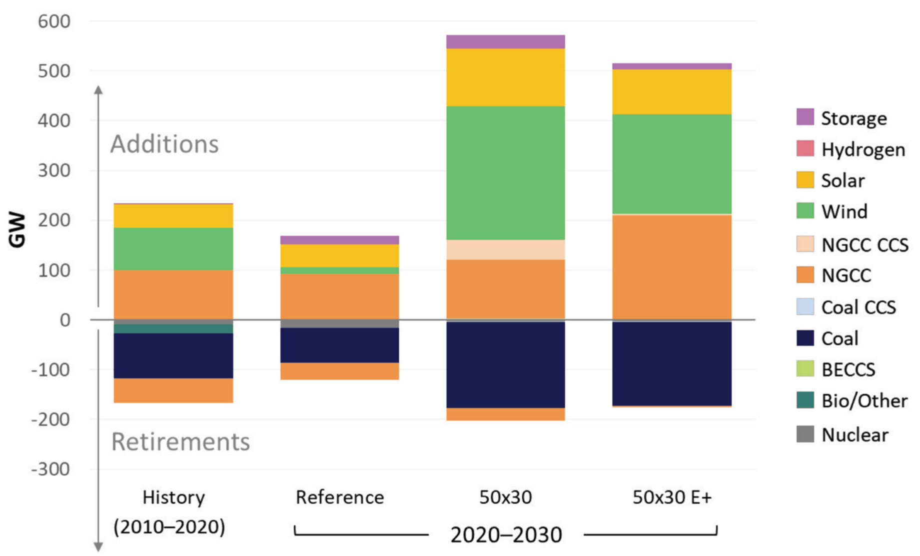

Figure 2. *Historical and projected capacity additions and retirements by technology, comparing decadal rates of change. Historical values come from Form EIA-860 data.*

[8] See for example, EPRI (2021). "Powering Decarbonization: Strategies for Net-Zero CO_2 Emissions," EPRI Report 3002020700.

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- **Electric sector technology pathways are sensitive to assumed costs and policies.** While significant additions of solar, wind, batteries, and natural gas and accelerated coal retirements are consistent threads through the scenarios, the precise future generation mix will be influenced by tax credits, renewable energy standards, the form of new federal policies (e.g., Clean Electricity Performance Program, EPA regulatory actions), fuel prices, technology advances, retail and wholesale electric market reforms, and post-2030 targets as well as local reliability needs and complementary policies related to resiliency, cybersecurity, and competitiveness (e.g., onshore manufacturing). For example:
  - Limits on natural gas capacity additions make continued use of existing coal assets viable in some regions.
  - Extension of credits for CCUS as contemplated in legislation could make coal with CCUS economically attractive.
  - Further reductions in renewable costs (via accelerated technology improvements or government incentives) could accelerate their deployment.
  - The post-2030 electric sector target (e.g., zero by 2035 or 2050) has relatively little impact on strategy for achieving the 2030 interim goal, as long as CCUS is a viable technology for getting to zero.

3. *Electrification and efficiency gains drive GHG reductions in transport, industry, and buildings.*

- **Electricity's share of end-use energy increases.** Electricity's share of end-use energy increases rapidly from 21% today to 29–33% by 2030. Though not pictured, the share grows to 24% in the Reference case, emphasizing that electrification (even without new policies) provides a range of efficiencies for consumers—lowering costs, energy use, and emissions (both CO_2 and key air pollutants) while improving productivity, product quality, and flexibility for many applications.
- **Transport leads the way, but electrification is a critical reduction strategy for all sectors.** Electricity provides 8–16% of end-use demand in transportation by 2030 versus less than 1% today. Buildings, which are already highly electrified, progress more slowly due to slower equipment replacement and because efficiency gains with existing loads partially offset increases in electric shares of space and water heating. Industrial electrification is somewhat less in the 50x30E+ scenario due to the lower marginal cost of reductions required.
- **Energy efficiency gains temper electricity and energy demand growth.** Population is projected to increase by 7% and GDP by 24% by 2030. The projected 16–23% growth in electricity demand by 2030, driven by economic growth and electrification, would be substantially higher but for efficiency-driven reductions in demands for lighting, cooling, and other traditional electric services. With half the new vehicle and heating purchases being non-electric over the next decade, the value of efficiency gains for these and other non-electric end-uses is paramount as well.
- **Rapid end-use changes mean quickly changing supply chains and buying habits of tens of millions of households.** Using transport to illustrate the nature and scale of the end-use challenge, 18 million new passenger vehicles are purchased in the U.S. each year adding to a fleet of 240 million registered vehicles. Accelerating emission reductions requires rapid change in purchase preferences coupled with accelerated turnover of the fleet.

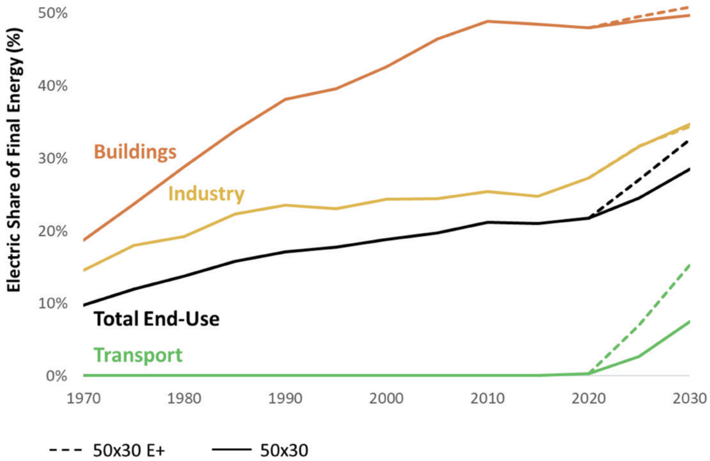

Figure 3. *Electricity share of final energy by sector and scenario. Historical values come from U.S. Energy Information's "State Energy Data System" (https://www.eia.gov/state/seds/).*

EXECUTIVE SUMMARY | KEY FINDINGS

4. Consistent emission reduction strategies for achieving 50x30 are emerging, but fundamental questions remain about how to support immediate action while building systems for planning and investment that are adaptive to new information.

- **A comparative analysis of public 50x30 studies suggests that these analyses agree on the key roles of efficiency, cleaner electricity, and electrification.** Although their perspectives differ on how fast change can occur in each sector, the studies all rely on these three pillars for near-term and deeper emissions reductions. A unique feature of this study is that the allocation of sectoral emissions reductions is a modeling outcome rather than an input assumption, allowing the analysis to identify where the lowest-cost reductions might be available to reach the 2030 target.
- **Studies agree directionally on accelerated deployment of solar, wind, and batteries, reduced use of coal and continued use of existing nuclear and hydropower.** While there is directional agreement on solar and wind, the studies differ significantly in the scale of change. For example, a study by LBNL[9] projects the addition of 1,200 GW of new solar, wind and batteries by 2030 (around twice the capacity additions of all types in EPRI's 50x30 scenario). A central point of agreement is the need to invest in the grid and change institutions (e.g., markets) to achieve any of the futures outlined by the modeling teams to drive the needed investments and maintain/improve reliability.
- **Studies agree that lowering non-CO_2 GHGs and enhancing the land sink will also be important for reaching the 2030 target.** Many do not explicitly model these emissions, but all acknowledge that they are integral to meeting the overall GHG target. Shorter-lived gases like methane may play a key role in moderating near-term climate change. Measures to enhance the net sink from natural and working lands (e.g., reforestation, agroforestry, wildfire management) lead to about a 1-gigaton (Gt) CO_2 sink by 2030.
- **Studies differ on the extent of additional firm capacity needed, and none of the studies has conducted full reliability assessments.**[10] As noted in the capacity buildout discussion earlier, EPRI modeling projects a need for firm capacity additions to partially offset coal and gas retirements.[11] Other 50x30 studies also add new gas capacity (with and without carbon capture) and battery storage, in addition to today's fleet of gas, nuclear, and hydropower to balance the system. None of the studies, including this one, perform reliability assessments. Some match hourly generation and loads and examine basic system operations (e.g., dispatch, ramping needs). However, with the large restructuring of the sources, delivery, and uses of power that all the modeling efforts project, detailed regional reliability assessments are needed for more granular guidance on investment and operational needs.
- **Studies differ on the pace of electric sector reductions.** While EPRI's assessment explores reductions across the economy based on economics, most of the other studies present illustrative pathways, generally assuming around 80% electric sector CO_2 reductions by 2030. EPRI's perspective is that given the policy, technology, and institutional hurdles that emission reduction efforts face in all sectors, understanding the full array of potential low-cost reductions and their achievability are critical to charting affordable, reliable, and equitable paths to the 50x30 target.

[9] Abhyankar, et al. (2021). "Illustrative Strategies for the United States to Achieve 50% Emissions Reduction by 2030," LBNL (Berkeley, CA).

[10] For a discussion of firm capacity in the context of California's net-zero goals, see, for example, Long, Jane C.S., Ejeong Baik, Jesse D. Jenkins, Clea Kolster, Kiran Chawla, Arne Olson, Armond Cohen, Michael Colvin, Sally M. Benson, Robert B. Jackson, David G. Victor, and Steven P. Hamburg. "Clean Firm Power is the Key to California's Carbon-Free Energy Future." Issues in Science and Technology (March 24, 2021).

[11] In scenarios where new gas additions were limited, some existing coal remained with infrequent operation to provide this capacity.

STRATEGIES AND ACTIONS FOR ACHIEVING A 50% REDUCTION IN U.S. GREENHOUSE GAS EMISSIONS BY 2030

INTRODUCTION

In April 2021, the U.S. updated its Nationally Determined Contribution (NDC) as part of the Paris Agreement, committing to achieve 50-52% reductions in economy-wide net greenhouse gas (GHG) emissions by 2030 relative to 2005 levels.[12] Reaching this goal requires the U.S. to roughly triple the rate of decarbonization compared to reductions in the previous 15 years (Figure 4). In 2019, net GHGs declined 13% from 2005 levels due primarily to electric sector reductions, which were 33% below their 2005 levels. As the NDC suggests, 2030 is an interim point along the pathway to reach economy-wide net-zero emissions by 2050, which would extend a similar pace of reduction through 2030 across two additional decades. Interim targets must balance near-term reductions with the imperative to move rapidly, reliably, affordably, and equitably toward the longer-term target.

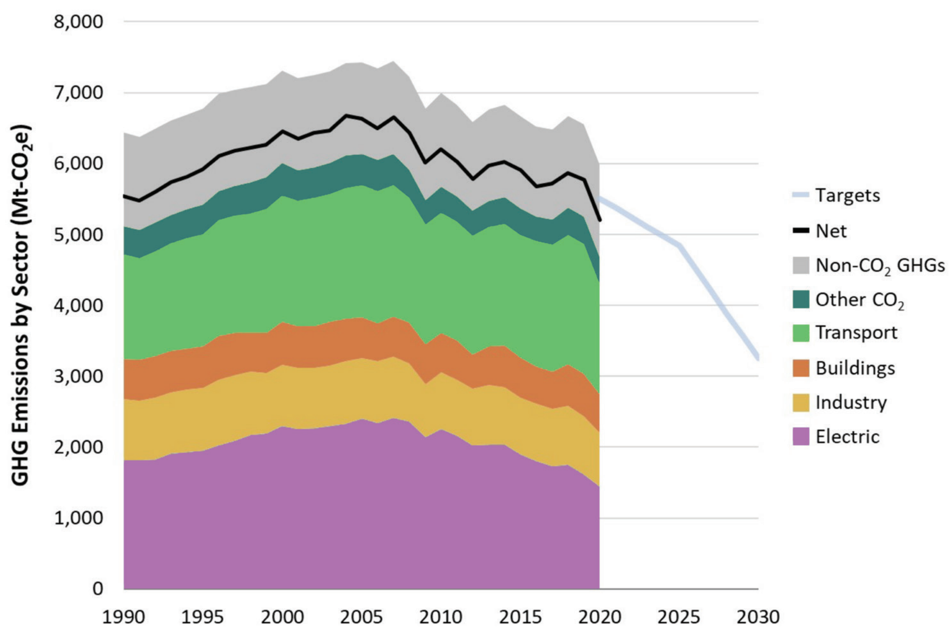

Figure 4. *U.S. historical GHG emissions by sector and future targets. Historical emissions are based on U.S. EPA's "Inventory of U.S. Greenhouse Gas Emissions and Sinks" with preliminary 2019-2020 data from the U.S. EIA. "Other CO_2" refers to non-energy CO_2 emissions. Net GHG emissions account for net negative emissions from the land sink. The discontinuity in 2020 emissions is primarily due to the COVID-19 pandemic, and expectations are that 2021 emissions will rebound with re-opening of economies.*

[12] "The United States of America: Nationally Determined Contribution" (link).

State targets and voluntary company goals can support the national 50x30 target. Seven states have legislated 100% renewable or clean electricity requirements before or by 2050—California, Maine, Nevada, New Mexico, New York, Virginia, and Washington. Eleven states have statutory targets for economy-wide emissions reductions ranging from 80% to net-zero levels. Governors in other states have set economy-wide executive targets, including Michigan (net zero by 2050) and Montana (GHG neutral by 2045–2050), amongst others. Most goals, whether legislated or aspirational, target mid-century.

Figure 5 shows a decomposition of 2019 GHG emissions by subsector. Emissions come from a wide variety of economic activities, including not only the energy system but also industrial process CO_2 emissions, non-CO_2 GHGs from agriculture, and other emissions from forestry and land use. Pathways to the 2030 NDC and 2050 net-zero target include reductions from almost everywhere across the economy to varying degrees.

Given these bold targets, this analysis explores strategies for achieving 50% reductions (relative to 2005) in economy-wide GHG emissions in the U.S. by 2030 and identifies challenges that achieving these goals may present. The analysis outlines actions to enable reductions in the electric sector, transport, buildings, and industry, including discussions of operational reliability, electrification opportunities, implications for customer affordability, and potential implementation challenges. Specific questions addressed in the report include:

- What are the sectoral shares of reductions across electric, industry, buildings, and transport for achieving the U.S. target under alternative assumptions about technology cost, performance, availability, incentives, uprating of existing assets, and post-2030 pathways?

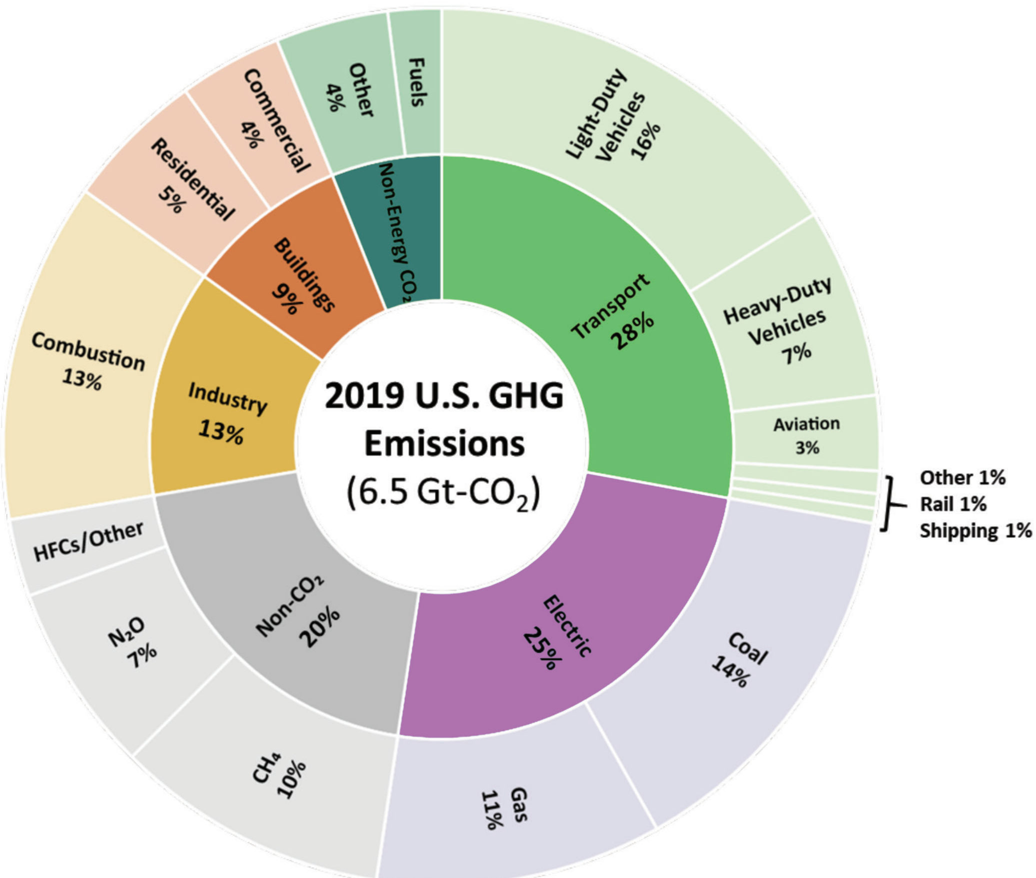

Figure 5. *U.S. GHG emissions by subsector in 2019. Emissions are based on U.S. EPA's "Inventory of U.S. Greenhouse Gas Emissions and Sinks."*

- What are the implications of accelerated electrification in reaching CO_2 reduction targets?
- How do pathways vary by region?
- What do the pathways imply for customers and communities?
- What are key implications of the scale and pace of change that other pathways analyses do not fully address (e.g., reliability)?

Recent modeling studies have investigated how the U.S. could roughly halve its net GHG emissions by 2030.[13] These studies have shown illustrative pathways for reaching the 2030 goal targeting different mixes of reductions from the electric sector and non-electric CO_2 emissions (Figure 6). Electric sector CO_2 reductions are generally assumed in these studies and range from 76–84%, reflecting ongoing policy discussions around 80% clean electricity, while their assumptions for the land sink range from -0.79 to -1.2 Gt-CO_2 per year. These assumptions imply non-electric CO_2 reductions (i.e., reductions of direct emissions from transportation, buildings, and industry) from 17–28% relative to 2005.

With the goal of reducing emissions quickly, affordably, and reliably across all sectors, this analysis examines scenarios with different levels of electric and non-electric reductions to show implications of alternate pathways. A unique feature is that the allocation of sectoral emissions reductions is a modeling outcome rather than an input assumption, allowing the analysis to identify where the lowest-cost reductions might be available to reach the 2030 target, with a particular focus on the extent of reductions that could be achieved through electrification.[14] Figure 6 illustrates potential allocations of electric and non-electric CO_2 reductions consistent with the 2030 GHG target and compares the two core 50x30 scenarios in this analysis with reductions in other studies. Scenarios falling in the green range achieve this 2030 target, and the scenario above the range indicates deeper reductions.

This study—like others that evaluate pathways to meet the 2030 goal and most net-zero pathway studies for the U.S.—provides directional guidance on the technologies that could play roles in reaching near-term targets. Companion white papers identify and address key issues in greater detail:

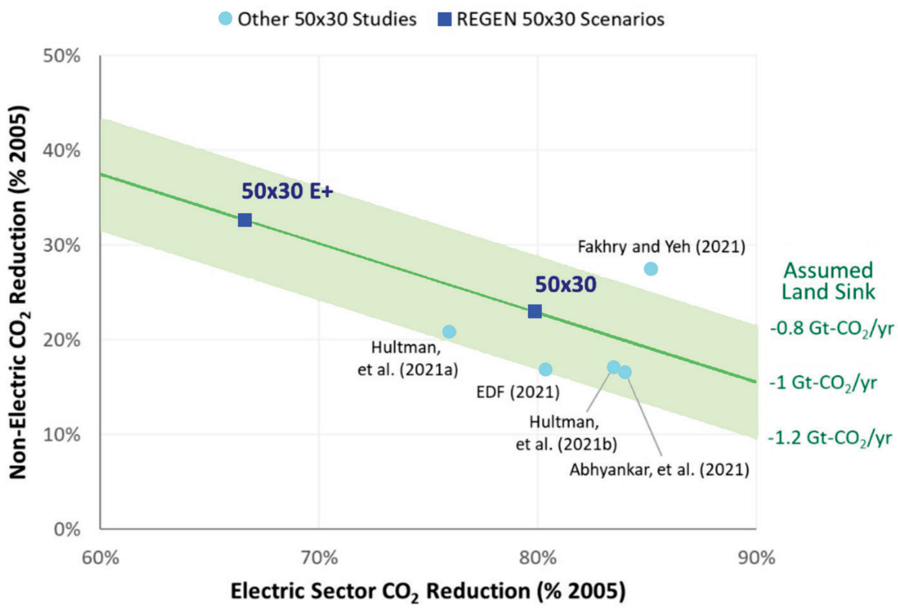

Figure 6. *Tradeoff between electric and non-electric CO_2 reductions to reach the U.S. 50% net GHG reduction by 2030. The green range illustrates how alternate assumptions about negative emissions from the land sink influence reductions required elsewhere. Light blue dots represent other 50x30 studies, and dark blue squares depict the core reference and accelerated electrification scenarios ("50x30" and "50x30 E+", respectively) in this analysis.*

[13] Studies depicted in this figure published analyses of the U.S. NDC "50x30" target. Abhyankar, et al. (2021) "Illustrative Strategies for the United States to Achieve 50% Emissions Reduction by 2030;" EDF (2021) "Recapturing U.S. Leadership on Climate;" Fakhry and Yeh (2021) "The Biden Administration Must Swiftly Commit to Cutting Climate Pollution at Least 50% by 2030;" Hultman, et al. (2021a) "Charting an Ambitious U.S. NDC of 51% Reductions by 2030;" Hultman, et al. (2021b) "America Is All In." Other research groups, notably Princeton University, Rhodium, and others have examined longer-term net-zero policies.

[14] This analysis is policy agnostic, examining the implications of generic reduction policies rather than focusing on the many important issues around policy design. Other EPRI analyses, e.g., EPRI Report 3002020121, assess choices in implementing an electric sector Clean Energy Standard.

- **Reliability.** Enhancing Grid Reliability and Resiliency in a Net-Zero Economy (http://mydocs.epri.com/docs/public/EPRI-Report-EnhancingEnergySystemReliability-20210804.pdf)
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- **Climate Policy Choices.** Analyzing Federal Clean Energy Standards: Policy Design Choices and Future Electric Power Sector Outcomes (https://www.epri.com/research/products/000000003002020121)

The next section discusses the modeling framework for this analysis and scenario assumptions. The subsequent section details the findings of this analysis. A concluding section summarizes key takeaways from the white paper and highlights opportunities for future research. An appendix provides additional detail regarding input assumptions and analysis results, including electric sector sensitivity analyses.

SCENARIOS AND MODELING

This section provides an overview of the modeling framework used in this analysis and scenario assumptions. Additional information is provided in the appendix and detailed model documentation.[15]

REGEN Model Overview

The analysis uses EPRI's U.S. Regional Economy, Greenhouse Gas, and Energy (REGEN) model, which integrates a detailed capacity planning and dispatch model of the electric sector and an economic model of non-electric sectors capturing end-use technology tradeoffs. The electric sector model makes simultaneous decisions about capacity planning, transmission expansion, and dispatch, including load profiles that reflect the evolving end-use mix. The model features hourly resolution for investment and operations, which better characterizes the economics of variable renewables, energy storage, and firm low-carbon resources relative to models with a dozen or so time periods. The end-use model captures technology choices with heterogeneity across different sectors, structural classes, and regions (Figure 7).

Scenario Design

The analysis centers on three core scenarios: A reference (which includes all on-the-books federal and state policies

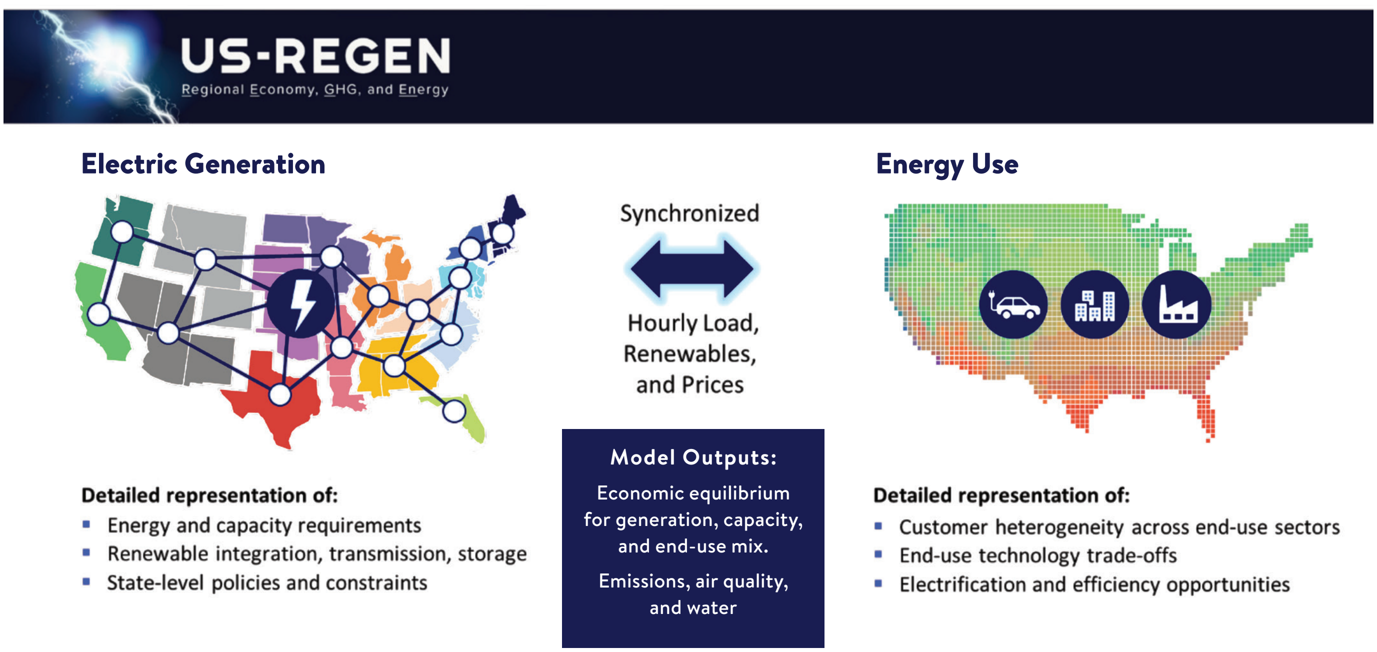


Figure 7. *Overview of the US-REGEN model. Full model documentation and other recent reports can be found at* https://esca.epri.com/.

[15] REGEN has been used extensively to explore energy system issues and potential policies. Full documentation and recent studies are available at: https://esca.epri.com/models.html.

and incentives)[16] and two 50x30 scenarios, as shown in Table 1. The 50x30 scenarios equalize marginal costs of reductions across sectors to reach the 2030 target at the lowest cost. Although this goal is operationalized with an economy-wide emissions cap, this implementation could be interpreted as a proxy for a suite of policies and incentives at federal and state levels to lower emissions consistent with a least-cost sectoral allocation. The two 50x30 scenarios vary the level of electrification, which alters the relative shares of emissions reductions in the electric and non-electric sectors:

- **Reference electrification ("50x30").** This scenario represents a cost-effective allocation of emissions reductions across the economy with standard REGEN assumptions about electrification and efficiency. As discussed in the next section, this scenario projects close to an 80% reduction in power sector CO_2 emissions relative to 2005 and a 23% reduction in non-electric CO_2 emissions as the least-cost strategy for achieving the 2030 economy-wide goal.
- **Accelerated electrification ("50x30 E+").** Given the considerable challenges with reaching 80% reductions in power sector emissions by 2030 (e.g., large increases in wind and solar capacity additions; intra-/inter-regional transmission build-outs; reliability questions raised by the scale, nature, and rapidity of system changes; regulatory/siting/permitting delays and land-use impacts; and potential reliance on an emerging technology—carbon-capture-equipped capacity), an alternate scenario examines how accelerated electrification could reach the 2030 goal if electric sector change is slowed. As shown in Table 1, this scenario assumes lower costs for end-use technologies and policies to encourage adoption, including accelerating stock turnover, lowering deployment barriers, and providing adoption incentives.

Additional electric sector sensitivity analyses to assess the viability and deployment risk for power sector resources are discussed in later sections.

All scenarios use EPRI inputs for technology cost and performance assumptions and U.S. Energy Information Administration assumptions on economic growth and fuel prices. These assumptions are consistent with advances in clean technologies (both supply- and demand-side options) and recent market trends.

The analysis assumes that the land sink, non-CO_2 GHGs, and non-energy CO_2 reductions evolve similarly to other 50x30 studies. Measures to enhance the net sink from natural and working lands (e.g., reforestation, agroforestry, wildfire management) lead to about a 1-gigaton (Gt) sink by 2030. As shown in Figure 8, these assumptions imply a 47% reduction in energy CO_2 relative to 2005—to almost exactly 3 Gt-CO_2/yr—to meet the 2030 50% goal. The U.S. NDC also has a goal "to reach 100 percent carbon pollution-free electricity by 2035," which is incorporated in the policy scenarios as a constraint on electric sector emissions to reach net-zero levels in 2035.

Table 1. *Core analysis scenarios and assumptions.*

	Reference (Current Policies)	50x30 (Reference Electrification)	50x30 E+ (Accelerated Electrification)
All Sectors: Economy-Wide CO_2 Cap Reaching 2030 Target		•	•
Electric Power: State/Federal Policies and Incentives	•	•	•
Electric Power: Post-2030 Target		Zero by 2035	Zero by 2035
Turnover of End-Use Equipment	Reference	Accelerated	Accelerated
End-Use Diffusion Parameters	Reference	Reference	High
Cost/Performance of Heat Pumps, Electric Vehicles, and Others	Reference	Reference	Advanced[17]
Incentives for Accelerated Electric Vehicle Adoption	None	None	Yes
Incentives for Accelerated Heat Pump Adoption	None	None	Yes

[16] Tax subsidies for clean energy are assumed to expire per legislated schedules. Efficiency standards are assumed to remain in force (not weakened by future regulatory or legislative changes). State-level legislative and regulatory requirements are assumed to be met.

[17] The accelerated electrification ("50x30 E+") scenario assumes reductions of $7,000/vehicle for light-duty, electric cars and trucks, capital cost reductions for electric alternatives for medium- and heavy-duty transport of 30% relative to reference levels, and heat pump adoption for new construction. Cost reductions in this scenario could be interpreted either as faster-than-expected cost declines or as policy-driven incentives.

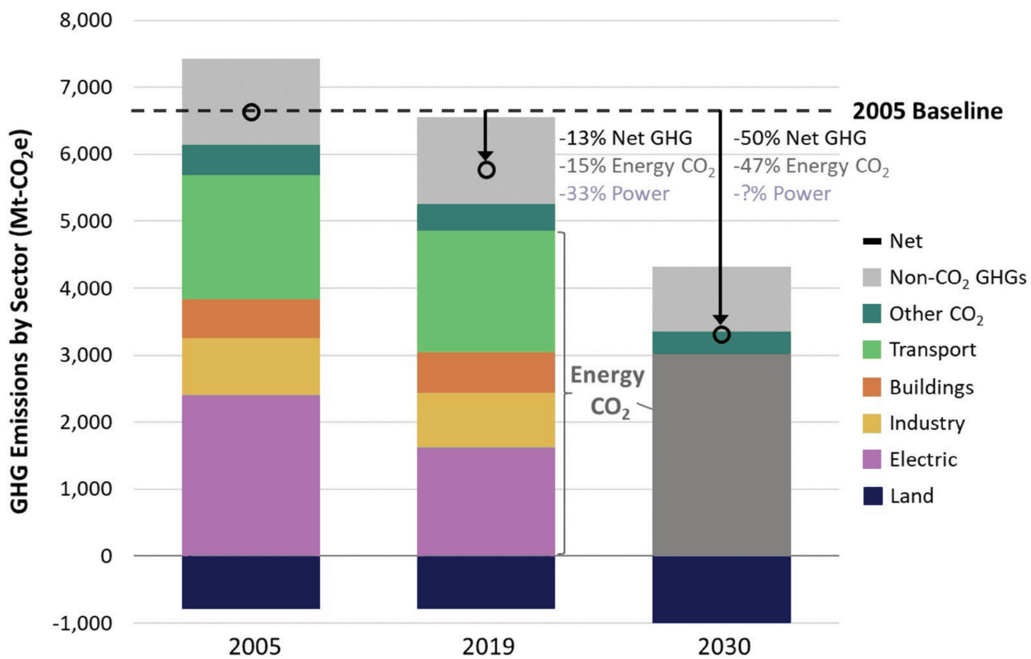


Figure 8. *U.S. historical GHG emissions by sector and 2030 target. Historical emissions are based on U.S. EPA's "Inventory of U.S. Greenhouse Gas Emissions and Sinks." "Other CO_2" refers to non-energy CO_2 emissions.*

Models are tools for systematically exploring insights about complex sociotechnical systems but are not crystal balls. Model simplifications are important to bear in mind when interpreting results and motivate additional studies. In some instances, models may underestimate potential emissions reductions due to understating technological change; in others, models may not capture on-the-ground realities that make decarbonization more challenging. Several modeling simplifications in REGEN are important to note in this study:

- **First.** The scenarios assume that the future policy and regulatory directions are clear, supply chains are ready, and actions to meet the goals begin immediately, while the reality is that policies are being discussed at the federal level (in late 2021). State-level implementation and ramping up action will take time, and costs may rise as companies compete for scarce resources.
- **Second.** The electric sector modeling does not explicitly incorporate operational constraints such as inertia, though there are efforts underway at EPRI to investigate how these dimensions impact both planning and operational decisions.[18] To reflect operational challenges with high shares of inverter-based resources, all scenarios include constraints on the maximum instantaneous non-synchronous penetration share, which is assumed to be 90% of generation for each hour in every model region.
- **Third.** An historical weather year (2015) is used for consistency of meteorologically driven load, solar, and wind data; more analysis is needed to understand impacts of inter-annual variability for sector-coupled analysis and electric sector outcomes.
- **Fourth.** The modeling does not include some low-carbon fuel production pathways such as biofuels and low-carbon hydrogen for end-use applications that could become more important toward 2050 as the economy-wide net-zero GHG target is approached.[19]

These limitations—combined with uncertainties about future technological change, economic growth, demographic changes—suggest that results should interpreted as indicative rather than predictive.

[18] Enhancing Grid Reliability and Resiliency in a Net-Zero Economy (http://mydocs.epri.com/docs/public/EPRI-Report-EnhancingEnergySystemReliability-20210804.pdf) introduces the reliability challenges by a changing grid and opportunities to address these issues though technology advances and institutional change. A related, Board-level modeling effort at EPRI aims to advance the art in integrated system planning (reference to ISSP). Linking generation, transmission, and distribution planning tools with customer models and consideration of physical climate change.

[19] Pathways to net-zero economy-wide emissions will be explored in an analysis planned for release later in 2021 as part of the EPRI and Gas Technology Institute-led Low Carbon Resource Initiative (https://www.epri.com/lcri).

RESULTS

This section highlights quantitative REGEN scenario outputs and qualitative discussions of key considerations. Results compare required efforts to reach 2030 goals relative to current and business-as-usual trends to contextualize possible challenges.

Economy-Wide Decarbonization

To achieve 50% reductions in GHG emissions by 2030, fundamental changes to all sectors are required relative to the current system and relative to a reference projection with current policies (Figure 9).[20] Reductions in energy-related CO_2 emissions to date have largely come from the power sector, which lowered its CO_2 by 33% between 2005 and 2019. Despite assumed growth in economic output and energy service demands by 2030 (increasing by 24% and 12%, respectively), CO_2 emissions in the reference scenario are projected to decline by 27% relative to 2005, including a 49% reduction in electric sector CO_2.

To reach the 2030 target, emissions reductions are greatest for the electric and transportation sectors (Figure 10). With reference electrification ("50x30"), 72% of total emissions reductions come from electricity (which reduces its CO_2 by ~80% from 2005 despite a 16% increase in load), while transport accounts for most of the remaining reductions. The last decade has seen significant reductions in the costs of technologies to decarbonize power and electric vehicles, enabling these sectors to make near-term reductions at relatively low cost compared to the other sectors. In industry, a combination of energy efficiency, electrification, and petroleum-to-gas switching are mostly offset by growing service demand, which increases by 20% to 40% across industrial sectors between 2020 and 2030, yielding a small net reduction. Achieving these reductions would likely require strong policy: The marginal cost adders are \$61/t-CO_2 in 2025, escalating to \$86/t-CO_2 in 2030 with a nearly \$100/t-CO_2 price by 2035 for the power sector to reach net-zero emissions (Figure 26 in the appendix).

Accelerated electrification creates more reductions in non-electric sectors, allowing the electric sector to delay more costly reductions while still achieving economy-wide 50% target. Additional reductions in the "50x30 E+" scenario are greatest for transport, but even in this scenario, the electric sector represents over half of economy-wide reductions (~66% lower CO_2 from 2005, repeating the reduction obtained between 2005 and 2019 over the next nine years).

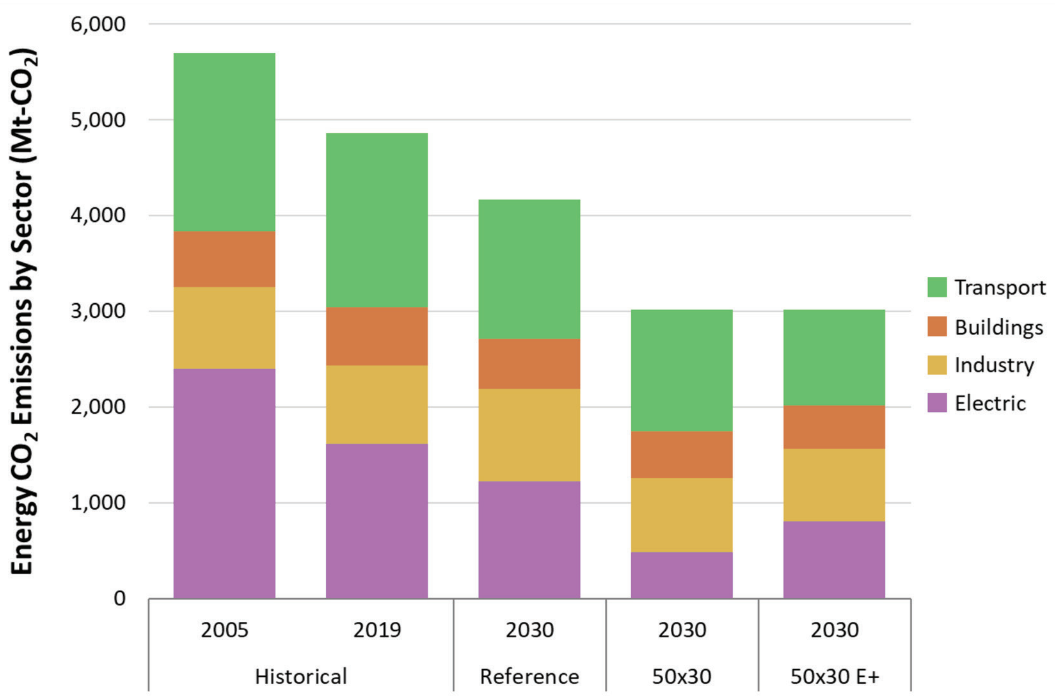
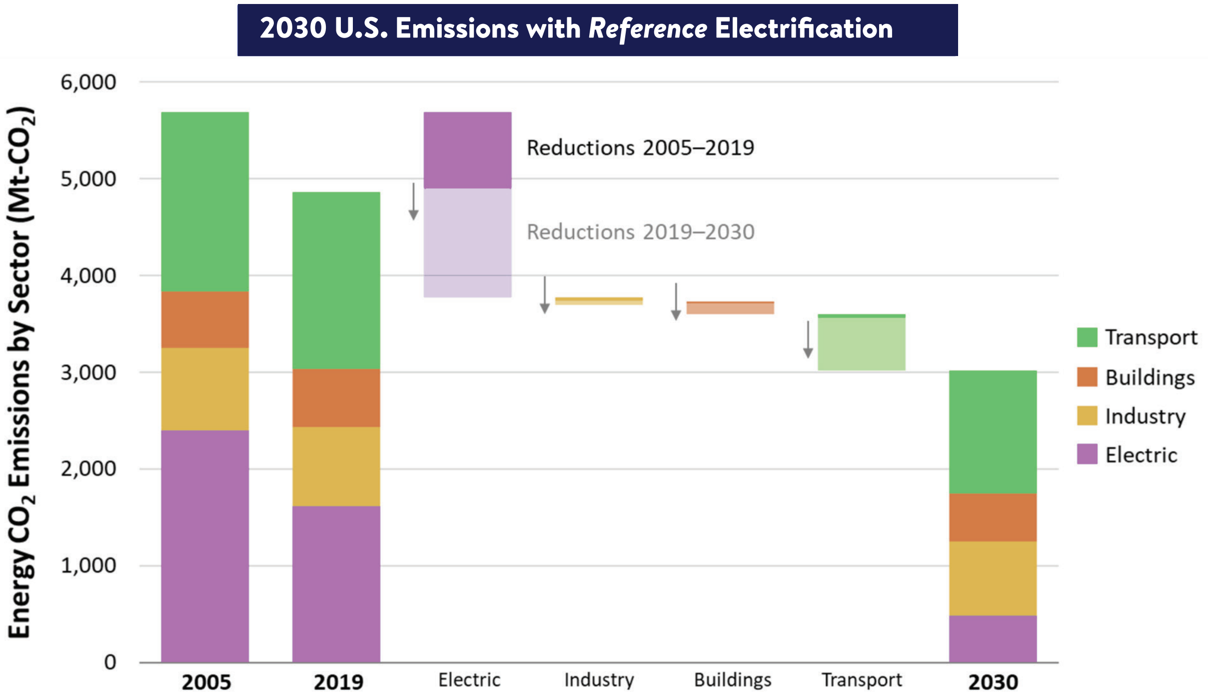


Figure 9. *U.S. historical energy CO_2 emissions by sector and 2030 scenarios. Historical emissions are based on U.S. EPA's "Inventory of U.S. Greenhouse Gas Emissions and Sinks."*

[20] Results focus on energy system CO_2 emissions given the scope of the modeling and large role that these emissions play in determining economy-wide GHG emissions. The analysis assumes that the land sink, non-CO_2 GHGs, and non-energy CO_2 reductions evolve similarly to other 50x30 studies. These assumptions imply a 47% reduction in energy CO_2 relative to 2005—almost exactly 3 Gt-CO_2/yr—to meet the 2030 50% goal.



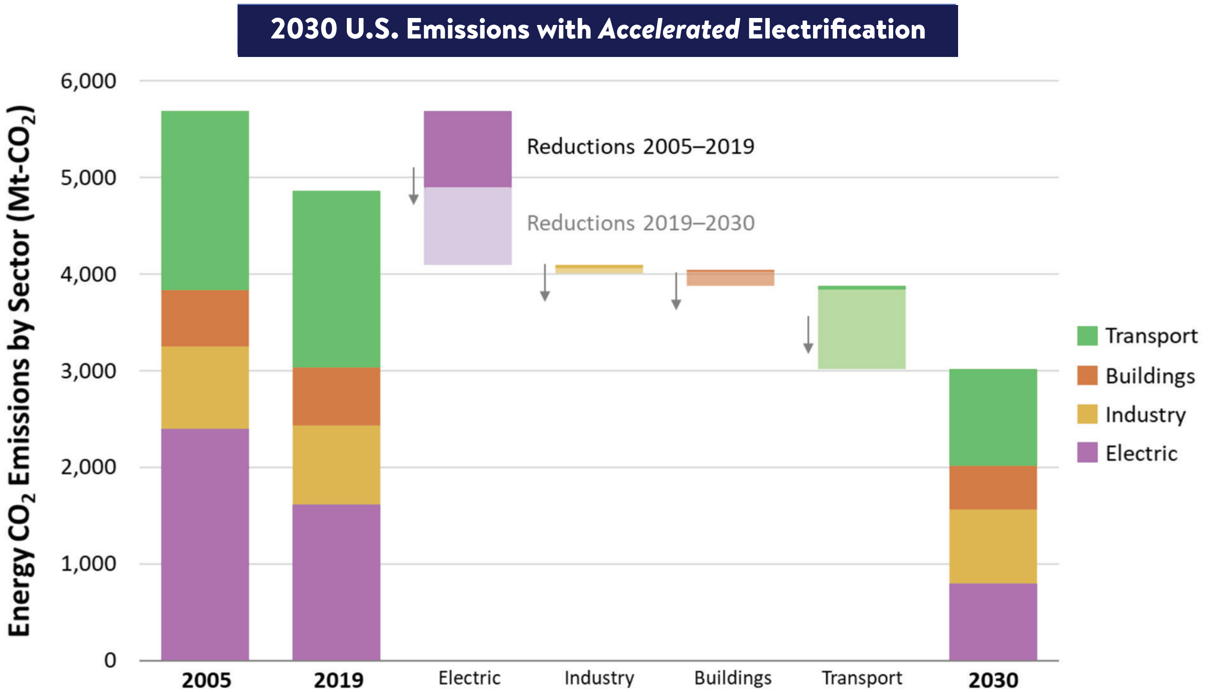


Figure 10. *Waterfall of U.S. energy CO_2 emissions from 2005 by sector for the reference electrification scenario ("50x30," top panel) and accelerated electrification ("50x30 E+," bottom panel). Historical reductions between 2005 and 2019 are shown in darker colors, and changes between 2019 and 2030 are shown in lighter colors.*

Reaching the 50% target by 2030 entails greater electrification, but levels vary based on assumptions (Figure 11). Many electrification opportunities (especially in transportation) are economic in the reference scenario. Emissions policies accelerate this fuel switching. Load growth relative to current levels is 16-23% by 2030 to the meet targets; however, end-use equipment replacement rates, relative costs, and other factors may limit the potential scope of additional electrification by 2030.

Costs associated with these pathways can be compared through a total energy service costs metric, which includes the costs of generating and delivering electricity to retail customers (e.g., transmission, distribution), non-electric end-use fuels (e.g., natural gas, petroleum), and non-energy costs from buying and maintaining equipment (e.g., appliances, vehicles). Tradeoffs across these expenditure categories and scenarios illustrate the scale of household and business spending patterns that must shift to accelerate the pace of decarbonization.[21]

Figure 12 shows how total electric sector expenditures (i.e., electricity consumption at retail prices) increase from roughly $400 billion per year in 2020 to a little over $500 billion annually across the decarbonization scenarios in 2030. This increase is due to higher prices (as discussed in the next section) and higher electricity demand. However, electricity is a relatively small component of total energy service costs, and electrification keeps total energy expenditures flat or declining despite the increase in electricity spending. Higher non-electric fuel expenditures may be rebated from carbon funds (which is assumed here), and how these policy revenues are spent determines total impacts on households and distributional impacts of policies.[22]

Non-energy spending accounts for almost two-thirds of energy service expenditures: Consumers currently spend about $1 trillion annually on fuels and $2 trillion on the purchase and maintenance of energy-consuming equipment. The largest component of non-energy costs is the annual spending on vehicles in the transport sector (comprised

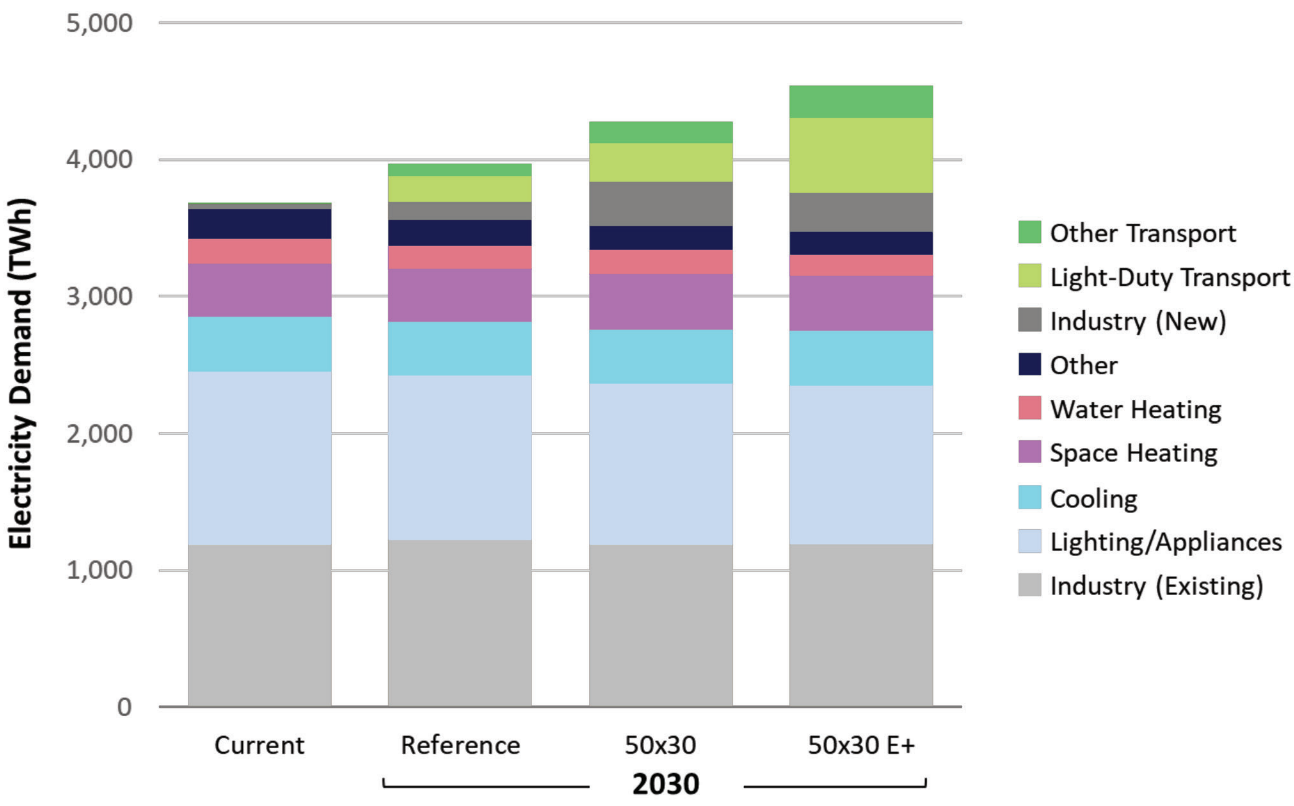


Figure 11. *Electricity demand by end use and scenario. 2030 values are outputs from the REGEN end-use model under a current policies reference, reference electrification ("50x30"), and accelerated electrification ("50x30 E+").*

[21] Total energy service cost is a more complete metric of customer costs than focusing on wholesale or retail electricity prices. This analysis tracks costs, some of which may be transferred from energy consumers to taxpayers, depending on the form of future policies.

[22] Carbon revenues are assumed to be recycled in this analysis.

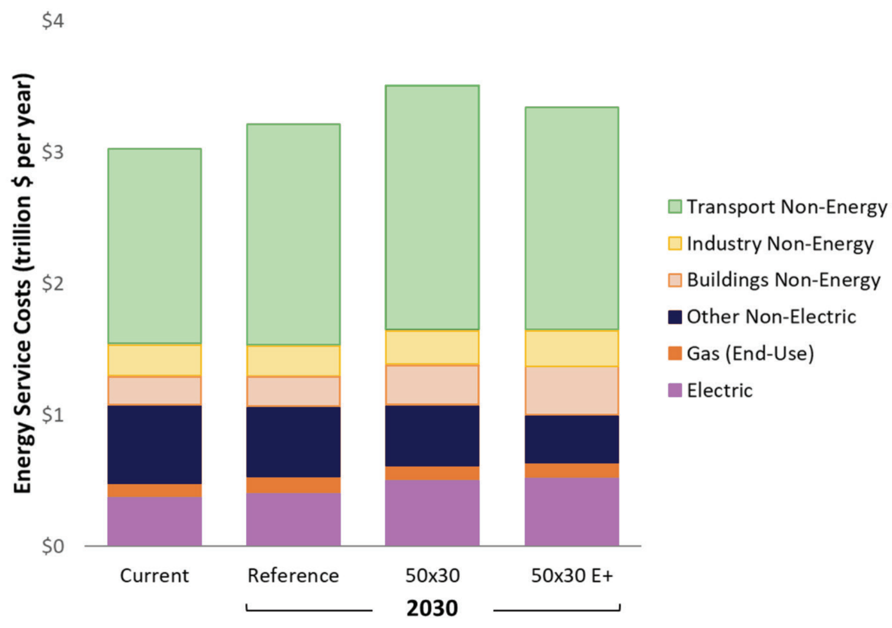


Figure 12. *Total economy-wide energy service costs by category and scenario. Values are shown net of carbon payments assuming 100% recycling. "Non-Energy" represents all non-fuel-related expenditures (e.g., equipment, maintenance).*

primarily of purchase, maintenance, and insurance costs). Although total energy service costs increase in absolute terms in the reference and policy scenarios relative to today, gross domestic product simultaneously grows by 24%, and service demand increases by 12%. Annual spending on energy services increases 4–9% from reference levels to meet the 2030 targets, which is an increase of $115–275 billion annually ($320–760 per person per year). Accelerated stock turnover in the 50x30 cases means more frequent replacement of capital, which leads to higher costs. The accelerated electrification case (50x30 E+) is lower cost overall by construction given the lower end-use purchase costs assumed in this scenario (noting that this metric only accounts for direct energy service expenditures and not possible tax subsidies that could lower purchase prices).

These energy system changes also have implications for emissions of SO_2, NOx, and other criteria air pollutants, reductions that have benefits for air quality and human health. As shown in Figure 13, substantial decreases in emissions occur in the reference scenario, and these changes are even larger in the two 50x30 policy scenarios. Differences in non-CO_2 electric sector emissions across the two 50x30 scenarios are relatively small due to coal-fired generation declines in both, which is reflected in the deep SO_2 reductions in the leftmost panels. The accelerated electrification scenario ("50x30 E+") has lower NOx, CO, VOC, and $PM_{2.5}$ emissions relative to the reference electrification case with the majority of these incremental benefits come from faster electrification of the transportation sector. Overall, these findings reinforce earlier analysis indicating substantial air quality benefits from electrification.[23] Electrification yields immediate emissions reductions that increase over time as electricity decarbonizes.

Electric Sector Implications

What could it take to reach the 2030 goal in the power sector? In the 50x30 scenario —where electric sector CO_2 is projected to reach 80% below 2005 levels—Figure 14 indicates that the historical annual maximum additions and retirements would have to be nearly exceeded each year for the next decade. The gas boom in the early 2000s led to an historic peak build rate of almost 60 GW/year, which is approximately the same level of investment projected to be needed annually (with a combination of wind, solar, gas with and without CCUS, and energy storage) to reach the 50x30 target. These levels of deployment have implications for permitting, labor availability, supply chains and land use, which could, in turn, impact cost and feasibility.

[23] EPRI performed several detailed regional assessments for electrification impacts on air quality, for example: Efficient Electrification in California: An Assessment of Energy System and Air Quality Impacts, EPRI 2020. 3002019494. An earlier report set of reports from EPRI and the Natural Resources Defense Council examine the air quality impacts of transport electrification: Environmental Assessment of a Full Electric Transportation Portfolio, Volume 1: Background, Methodology, and Best Practices. EPRI 2015.3002006875.

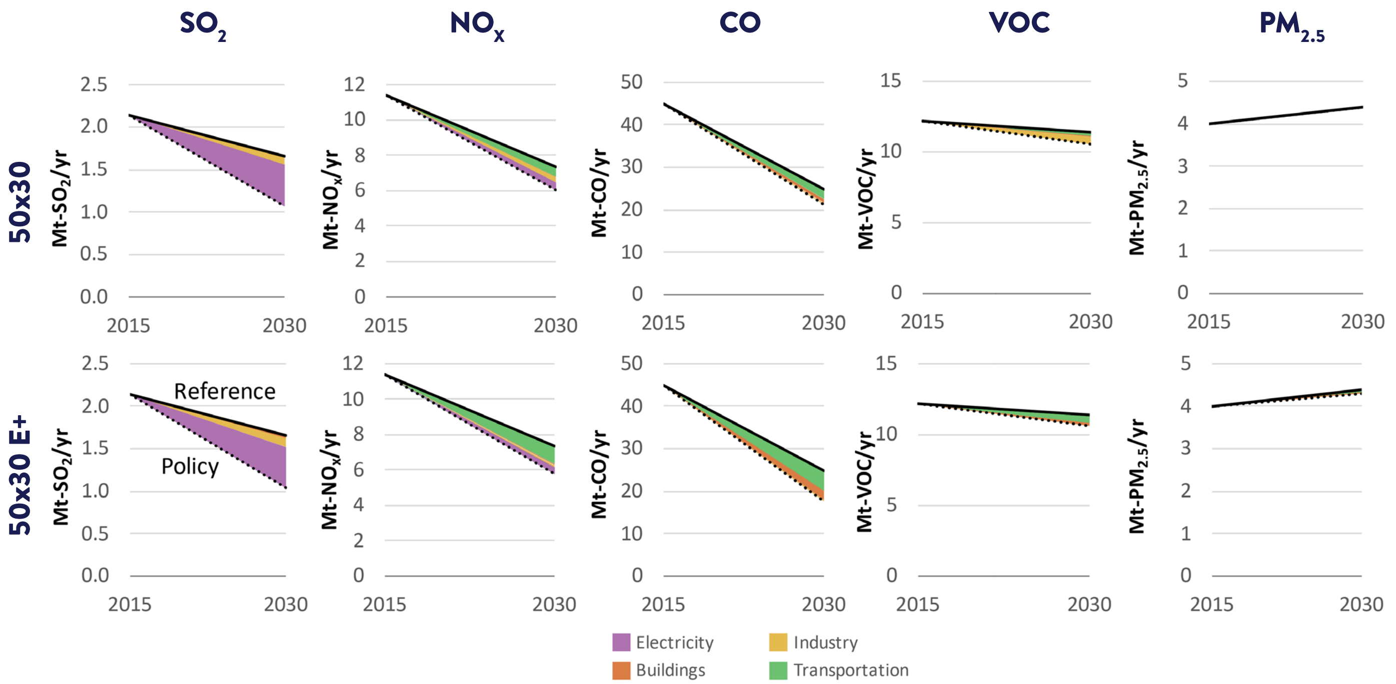


Figure 13. Changes in economy-wide emissions between 2015 and 2030 by sector, pollutant (columns), and scenarios (rows). The top black line in each panel represents emissions changes in the reference scenario, and the lower dotted line represents policy-induced changes.

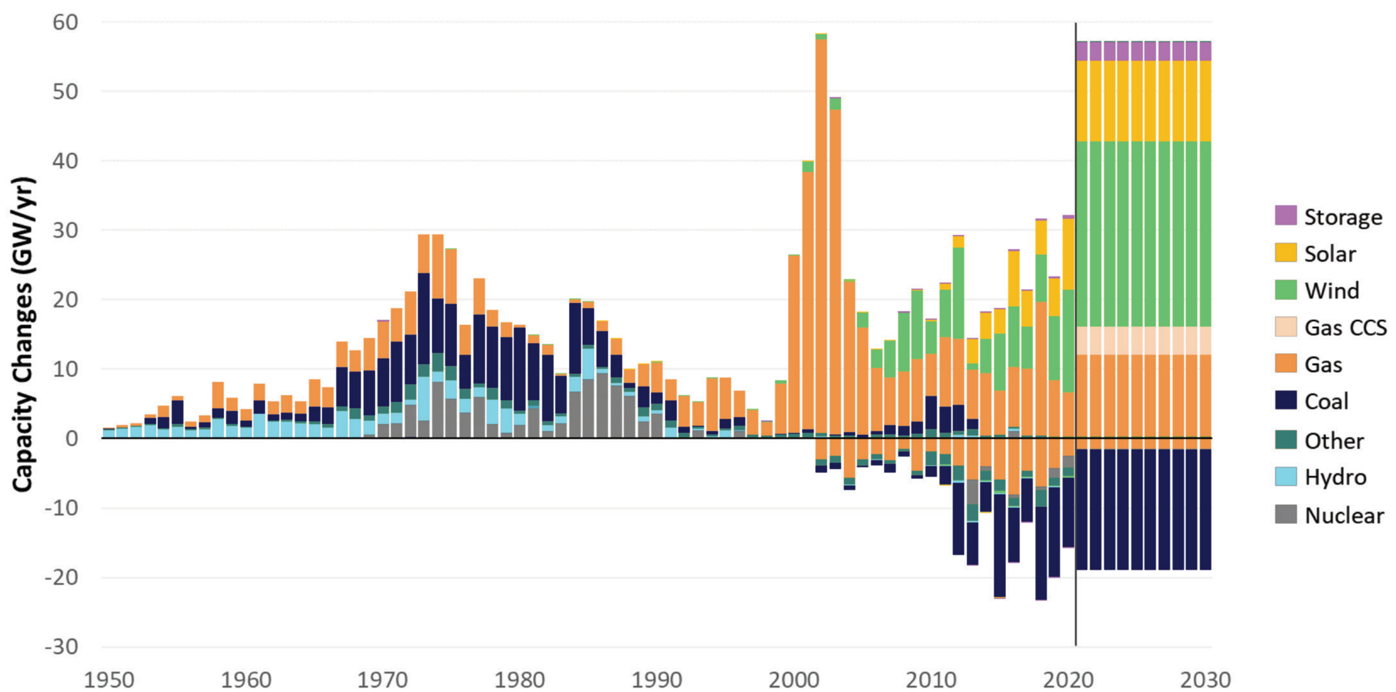


Figure 14. Historical and projected capacity additions and retirements by technology. Projections show the average annual build rate in the reference electrification scenario ("50x30"), which reaches 80% electric CO_2 reductions by 2030. Although the average rate is shown, capacity additions will likely ramp up over time, assuming policy incentives are consistent over time. Historical values come from Form EIA-860 data.

Beyond these accelerated levels of generation installations, intra- and inter-regional transmission investment could be extensive, which raises additional siting, permitting, and cost allocation questions. REGEN models inter-regional transmission expansion and trade decisions and reflects the costs of both inter- and intra-regional transmission additions. Increases in transmission and inter-regional electricity trade are valuable for meeting the 2030 and deeper emission reduction goals (Figure 15). There are currently about 110,000 GW-miles of inter-regional transmission nationally, and under the "50x30" scenario, inter-regional transmission increases by roughly 20,000 GW-miles.

Higher inverter-based resource shares, widespread plant closures, rapid end-use electrification, and other system changes create reliability questions concerning the resource adequacy, stability, and resiliency of future modeled systems.[24] For more than a century, electricity generation has been dominated by large rotating machinery – turbines driven by water, steam, or combustion – that provided capacity and energy when needed as well as reliability services (e.g., voltage regulation, inertia) that keep the alternating current system running. As generation shifts towards more inverter-based resources, these reliability services will increasingly have to be engineered, new reliability metrics defined, and electricity markets adapted to compensate the firms (and households) that supply them.

Figure 16 illustrates one measure of the supply-side change, showing how regional shares of wind and solar generation and the frequency of hours with high instantaneous penetration can increase, especially in regions with better quality variable renewable resources. Today, it makes the news if solar plus wind comprise a substantial fraction of load in a complex grid for even an hour.[25] In the 50x30 scenario, which projects 32% of power nationally coming from solar and wind, four large regions could see solar and wind comprising 70% or more of power for over half of the year and 90% for hundreds to thousands of hours, entering fundamentally new operational regimes. Note that other studies that project 50–60% of 2030 power generation (twice the penetration in the 50x30 scenario) from solar and wind would necessarily operate many more hours with extremely high shares of renewables.

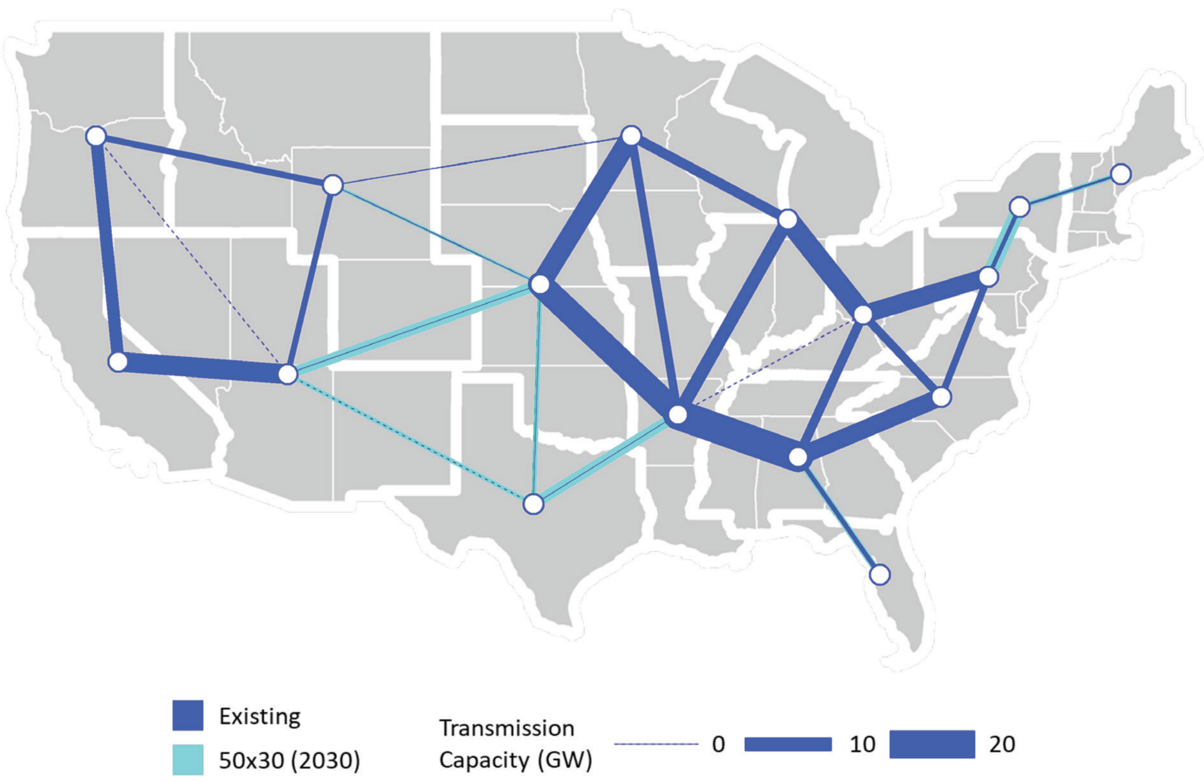


Figure 15. *Transmission capacity (GW) across model regions in 2015 (dark blue) and under the "50x30" scenario in 2030 (light blue). Existing inter-regional capacity is based on NREL data.*

[24] See Enhancing Grid Reliability and Resiliency in a Net-Zero Economy (Summer Seminar

[25] See for example, the April 2021 story about renewables (led by solar and wind) providing generation to cover over 90% of California's demand for several hours.

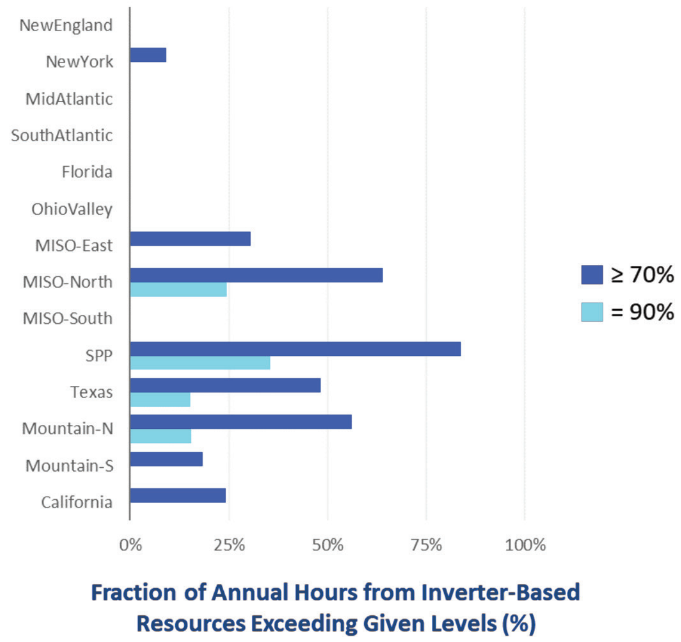


Figure 16. *Regional shares of annual hours with inverter-based resources exceeding given levels. Values are shown for the "50x30" scenario in 2030. Note that the regional constraint on hourly non-synchronous penetration places an upper limit at 90%.*

If unanticipated challenges prevent the electric sector from moving at this rapid pace (e.g., if permitting constrains the rate of change, if supporting policy is delayed, if CCUS cannot be deployed widely), how can the 2030 economy-wide climate commitment be reached? The accelerated electrification scenario ("50x30 E+") provides an alternate decarbonization pathway that reaches the 2030 goal while easing some of the electric sector challenges.

Figure 17 illustrates how moving from the reference to the accelerated electrification 50x30 scenario implies both increased load and a relaxed emissions constraint (i.e., moving from 80% CO_2 reductions for the electric sector relative to 2005 to 66%, where faster non-electric emissions reductions give the electric sector headroom and more time to work out challenges to reach net zero by 2035). Accelerated electrification leads to slower renewable growth in all regions (both in TWh and generation share terms), the South avoids installing gas with CCUS by 2030,[26] and the Midwest avoids very high exports and associated transmission changes (Figure 15).

Nevertheless, this figure suggests that the 2030 target leads to rapid changes in the generation mix and trade across all regions and scenarios, albeit with variation across different systems. CO_2 reductions are highest in regions with lower-cost abatement options. For example, higher renewable resource quality in the West and Midwest lead to greater shares of wind and solar generation.

Key actions by 2030 in the electric sector across both 50x30 scenarios include (national generation totals by technology are summarized in Figure 27 in the appendix):

- **Reduce coal generation and manage coal retirements (community impacts, jobs, financial).** The transition from coal will call for thoughtful consideration of regional reliability, affordability, and environmental justice. Plant closure and repurposing decisions will have significant community impacts in many locations. They can also have rate and financial implications resulting from plants that are not fully depreciated when retired.
- **Expand grid to maintain reliability with high wind and solar and electrification of other sectors.**
  - Ensure adequate firm backup capacity, including adding new gas capacity to replace coal and balance renewables
  - Build associated transmission (intra-region essential, inter-regional valuable)

[26] The 50x30 scenario with reference electrification deploys approximately 40 GW of CCUS-equipped gas capacity by 2030 and 2.8 GW of biomass with CCUS.

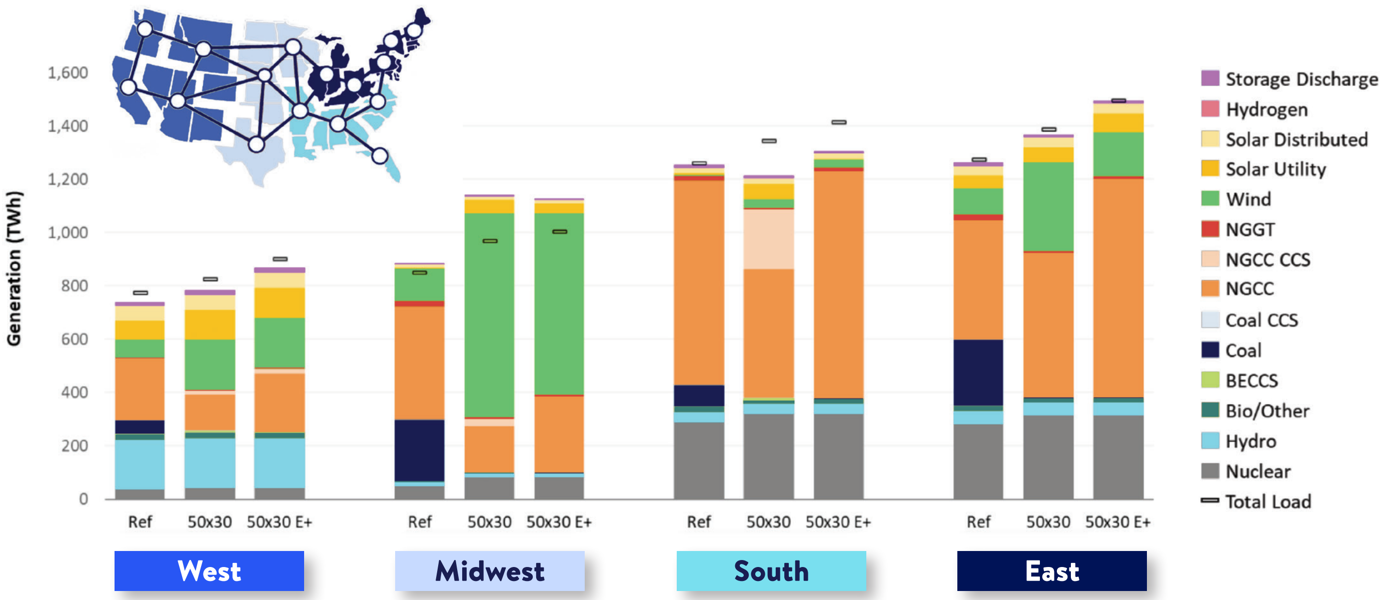


Figure 17. *Generation by technology, scenario, and reporting region in 2030. Bars show the electric sector mix under the reference ("Ref"), 50x30 scenario with reference electrification ("50x30"), and 50x30 scenario with accelerated electrification ("50x30 E+").*

- **Extend operation of existing nuclear and hydropower and pursue uprates where appropriate.** These plants are projected to provide 16–17% of generation in 2030 and are low-cost contributors to meeting climate targets, but face economic challenges in today's markets.
- **Develop and demonstrate technologies for clean firm capacity.** Such technologies include CCUS-equipped capacity, advanced nuclear, hydrogen, and long-duration energy storage, which will be increasingly important as net-zero goals are approached.[27]

All 50x30 scenarios include replacing coal generation with gas and renewables, and emissions reductions come from this lower coal output (Figure 28 in the appendix).

Figure 18 illustrates the magnitudes of electricity price changes across regions.[28] The 50x30 targets increase electricity prices across all regions and scenarios, relative to the reference scenario and to current prices. The accelerated electrification case has slightly lower prices in 2030 due to less stringent abatement, but prices are similar by 2035 to reach the net-zero electric sector target. The South and East have higher price growth due in part to their lower quality renewable resources.

Cumulative capacity additions and retirements are a leading driver of higher electricity prices. Figure 19 suggests that 50x30 scenarios entail significant accelerations in investments relative to historical levels. Annual wind and solar additions are two to three times their historical values: Averaging 13 GW/yr between 2010 and 2020 and increasing to 29 GW/yr with accelerated electrification ("50x30 E+") and 38 with reference electrification ("50x30"). Accelerated electrification and smoother evolution of build rates could help with possible scaling challenges and might better accommodate political, social, and cultural dimensions of transition. But the scale of transformation is still significant relative to historical and business-as-usual levels, implying challenges for research and development, siting, market changes, reliability, and grid modernization to varying degrees.

[27] A perspective on technology needs to achieve net-zero electric sector emissions is provided by: EPRI (2021). "Powering Decarbonization: Strategies for Net-Zero CO_2 Emissions," EPRI Report 3002020700.

[28] Prices include generation and new bulk transmission but do not reflect intra-regional transmission and distribution costs, which are related to delivery from wholesale markets to retail customers. Prices reflect implicit CO_2 shadow prices from 50x30 policies, which increase electricity prices. Note that other proposed policies such as tax credits and tradable performance standards (that combine a tax on emissions with an output subsidy) can depress prices, as demonstrated in the sensitivity in the appendix.

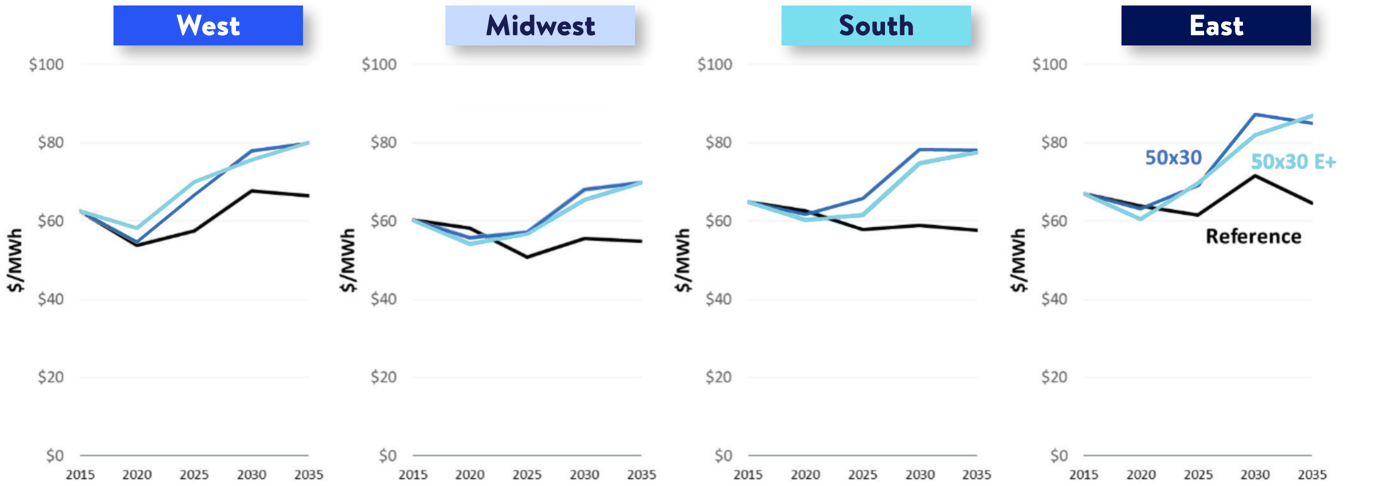


Figure 18. *Regional electricity generation prices by scenario over time. Average annual prices reflect generation and new bulk transmission.*

The analysis also conducts a range of electric sector sensitivities to examine how assumptions about electric sector technology cost and availability alter decarbonization pathways. Table 2 in the appendix summarizes these scenario assumptions, where additional constraints or alternate costs of technologies show how investment and cost outcomes may vary (e.g.) if new CCUS-equipped capacity and transmission are limited or if renewables have lower (or higher) costs than projected. These sensitivities suggest that:

- **Technological cost and availability assumptions alter the generation mix.** However, there are many robust near-term elements, including very low or no coal generation,[29] higher contributions from wind and solar, maintaining existing nuclear and hydropower, and expanding gas capacity (Figure 30 and Figure 31).
- **Wind and solar generation shares are 32% to 46% nationally in the "50x30" scenarios (and 25% to 40% in the "50x30 E+" scenarios) with high regional and intra-annual variability.** Variable renewables deployment is highest when their costs are assumed to be low and when new gas capacity (with and without CCUS) is constrained.

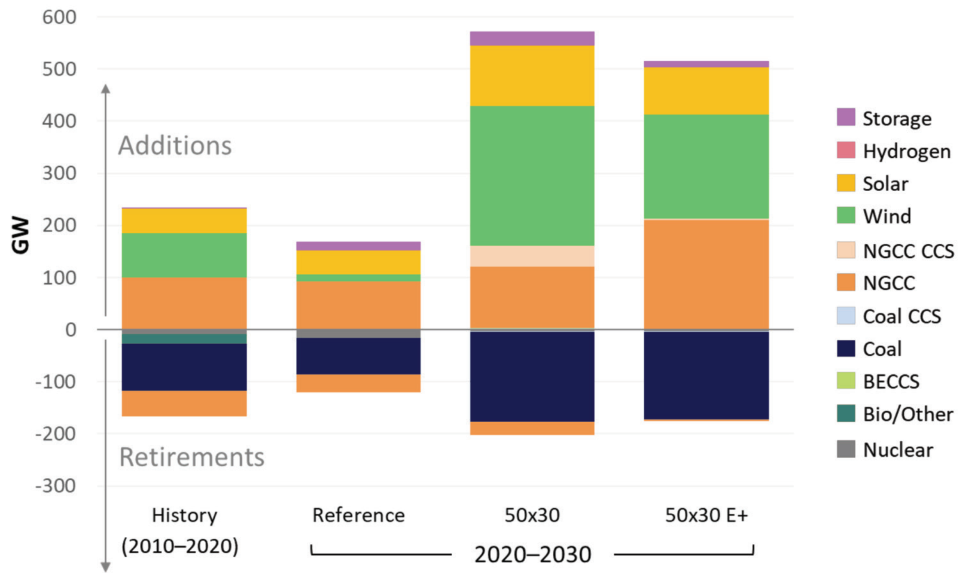


Figure 19. *Historical and projected cumulative capacity additions and retirements. Historical values come from Form EIA-860 data.*

[29] Coal capacity is very low across all scenarios. If coal is valuable for aspects of reliability not explicitly included in this analysis, an implication is that these units would need revenues beyond energy and capacity to prevent retirements. In the 50x30 scenarios, coal capacity receives little energy revenue due to its high emissions intensity and limited capacity revenue unless gas capacity constrained.

THE ROLE OF FIRM CAPACITY IN ELECTRIC SECTOR CO_2 REDUCTIONS

Firm capacity—resources that can meet demand when needed over long durations in all seasons—is important for system balancing and ensuring resource adequacy, reliability, and resiliency. All 50x30 scenarios exhibit accelerated retirements of existing coal capacity, which increases the need for deploying new firm resources. Given costs and emissions constraints in these scenarios, new natural gas combined-cycle (NGCC) capacity is deployed with and without CCUS to replace coal, balance renewables, and minimize costs. NGCC without CCUS displaces two-thirds of retiring coal in the reference electrification (50x30) scenario, but in the accelerated electrification case, gas additions exceed coal retirements by about 20% due to rising load and the lower implied CO_2 price.

The appendix provides a deep dive analysis illustrating the economic viability of these gas additions even as CO_2 targets tighten after 2030. NGCC plants run with lower capacity factors over time and are used primarily as capacity resources, and their emissions are balanced with a small amount of negative emissions from carbon removal as the power sector reaches net-zero emissions in 2035.

When new NGCC capacity without CCUS is not allowed, capacity increases for CCUS-equipped gas and combustion turbines. When CCUS is simultaneously restricted, coal capacity remains online, and capacity also increases for combustion turbines, renewables, energy storage, and hydrogen.

- **New gas capacity is a key asset for firm capacity as coal retires.** New NGCC capacity ranges from 0 to 130 GW in sensitivities around the "50x30" scenario.
- **CCUS-equipped generation appears in many "50x30" scenarios, ranging from 0 to 85 GW across sensitivities.** This is primarily NGCC with CCUS, but extension of 45Q tax credits can lead to coal retrofits. Demand for CCUS increases with higher renewable costs and when gas without CCUS is not allowed. CCUS deployment is lower with low renewable costs, constraints on CCUS, and with accelerated electrification (since the need for reductions from the electric sector is reduced).

Although this analysis focuses on 2030, scenarios were modeled past 2030 to ensure that these pathways are consistent with longer-term goals, including the 2035 electric sector net-zero goal included in the U.S. NDC.

Transport Implications

One of the largest sources of emissions reductions and load growth to meet the 2030 target is passenger transport. Declining battery costs drive down the purchase price of plug-in hybrids and battery electric vehicles (EVs). Total ownership costs of EVs are lower once fuel and maintenance costs are taken into account, which drives economic adoption for many households in the reference case (Figure 20, left column). However, new sales of EVs would have to increase dramatically from today's levels (roughly 2.3%) to reach 50% emissions reductions economy-wide by 2030. By 2030, EVs are projected to comprise 45-75% of new sales—20 to 30 times current levels. Due to the large existing fleet of cars, the share of vehicle miles travelled (VMT) and emissions changes lag far behind changes in the new sales share, which presents a challenge for reaching 2030 goals.

Electrification and improved fuel economy in other transportation segments will also be valuable in reaching the 2030 goal. For the 50x30 scenarios, electricity's share of final energy for bus/transit/rail increases from roughly 2% today to 14–20% by 2030. Similarly, electricity's final energy share for medium- and heavy-duty trucks increases to 10–17% by 2030. This high degree of electrification has implications for infrastructure needs (e.g., charging) and load shape flexibility, which are important areas for detailed regional follow-on analysis.

Building Implications

All scenarios project continued increases in electricity's share of final energy, mostly driven by transport electrification. Electricity's share of final energy rises from 21% today to 29% by 2030 in the "50x30" scenario, and to 33% in the "50x30 E+" scenario (Figure 21). Buildings are the most electrified sector in absolute and relative terms today. Although transport and industry gain ground in reaching the 50% target by 2030, the buildings sector remains the highest electric share of final energy. Overall, this figure illustrates the discontinuity from historical trends that would be needed to reach a 50% reduction goal by 2030, especially with slower electric sector reductions.

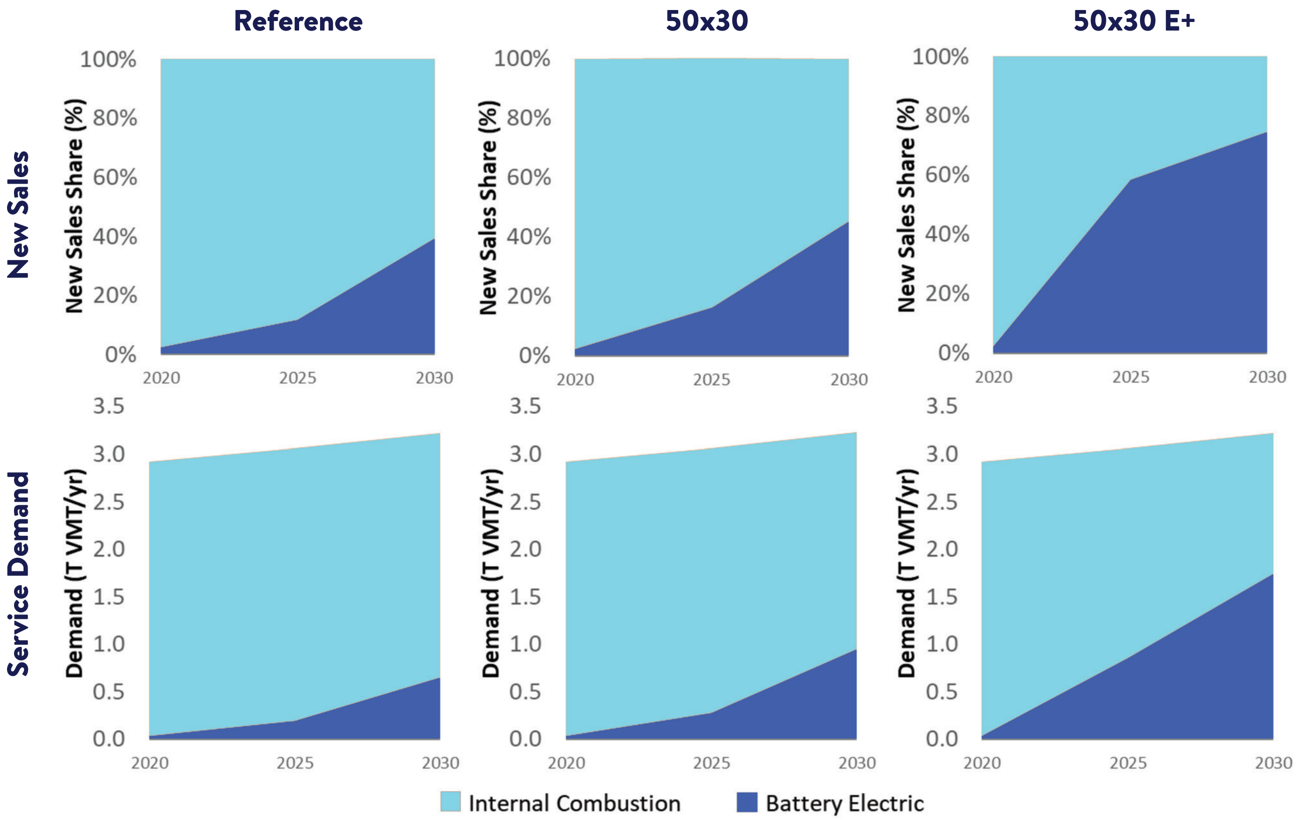


Figure 20. *Light-duty vehicle new sales share (bottom row) and service demand (top row) by technology type and policy scenario (columns). Service demand is expressed in terms of trillion vehicle miles traveled per year.*

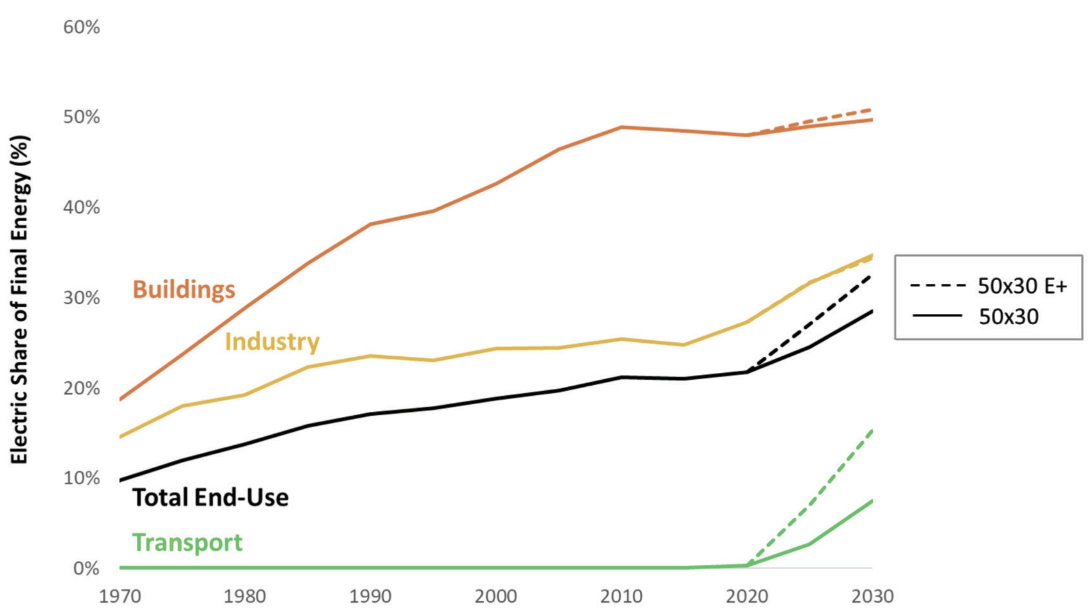


Figure 21. *Electricity share of final energy by sector and scenario. Historical values come from U.S. Energy Information's "State Energy Data System" (https://www.eia.gov/state/seds/).*

Heat pump cost and performance improvements make space heating electrification a cost-effective decarbonization strategy for many residential and commercial buildings. The share of residential heated floor space increases from roughly 35% of heated square footage today to 49–57% by 2030. However, the relatively slow pace of equipment turnover limits total service demand that can be electrified by 2030. The conversion of fossil-fuel heating to electricity can reduce CO_2 emissions and alter electricity demand profiles, though peak demand impacts can be managed with advanced heat pumps, gas supplements, and demand response.

Industrial Implications

Emissions reductions in the industrial sector by 2030 come from energy efficiency and fuel switching. These trends barely offset growing service demand, which increases by 20-40% between 2020 and 2030, depending on the industrial sector. Figure 22 compares historical and projected final energy by fuel and end use. For the industrial sector, electricity use grows for processing heating/cooling and facilities. Another notable trend is fuel switching from petroleum to natural gas (e.g., for feedstocks).

Overall electrification shares in the industrial sector increase from roughly 27% today to 34–35% in 2030 (Figure 21). Industrial end uses are slightly more responsive to CO_2 incentives, which is one reason why electricity demand in industry is higher in the "50x30" scenario relative to the "50x30 E+" scenario (Figure 11) owing to its higher implied CO_2 price.

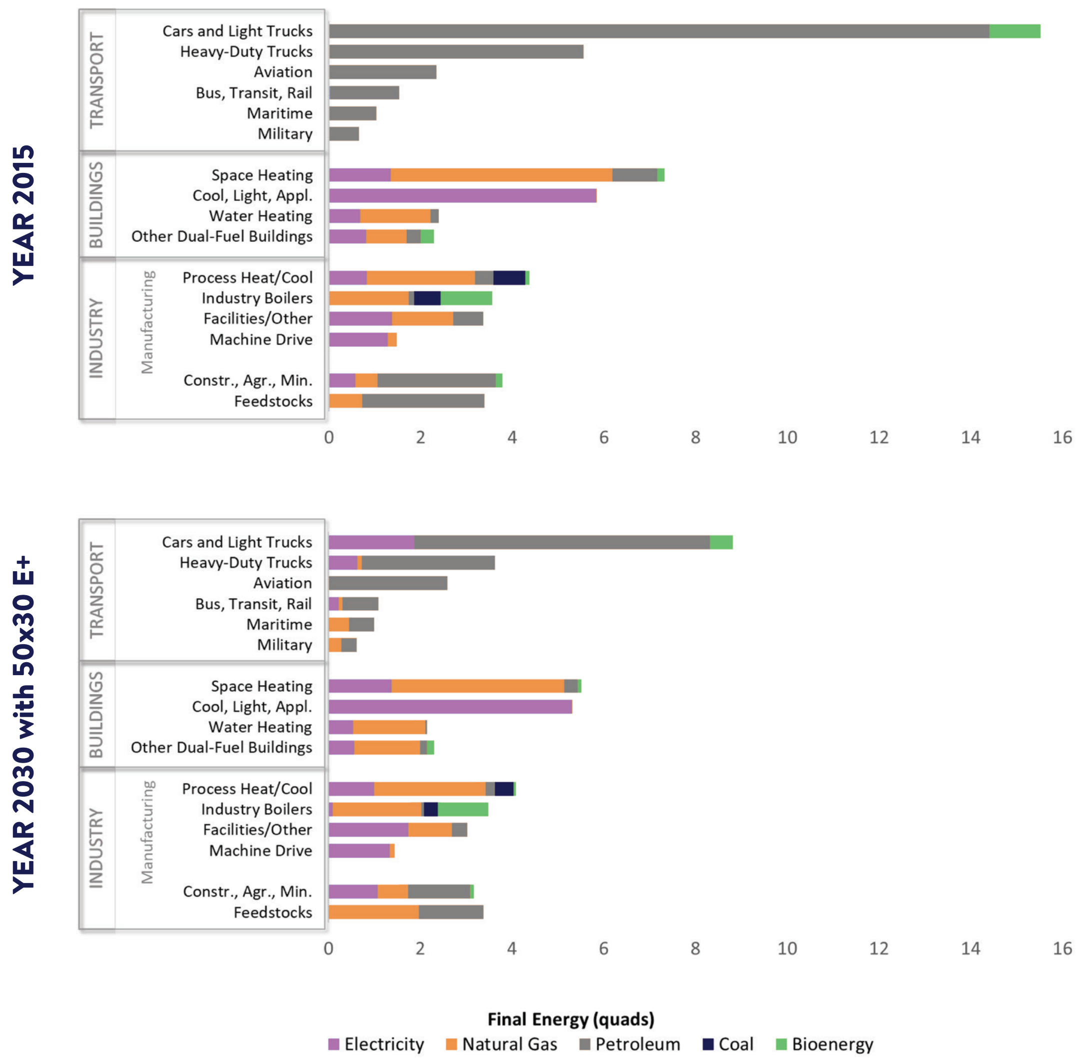


Figure 22. *Final energy by end use and fuel in 2015 (top panel) and 2030 in the accelerated electrification ("50x30 E+") scenario (bottom panel). End uses are aggregated into major reporting categories.*

DISCUSSION AND NEXT STEPS

Key Takeaways

This white paper highlights key themes for reaching the U.S. goal of 50% emissions reductions by 2030:

- **Central role of the electric sector.** Electrification and power sector CO_2 reductions are key strategies for reaching the 2030 target.
- **Accelerated electrification.** Aggressive deployment of electric end-use technologies is key to meeting the 50x30 target, especially in transportation, which can offset more costly reductions in the electric sector (e.g., avoid immediate, widespread deployment of CCUS or more expensive technology options).
- **Reliability.** System changes—including retirements of existing fossil capacity and higher renewable shares—require advances in operational practices and grid technologies to ensure reliability. Firm capacity will be a key asset. Additional analysis to evaluate reliability dimensions of the transition will be important.
- **Customer impacts.** Decarbonizing the economy involves fundamentally redirecting customers' energy equipment choices and changes in expenditures.

Figure 23 summarizes differences between the two 50x30 scenarios. Challenges associated with the reference electrification ("50x30") scenario include:

- 80% reductions in electric sector CO_2 emissions and 23% reductions in non-electric CO_2 by 2030
- Higher wind/solar shares; transmission build-outs; higher electricity prices and energy service costs; CCUS scale up; higher CO_2 prices; higher non-CO_2 emissions

Challenges associated with the accelerated electrification ("50x30 E+") scenario include:

- 66% reductions in electric sector CO_2 emissions and 33% reductions in non-electric CO_2 by 2030
- Aggressive end-use deployment (e.g., electric vehicles); faster pace to reach 2035 net-zero goal; greater gas capacity at risk with future policy changes

All 50x30 scenarios require significant efforts beyond business-as-usual trends (reflected in the "Reference" scenario) and from current systems.

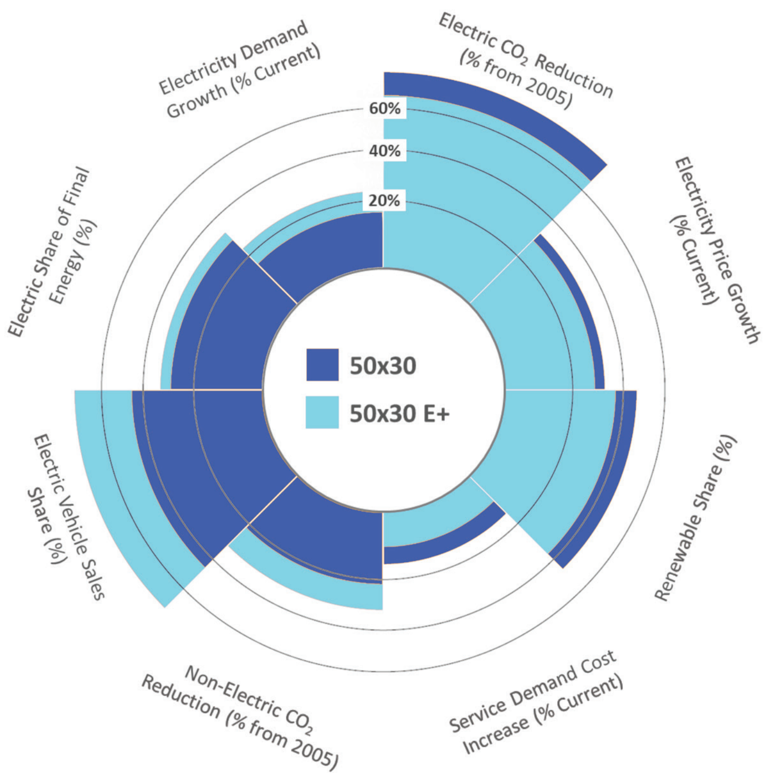


Figure 23. *Overview of changes in key indicator metrics in the reference electrification ("50x30") and accelerated electrification ("50x30 E+") scenarios. Metrics on the right half are ones where the reference electrification is higher, and indicators on the left are higher with accelerated electrification.*

Next Steps

There are many opportunities for additional research related to this analysis:

- **Explore in more depth the fundamental concepts of affordability, reliability, and equity.** As noted in several places in this report, none of the 50x30 studies to date have conducted reliability assessments. There is a critical need to better link this class of capacity expansion and production costing models with transmission, distribution, customer, and reliability analyses. Understanding the cost of the transition, who pays, and how much is essential to success. Expanding the analysis beyond a discussion of wholesale electricity prices, to retails prices, and costs of energy services is critical for understanding and affecting customer choice. Also, a complete accounting of costs—whether paid by ratepayers or taxpayers—provides a clearer measure. And equity considerations, which are poorly defined and understood today, will be essential to ensure that all participate in the transition and benefit from it.
- **Conduct regional studies and assessments to examine dynamics for reaching 2030 goals in greater detail.** More detailed analyses can help stakeholders to understand potential challenges (e.g., permitting, land use) associated with reaching the 50x30 goal. As the regional results in this analysis suggest, pathways will likely vary significantly by region. More detailed studies can examine potential bottlenecks, opportunities, and impacts, including managing sector- and region-specific employment, skilled labor needs, supply chain issues, and infrastructure challenges. EPRI plans to release additional white papers in 2021 that explore the supply chain and labor needs along with analyses of actions to leverage existing nuclear and transmission infrastructure.
- **Accelerate transmission and grid transformation to enable rapid expansion of wind and solar generation.** Operational and market issues will have to be addressed with renewables penetration projected to exceed current thresholds for non-synchronous resources for large fractions of annual hours in many regions and scenarios. New grid operational control and protection capabilities will likely be needed for day-to-day operation, electricity market reforms will be needed to support generation investment and grid flexibility, and grid modernization will be essential to efficiently integrate distributed resources and expand demand response.
- **Conduct research, development, demonstration, and deployment to facilitate net-zero goals in the electric sector and broader economy.** A wide range of collaborative research will be valuable to understand challenges associated with these goals to establish technologies and move costs down for hydrogen, CCUS, carbon removal, biofuels, and other solutions. Pathways to net-zero economy-wide emissions will be explored in an analysis planned for release later in 2021 as part of the EPRI- and Gas Technology Institute-led Low-Carbon Resources Initiative (https://www.epri.com/lcri). This research can help energy systems to move rapidly, reliably, affordably, and equitably toward the 2050 net-zero target.

APPENDIX

More detailed documentation for the REGEN model can be found in EPRI (2020), and additional applications of the model can be found at https://esca.epri.com/. REGEN provides customizable regional resolution and accounts for differences in regional policy, resources, and demand.

Reference capital cost assumptions over time by technology are shown in Figure 25. The figure also includes assumptions in the low renewables and battery cost sensitivity, which uses values from NREL's Annual Technology Baseline (ATB) 2019 "Low" scenario.

Figure 26 shows the economy-wide CO_2 shadow price over time by scenario. Implied marginal costs of emissions reductions are lower in the accelerated electrification ("50x30 E+") scenario due to the lower costs of electrification in this scenario.

Figure 27 shows the national generation mix by technology across the 2030 scenarios. Note that the bulk of wind generation nationally comes from onshore wind. Offshore wind is driven by state mandates totaling 23 GW by 2030 and nearly 35 GW by 2035.

Historical and projected power sector CO_2 emission are shown by technology in Figure 28.

Figure 29 provides a deep dive into the economics of an NGCC plant to illustrate how gas additions can be economically viable even as CO_2 reductions increase after 2030. As earlier results demonstrate, NGCC capacity can help with resource adequacy as coal retires, which is key driver of CO_2 reductions by 2030. New NGCC supports near-term CO_2 reductions and consistent with long-term net-zero targets, as power sector CO_2 emissions reach net-zero levels by 2035. A key point is that gas capacity operates with lower capacity factors in the future, and the firm backup role gas plays for variable renewables means that net revenues increasingly come from providing capacity during high-priced hours. The remaining CO_2 beginning in 2035 is offset with carbon removal, and these payments for permits/offsets to operate under the cap are shown in green on the figure. The model's optimization ensures that the investment cost for any new capacity is balanced by the discounted stream of net operating revenues over its investment life, and these results demonstrate how most of the net present value of revenues come in the first decade of operation, especially since prices are higher to reach the 2030 targets (Figure 18).

The analysis also includes a range of sensitivities to examine how assumptions about electric sector technology cost and availability alter decarbonization pathways. Table 2 summarizes these "what if" scenarios and their assumptions.

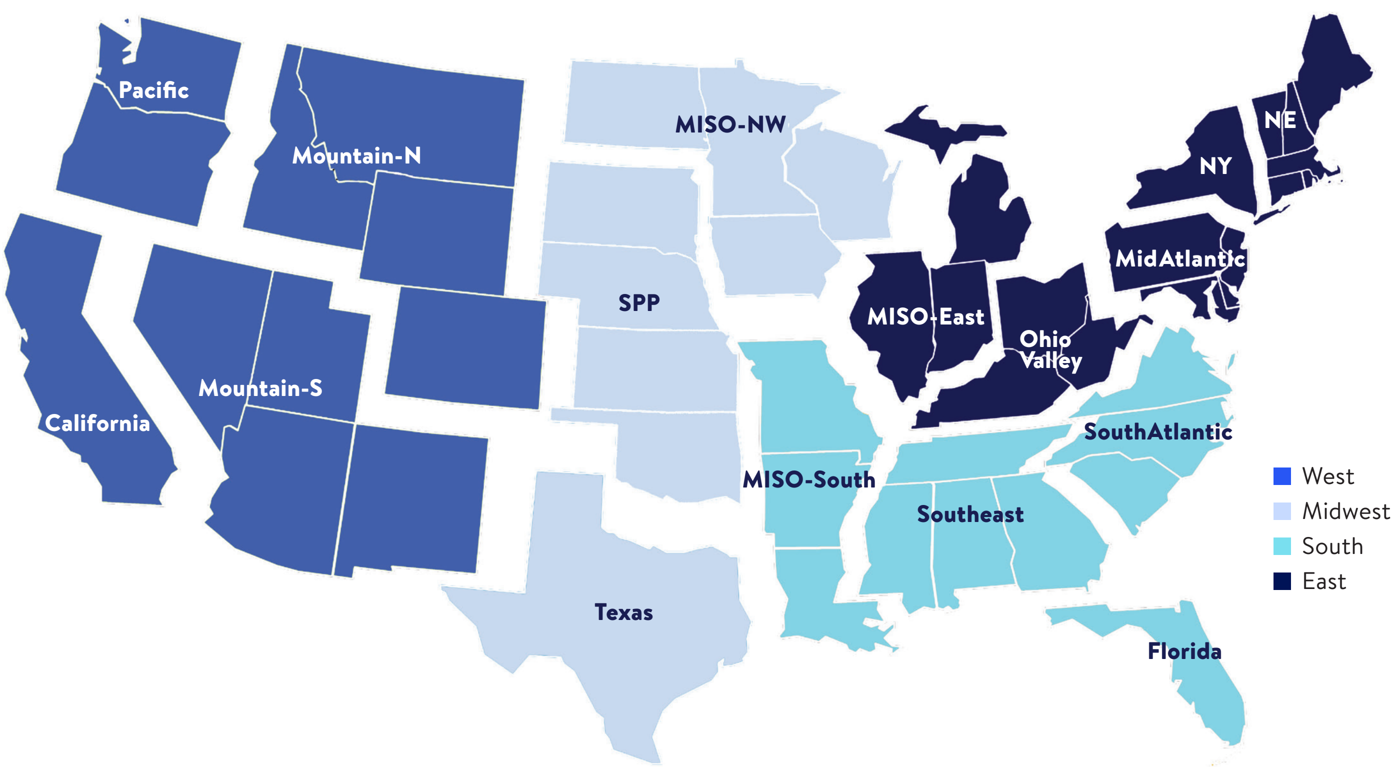


Figure 24. *Regional aggregation for model regions in this analysis. Colors illustrate configurations for reporting regions.*

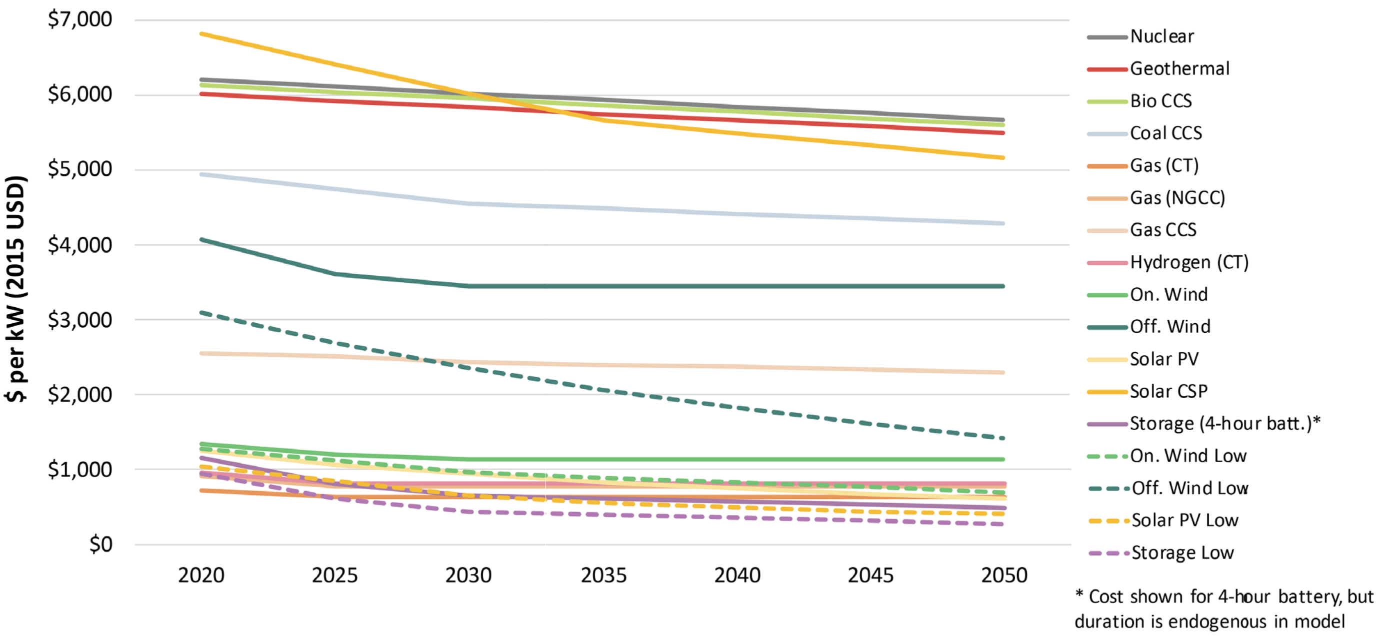


Figure 25. *Capital costs for electric sector technologies. Solid lines represent reference costs, and dotted lines indicate low-cost sensitivity from NREL's Annual Technology Baseline (ATB) 2019 "Low" scenario. Average national costs are shown; installed capacity costs vary by region in the model.*

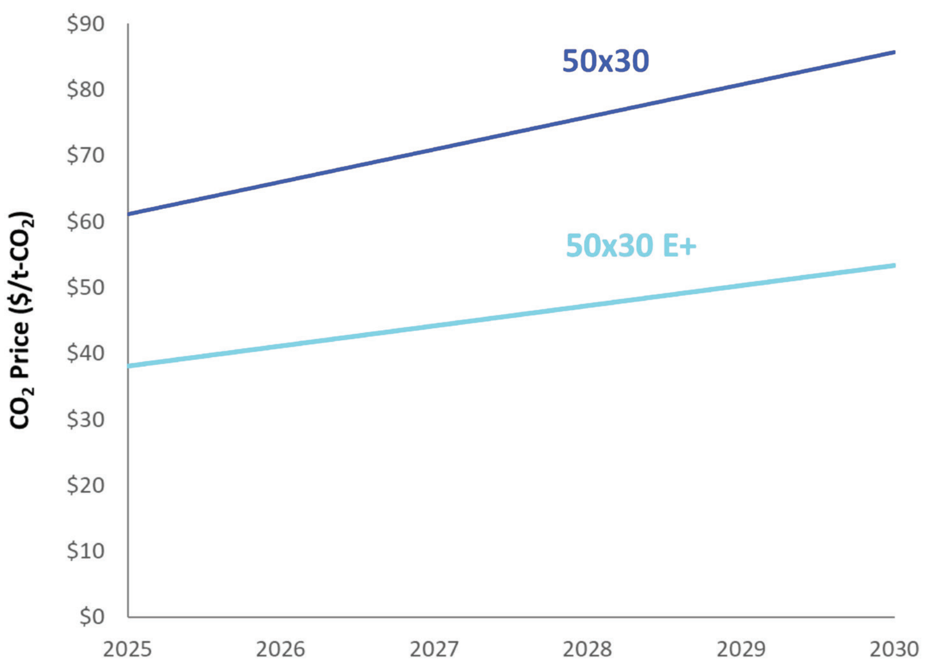


Figure 26. *Economy-wide CO_2 shadow prices by scenario over time. Prices are model outputs.*

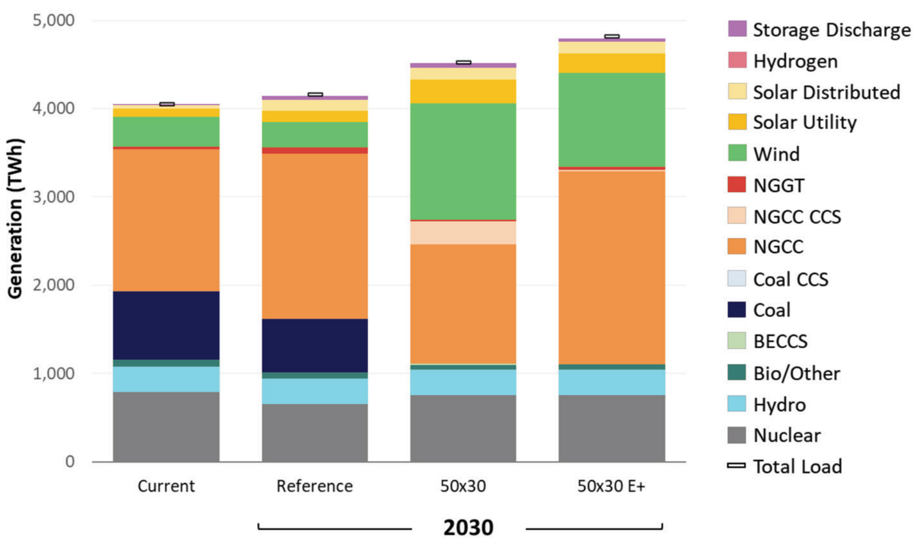


Figure 27. *National generation by technology and scenario. Bars show the electric sector mix under the reference, 50x30 scenario with reference electrification ("50x30"), and 50x30 scenario with accelerated electrification ("50x30 E+").*

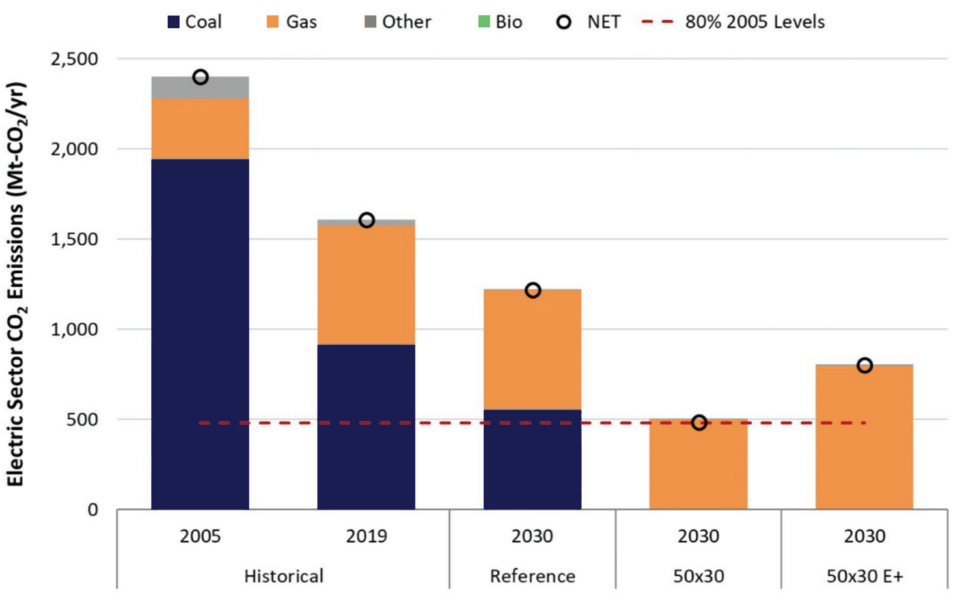


Figure 28. *Electric sector CO_2 emissions by scenario and technology. Bars show the electric sector mix under the reference, 50x30 scenario with reference electrification ("50x30"), and 50x30 scenario with accelerated electrification ("50x30 E+").*

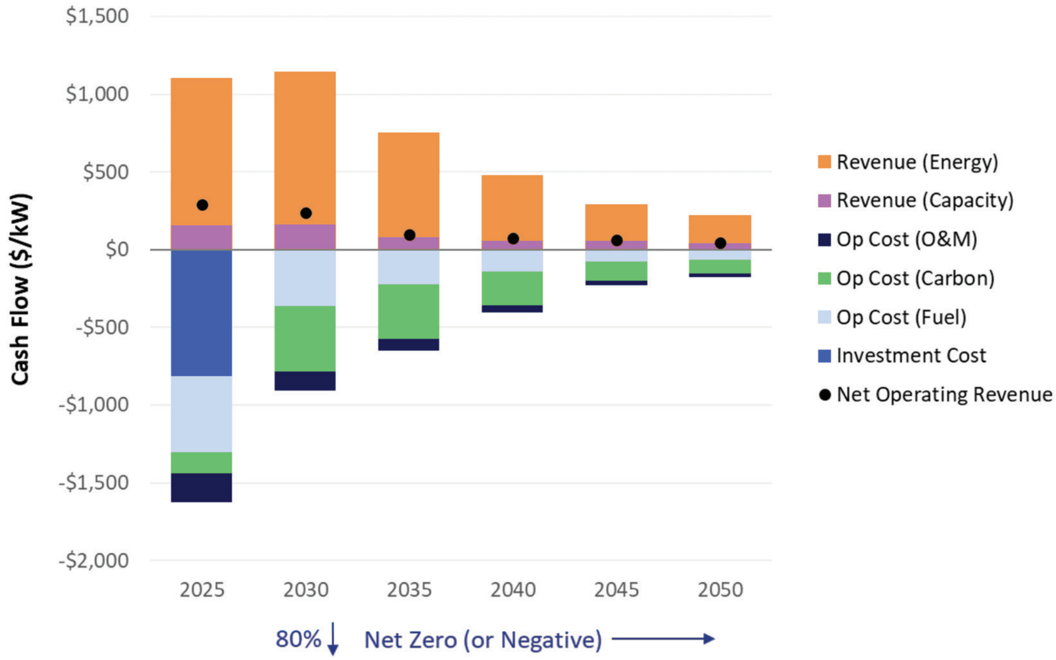


Figure 29. *Cash flow analysis for an illustrative NGCC unit built in 2025 under the "50x30" scenario. Discounted revenues, costs, and net operating revenues are shown for each five-year period. Values are shown for the Mid-Atlantic region (Figure 24).*

Table 2. *Electric sector sensitivities and assumptions.*

Scenario	Abbr.	Sensitivity Assumptions
Reference	50x30	N/A
Tax Credit Extensions	TaxCr	Extensions of ITC, PTC, and 45Q similar to proposed GREEN Act
Carbon-Free	CF	Electric sector "Carbon-Free" in 2035
Lower Renewable/Battery Costs	LoRE	Costs for wind/solar/batteries exhibit faster declines (see backup slide for details)
Higher Renewable/Battery Costs	HiRE	Inflationary pressures (e.g., from global demand for raw materials) increase costs
No New NGCC Capacity	NoGas	No new NGCC capacity
No Carbon Capture	NoCCS	No new CCUS-equipped capacity
No New NGCC or CCUS	NoGasCCS	No new NGCC or CCUS-equipped capacity
No New Transmission	NoTr	Inter-regional transmission capacity constrained to base year values
Operating Reserves	OR	Including detailed operating reserves
Uprates for Nuclear and Hydro	Uprate	Increasing existing nuclear/hydro capacity by 10%

Figure 30 (Figure 31) shows generation and capacity for the reference (accelerated) electrification scenario across different electric sector sensitivities. These sensitivities illustrate scenario-specific variability in the mix, but also elements that are robust across assumptions about technological cost and availability. For instance, all scenarios exhibit much higher variable renewables generation than today, as generation shares in the "50x30" scenario range from 32 to 46% nationally (with hydro and biomass adding 7% to 8%. Installed wind and solar capacity in the reference electrification scenario is nearly equal to peak load.

Higher demand in the accelerated electrification scenario ("50x30 E+") is met with increased generation from gas (Figure 31). Renewables and energy storage deployment are higher than the reference scenario but lower than the "50x30" scenario with reference electrification.

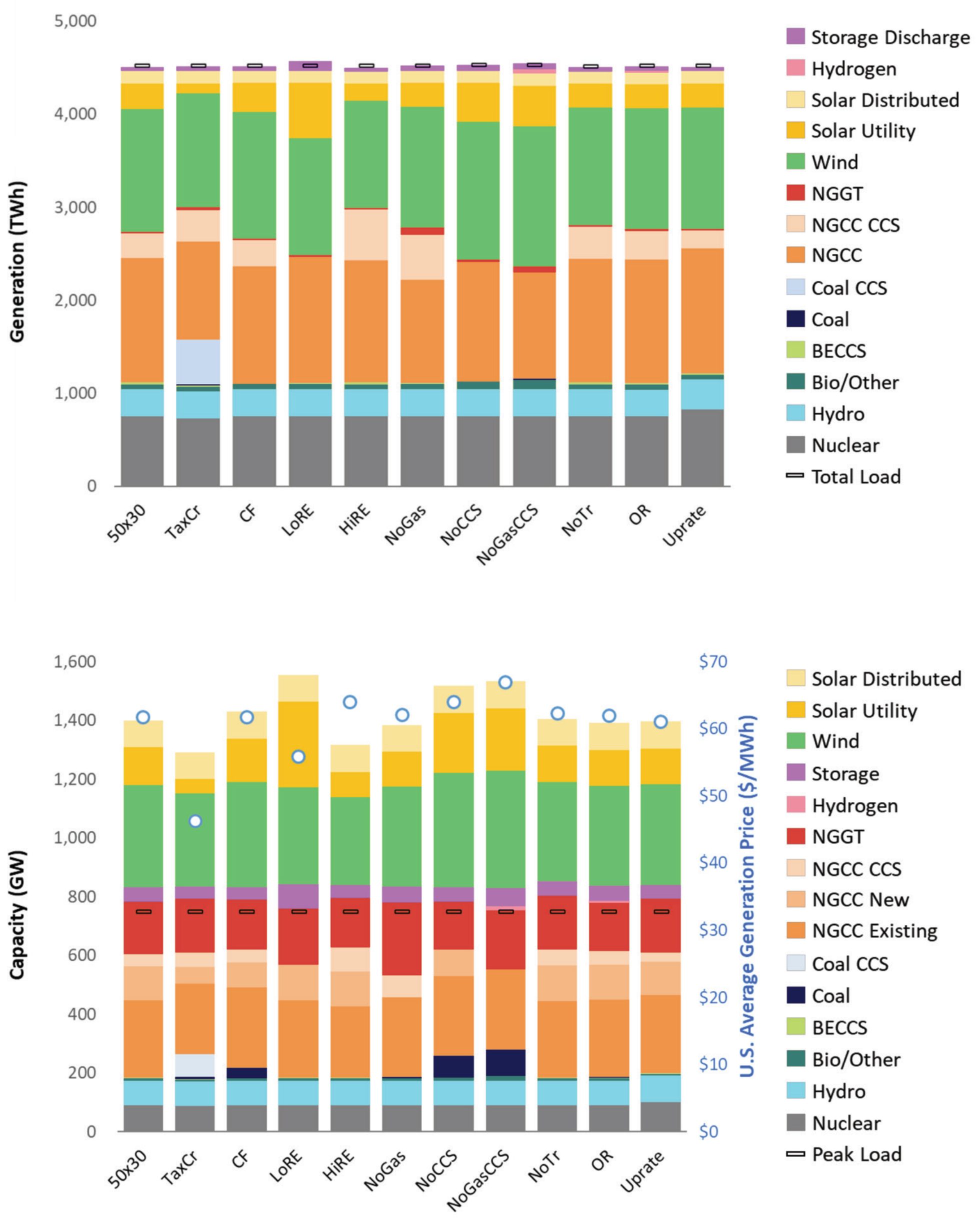


Figure 30. *Generation (top panel) and capacity (bottom panel) by technology and scenario under the reference electrification ("50x30") scenario. The bottom panel also includes the U.S. average generation price.*

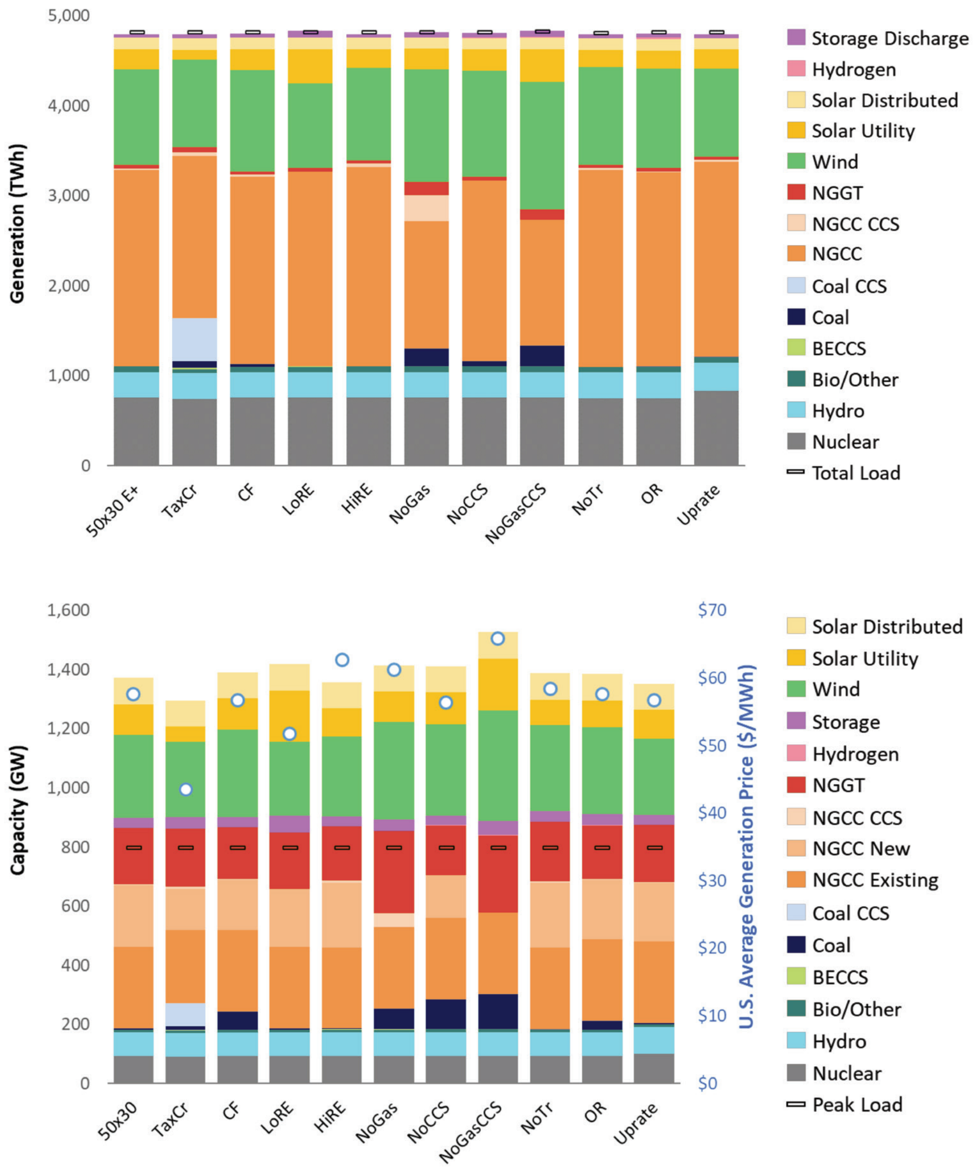


Figure 31. *Generation (top panel) and capacity (bottom panel) by technology and scenario under the accelerated electrification ("50x30 E+") scenario. The bottom panel also includes the U.S. average generation price.*

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