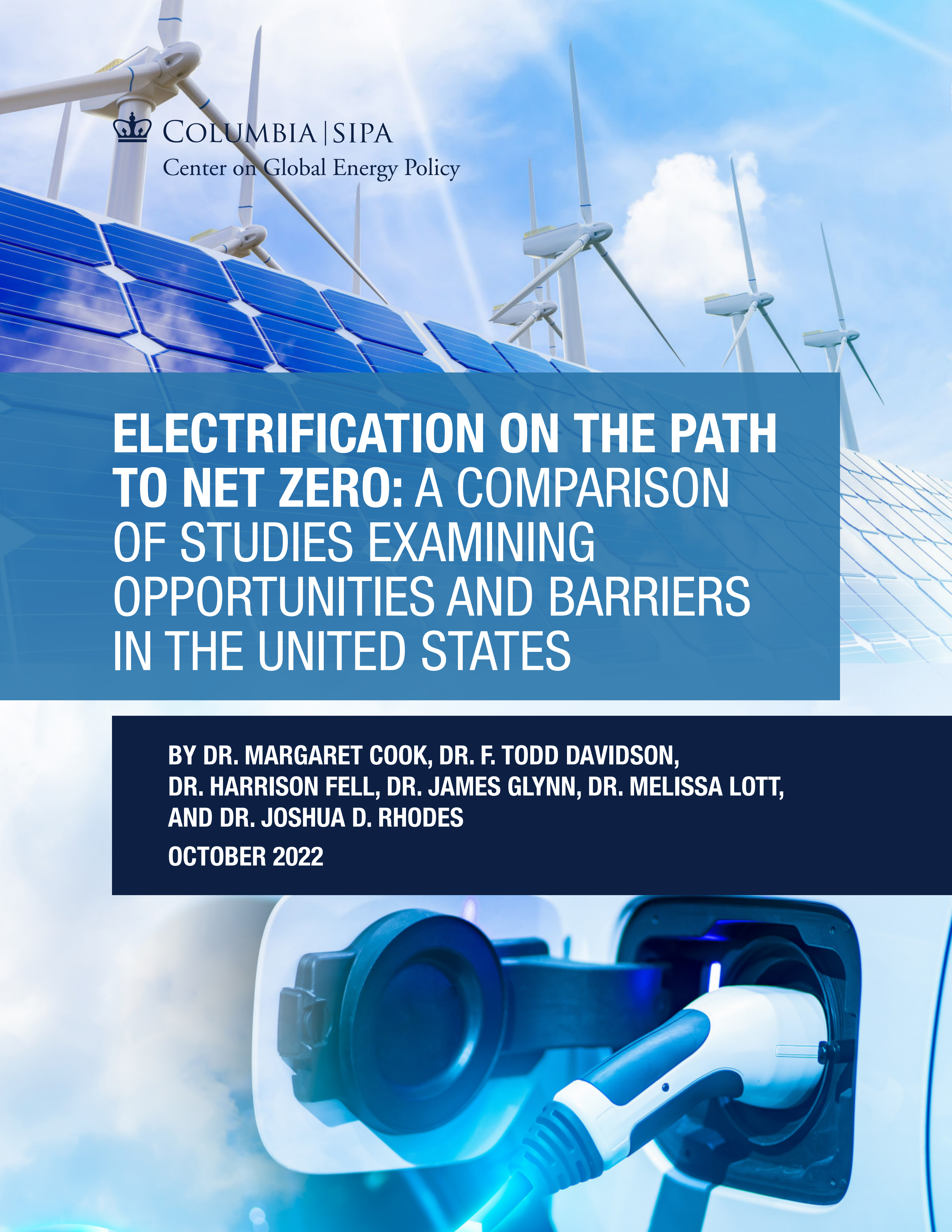

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ELECTRIFICATION ON THE PATH TO NET ZERO: A COMPARISON OF STUDIES EXAMINING OPPORTUNITIES AND BARRIERS IN THE UNITED STATES

BY DR. MARGARET COOK, DR. F. TODD DAVIDSON, DR. HARRISON FELL, DR. JAMES GLYNN, DR. MELISSA LOTT, AND DR. JOSHUA D. RHODES

OCTOBER 2022

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ACKNOWLEDGMENTS

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Dr. James Glynn is a Senior Research Scholar at the Center on Global Energy Policy. He leads the Energy Systems Modelling Program. He has over 15 years of experience within energy systems analysis, energy technology research, development, and deployment, collaborating with governments, technologists, utilities, suppliers, and energy analysts in the United States, Europe, and Asia. His published work spans the whole integrated energy system, including energy, economy & climate. Dr. Glynn is internationally recognized for his energy systems modeling innovations across hybrid modeling methods, uncertainty methods, and energy security assessments. James currently serves on the Integrated Assessment Modelling Consortium (IAMC) scientific working group (SWG) in climate-related Financial Analysis.

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He is an EU-commission invited expert in energy systems modeling and a reviewer of the EU Commission's DG-ENER new energy systems model METIS. He has given expert witness testimony to government committees on carbon capture and storage (CCS), carbon budgets, and net-zero carbon energy systems transition. He has served on the scientific advisory boards for multiple national and European research projects, such as the German DLR BEAM-ME project on high-performance optimization algorithms. He collaborates on numerous international energy-climate networks, including the Integrated Assessment Modelling Consortium (IAMC) and JPI-Climate. He is an affiliate invited member of the IEA-ETSAP executive committee. He has successfully led multiple national and international research & consulting project consortia.

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3. the impact of future climate on the technical operation of the energy system,
4. the role of direct air carbon capture and storage in global mitigation scenarios,
5. the impact of local air pollution on equitable global decarbonization,
6. as well as the development of the first zero-carbon energy system pathways for Ireland consistent with the Paris Agreement.

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IEEE Women in Power, and a Forbes 30 under 30 in Energy. In 2022, she was selected to serve on the United Nations Council of Engineers for the Energy Transition (CEET), which will serve as an independent advisory council to the UN Secretary-General.

Dr. Lott specializes in technology and policy research, working to increase our understanding of the impacts of our energy systems on air pollution and public health. She directly applies this understanding to help decision-makers mobilize technology and policy solutions to support the transition to net-zero energy systems. She has authored more than 350 scientific articles, columns, op-eds, journal publications, and reports. Dr. Lott was previously a founding author on Scientific American's Plugged In. An active public speaker, she has been featured in interviews with international news organizations including the New York Times, Wall Street Journal, PBS, the BBC World Service, The Guardian, Good Morning America, National Public Radio, the Wall Street Journal, Bloomberg, ABC News PM in Australia, and Scientific American magazine's French edition.

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EXECUTIVE SUMMARY

There is a strong and growing consensus that a simultaneously growing and decarbonizing electricity sector is necessary to meet declining greenhouse gas emissions targets. Rallying cries to "electrify everything" have captured the focus of many headlines and policy forums in recent years. However, there are important questions that remain unanswered about the electrify everything movement, including the technical, social, and political feasibility of the approach, as well as the affordability and equitability of implementation. While reducing emissions is paramount in mitigating the negative impacts of the energy system to the environment and human health, it is also critical that changes to energy infrastructure are both socially and politically acceptable, as well as affordable to help ensure an economically vibrant future. These nuanced dynamics are not easily articulated in public forums regarding the goal to electrify everything. A more detailed assessment of the problem might discover a better path forward.

This report, part of the Power Sector and Renewables Research Initiative and Energy Systems Modeling Analytics program at Columbia University's Center on Global Energy Policy, in conjunction with IdeaSmiths, examines eight recent major US studies on the topic. Six of the studies focus on strategies and pathways to a net-zero energy system and two assess the value of electrification and expanded transmission networks. This work serves to compare their assumptions and results. The authors' purpose in analyzing the studies was threefold. First, the report explores the degrees of electrification in the United States that might be needed to achieve net-zero pathways as well as where and how electrification could occur under model assumptions. Second, it examines the relative roles of variable generation resources (e.g., wind and solar), energy storage (both short- and long-duration), and firm low-carbon power (e.g., natural gas with carbon capture, nuclear, hydro, and geothermal) in the energy transition to meet increasing levels of clean electricity demand. Finally, the report examines the barriers that could hinder both increased electrification and decarbonization of the pivotal power sector.

By examining and comparing the studies and scenarios within them, the authors were able to identify shared themes resulting in robust insights that can be useful in informing policy makers and guiding other decision-making processes. Broad recommendations across studies include: (1) decarbonizing electricity; (2) electrifying end uses; (3) lowering energy demand; and (4) increasing transmission, distribution, and energy storage infrastructure. Seven major barriers to expanding electrification include challenges around: (1) the pace of transition, (2) technology advancement, (3) infrastructure siting, (4) equipment cost, (5) supply chains, (6) human capital/jobs, and (7) public support.

To attain the various decarbonization goals analyzed in these studies, federal, state, and/or local regulators would need to implement an array of policies to accelerate the pace at which clean energy technologies are deployed. While the studies generally do not compare specific policies but rather the least-cost path(s) to achieving certain decarbonization targets, none of their reference scenarios indicate the energy sector will decarbonize fast enough to meet emissions targets without additional policies.

Other key findings regarding the potential for electrification in the United States drawn from the eight studies include the following:

- To meet the demands of an electrified economy, electricity generation will need to grow rapidly, up to four times current levels. Starting in 2020, current electricity generation levels of 3,900-4,300 terawatt-hours (TWh) will need to grow to between 5,000-16,000 TWh in 2050, depending on the degree of electrification and its sources.
- All studies indicate a future that heavily relies on renewable technologies such as wind and solar while reducing use of fossil fuels and phasing out coal by 2035. Of the five studies modeling scenarios out to 2050, wind and solar were expected to supply 43–91% of electricity generation, a 5- to 15-fold increase compared to today's levels.
- A wide mix of technologies will be needed to achieve deep decarbonization within the power sector. Pursuing a 100 percent variable renewable energy electricity system is likely to cost more than pursuing a diversified portfolio that also includes firm, low-carbon generation technologies such as geothermal and nuclear as well as various forms of energy storage (e.g., batteries, hydrogen, etc.).
- The studies' scenarios also rely on increased transmission and flexible demands to efficiently deploy renewable energy resources across time and space. The required scale of transmission expansion is significant: One study estimates that $2.7 trillion in investment will be needed between 2020 and 2050, and another study assumes up to a 70 percent increase in total resource cost due, in part, to a 1,200 percent increase in transmission capacity over that currently installed.
- Despite the shift toward electrification, all studies include some continued use of some gaseous fuels, though the role of hydrogen and other synthetic gases varies greatly depending on assumptions.
- Multiple studies note that incentives for consumers of electric vehicles, heat pumps for space and water heating, and electric cooking could assist in increasing the pace of transition. In the highly electrified scenarios, the transportation sector sees rapid growth in EV sales across all vehicle classes, particularly light-duty vehicles. The same scenarios estimate that 100% of residential and commercial heating and cooking appliance sales need to be electric by between 2030 and 2040, and that by 2050, 95–100% of heating and cooking demand in the United States needs to be met by electricity.
- The studies find that some industry shifts to electrification due to efficiency gains, such as iron and steel making via electric arc-furnaces. However, for harder-to-electrify end uses such as freight, aviation, and other industry (e.g., cement, ammonia, hydrogen, biofuels, etc.), the studies favor the use of low-carbon fuels, increasing fuel efficiency, and pairing some end uses with carbon capture.

All of the studies examined in this report were completed prior to passage of the Inflation Reduction Act of 2022 (IRA). The IRA might shift the cost burden for different decarbonization solutions, but it does not invalidate the findings of the studies. While the IRA makes significant progress in addressing many challenges related to decarbonization, additional electrification hurdles will need to be overcome on the path to net-zero carbon emissions, as highlighted in this report.

CHAPTER 1: OVERVIEW OF MAJOR THEMES

To electrify many of the energy demands across the economy—a goal often considered vital to mitigating the negative impacts of climate change on human health and the environment while keeping energy affordable—the electricity sector must simultaneously grow and decarbonize. This report analyzes eight studies focused on the United States to explore the degree to which, as well as where and how, electrification might occur in net-zero pathways. It also examines relative roles of variable generation (VG) resources (e.g., wind and solar), energy storage (both short and long duration), and firm low-carbon power (e.g., natural gas with carbon capture use/storage, nuclear, hydro, geothermal) in the energy transition to meet increasing levels of electricity demand. The report concludes with recommendations based on its findings.

This analysis reviews six prominent studies that discuss strategies and pathways to achieve a net-zero energy system economy and two that focus on the value of electrification and expanded transmission networks. Table 1 and Table 2 provide a list of the studies and their scenarios considered in this report.

Table 1: Studies evaluated in this report

Study name	Abbreviation	Reference
Princeton's "Net-Zero America"	Princeton	Larson et al. 2020
"Carbon-Neutral Pathways for the United States"	Williams	Williams et al. 2021
Vibrant Clean Energy's "Zero by 2050"	VCE	Vibrant Clean Energy 2021
"The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050"	White House	The White House 2021 (Global Change Assessment Model team)
Electric Power Research Institute's (EPRI) "Powering Decarbonization: Strategies for Net-Zero CO_2 Emissions"	EPRI	Blanford et al. 2021
Berkeley's "2035 Electricity" and "2035 Transportation" reports	Berkeley 2035	Phadke et al. 2020; Bald-win et al. 2021
National Renewable Energy Laboratory's (NREL) "Electrification Futures Study"	EFS	Jadun et al. 2017; Hale et al. 2018; Mai et al. 2018; Sun et al. 2020; Murphy et al. 2021; Zhou and Mai 2021
NREL's "Interconnections Seam Study"	Seams	Bloom et al. 2021

Table 2: Study scenarios reviewed

Study abbreviation	Scenario	Description
Princeton	REF	Reference
Princeton	E+	High electrification
Princeton	E-	Less-high electrification
Princeton	E-B+	High biomass
Princeton	E+RE-	Renewable constrained
Princeton	E+RE+	100% renewable
Williams	Reference	Reference
Williams	Central case	High electrification
Williams	Low land	Land is constrained
Williams	Delayed electrification	Electrification is delayed
Williams	Low demand	Demand is constrained
Williams	100% renewable primary energy	100% renewable
Williams	Net negative	Carbon emissions are reduced beyond net zero to net negative
VCE	EBAU	Economic (not carbon constrained electricity sector) projections with electrified economy through 2050 (with distributed energy resources [DER], cooptimization, and novel tech)
VCE	EBAU-	Economic (not carbon constrained electricity sector) projections with electrified economy through 2050 (without DER co-optimization or novel tech[1])
VCE	ECE	100% clean economy by 2050 (with DER co-optimization and novel tech)
VCE	ECE-*	100% clean economy by 2050 (without DER co-optimization or novel tech but with expanded available variable renewable electricity [VRE] and storage buildout rates)
VCE	ECE HVDC	100% clean economy by 2050 (with DER co-optimization and novel tech and HVDC macrogrid by 2025)
VCE	ECE HVDC+	100% clean economy by 2050 and clean electricity by 2035 (with DER co-optimization and novel tech and HVDC macrogrid by 2025)
VCE	ECE HVDC-	100% clean economy by 2050 and clean electricity by 2035 (without novel tech and with HVDC macrogrid by 2025)

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Study abbreviation	Scenario	Description
VCE	ECE HVDC-*	100% clean economy by 2050 and clean electricity by 2035 (without novel tech and with HVDC macrogrid by 2025 but with expanded available VRE and storage buildout rates)
VCE	ECE HVDC--	100% clean economy by 2050 and clean electricity by 2035 (without DER co-optimization or novel tech and with HVDC macrogrid by 2025)
EPRI	Reference	Reference
EPRI	Net zero by 2050	Net-zero electricity sector by 2050
EPRI	100% renewable by 2050	100% renewable
Berkeley 2035	Baseline	Reference
Berkeley 2035	90% clean by 2035	Policy of 90% clean energy by 2035
EFS	Reference	Reference
EFS	Medium	Medium electrification
EFS	High	High electrification
Seams	Base Case	Reference
Seams	Design 1	Existing B2B facilities are replaced at their current (2017) capacity level and new air capture (AC) transmission and generation are co-optimized to minimize system-wide costs.
Seams	Design 2a	D2a: Existing B2B facilities are replaced at a capacity rating that is co-optimized along with other investments in AC transmission and generation.
Seams	Design 2b	D2b: Three HVDC transmission segments are built be-tween the Eastern Interconnection and Western Inter-connection, and existing B2B facilities are co-optimized with other investments in AC transmission and generation.
Seams	Design 3	D3: Macrogrid (a nationwide HVDC transmission net-work) is built, and additional AC transmission and generation are co-optimized to minimize system costs.

While each study differs in its approach, it was possible to compare general trends and assess similar scenarios across studies, including (1) the reference or business-as-usual (BAU) scenarios, (2) the main expanded electrification scenarios, (3) the increased renewable energy (RE) scenarios, and (4) the lowest cost scenarios. By examining and comparing the studies and scenarios shown in Table 1 and Table 2, respectively, this analysis was able to identify shared themes that appeared across studies, which could be useful in informing policy-making and other decision-making processes.

In general, the models used in these types of studies are seeking to develop the most cost-effective pathways toward their goals, such as decarbonization. Ideally, the models would include all forms of cost, including capital costs for construction of infrastructure, variable costs for maintaining and operating infrastructure, associated impacts from policies, including but not limited to tax credits, and the comprehensive assessment of indirect costs (e.g., road building and waste disposal), as well as externalities (e.g., emissions and impacts on biodiversity). However, the models are not comprehensive nor consistent in their treatment of costs. For example, to the authors' knowledge, the models do not account for every change within the economy that is required to enable changes in infrastructure (e.g., the cost of constructing new roads to install wind turbines or other large infrastructure at a greenfield site). The studies also do not consistently quantify the impacts of externalities related to infrastructure development (e.g., beyond the cost of carbon, what is the specific cost of potential biodiversity loss locally and globally as a result of choosing different pathways?). For example, the Regional Energy Deployment System (ReEDS) model used by Berkeley and NREL in EFS does not include environmental or health externalities. The Seams study states benefits/costs reported should be considered lower bounds as they do not reflect externalities. VCE does not consider social costs. Berkeley 2035 and Princeton both report social costs such as health impacts separately from the objective function (i.e., these costs do not affect model outcomes but are calculated for each scenario). EPRI considers a scenario with a price on carbon but not a social cost of carbon. This scenario is separate from the net-zero scenario analyzed in this report. Despite those limitations, the studies analyzed here represent some of the most holistic assessments of costs associated with modifying domestic energy infrastructure on a path to net-zero carbon emissions. A more detailed discussion of the methodologies used for assessing cost in each of the studies is provided in the System Costs section, including Table 3.

The different scenarios in each study are created by a combination of changing input prices that directly impact the pathways, such as the future cost of natural gas or solar photovoltaic (PV), and/or applying constraints that the model must adhere to as it develops a least-cost path forward, such as limits to transmission builds or binding carbon budgets. Much thought and effort go into the model inputs for each scenario because they seek to emulate real-world economic and societal constraints while charting the optimal path forward. The reader can examine the original studies to gain additional insight regarding what costs they do and do not include in their modeling scenarios and how assumptions are managed to alter the different scenarios.

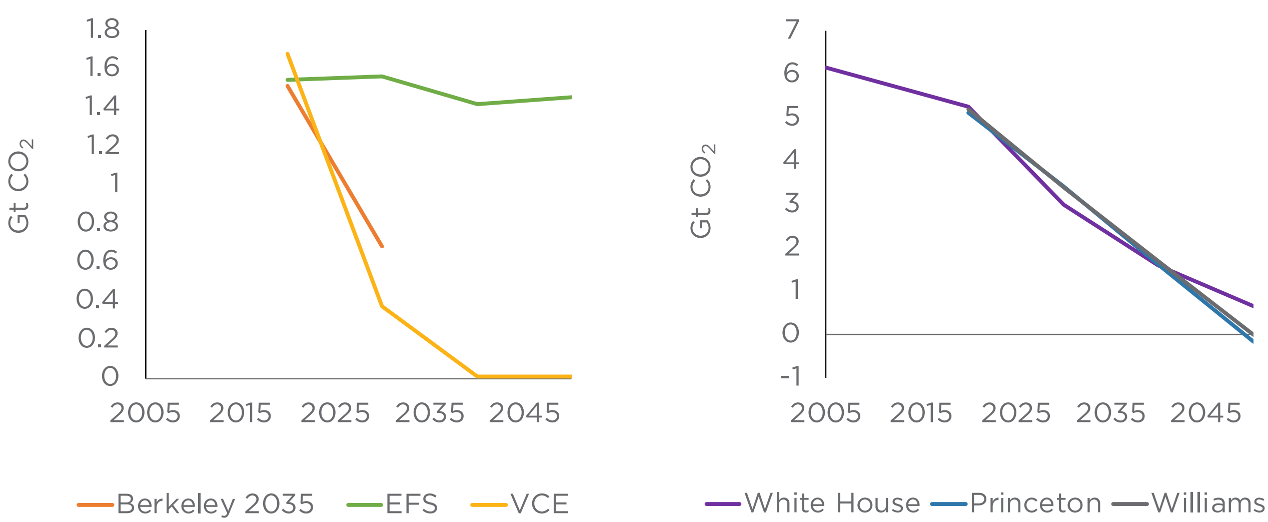
The studies by Princeton, Williams et al., Vibrant Clean Energy, the White House, and EPRI (1–5) each explore pathways to achieve net zero by 2050. EPRI's study also evaluates additional pathways, including achieving net-zero electric sector emissions by 2035. The Berkeley 2035 Electricity and Transportation reports each evaluate one policy scenario: (a) achieving 90 percent clean electricity by 2035 and (b) achieving 100 percent electric light-duty vehicle (LDV) sales by 2030 and 100 percent electric medium-duty vehicle (MDV) and heavy-duty truck sales by 2035.

The Electrification Futures Study explores expanding demand-side electrification. Whereas the Interconnections Seams Study focuses on multiple transmission scenarios, including expanding high-voltage direct current lines and creating a macrogrid across the nation. Both studies evaluate these changes against multiple generation profiles and constraints.

A summary of the pace of carbon emissions reductions modeled by the studies is shown in Figure 1.

Figure 1: Carbon reduction timelines across studies

Electricity sector CO_2 emissions **Economy-wide CO_2 emissions**



Note: Economy-wide values are the White House average CO_2 emissions; Princeton E+, E-, E-B+, and E+RE- (E+RE+ is similar); and Williams Central Case, Delayed Electrification, Low Demand, and Low Land (Net Negative and 100% Renewable Primary Energy have further reductions). Electricity sector values include Berkeley 2035 (electricity), EFS High, and VCE ECE HVDC+ (clean economy and clean energy scenarios ECE HVDC--, ECE HVDC-, and ECE HVDC- have similar trajectories). The EFS study was an electrification study, not a net-zero study, so its electricity sector emissions were not required to get to zero carbon emissions by 2050.*

Consensus and Constraints of Electrification on a Path to Net Zero

Electrification Strategies on a Path to Net Zero

The studies evaluated indicate that expanding electrification on a path to net zero[2] is possible but challenging—no technology, policy, or behavioral change is sufficient on its own. The pathways explored in each of the studies suggest profound changes are needed across the economy to reach net zero and often touch on similar themes and recommendations, including the following:

- Reducing fossil fuel use, including eliminating coal generation by 2035.
- Replacing fossil fuels with carbon-free energy sources, mainly wind and solar. Some

scenarios within the studies also expand traditional or advanced nuclear, as well as hydro and geothermal.

- Deploying a diversified set of technologies is estimated to be the least-cost path toward reducing emissions in the electricity sector. These technologies include having firm, low-carbon power generation, such as natural gas with carbon capture and storage (CCS)/carbon capture, utilization, and storage (CCUS), nuclear, etc.
- Short- and long-term energy storage is considered important, although not a dominant requirement unless policies require 100 percent renewable electricity. Some of the modeled scenarios also include high blends of hydrogen (H2) in gas turbines, wherein the hydrogen is produced from excess wind and solar and thus serves as a solution for long-term energy storage.
- Expanding transmission to enable increased electricity generation needs. Expanded renewable generation, particularly distributed generation, cannot satisfy future demands without adequate transmission. While transmission is expensive, a lack of transmission can cost more by leaving generation assets stranded or increasing congestion in electricity networks. Net-zero studies strive to optimize the location of transmission installations near locations with high levels of supply or demand. The Seams study further highlights that connecting the eastern and western grids may be a more economic national strategy than keeping them separate, with the objective of accessing higher quality resources, bridging climate zones, and mitigating the impact of regional, transient weather patterns.
- Increasing electrification of residential, commercial, industrial, and transportation sector end-use demands. The residential and commercial sectors must rapidly expand sales of heat pumps for space and water heating and electric resistance/induction for cooking to 100 percent of sales by 2030–2040. The transportation sector must rapidly expand electric vehicle (EV) sales in all vehicle classes. Light-duty electric vehicle sales should reach 100 percent of sales by 2040–2050 while electric medium- and heavy-duty trucks, which might also be fueled by hydrogen, need to reach 100 percent of sales by the same decade.
- Flexible demands that can shift consumption in time and/or space can help maintain the reliability of a grid that depends more on variable energy supplies.
- Reducing energy demand through efficiency and conservation with technology and infrastructure changes, such as improving a building exterior's thermal properties, will help enable greater adoption of electrification solutions because lower heating demand can be met by less power-intensive electric heat pumps. Increased industrial productivity via improved machinery or processes can also reduce the amount of energy required per manufactured unit. While not explicitly addressed in the studies, improved machinery or processes remains an important proxy for energy efficiency.

To deploy the significant clean energy capital and infrastructure needed to reach the various decarbonization goals analyzed in these studies, federal, state, and/or local regulators would need to implement an array of policies. That is, none of the reference scenarios from these studies indicate the energy sector will decarbonize in a timely manner without additional policies.

Note also that the policies implemented to decarbonize the energy sector will ultimately determine the decarbonization path the US will take. Different types of energy policies have varying levels of economic efficiency in achieving decarbonization. For example, attempting to reach a decarbonized energy sector via tax rebates and subsidies will likely lead to a different set of investments than, say, a policy that decarbonizes through a clean energy standard or emissions tax. Similarly, the policies employed to encourage load reshaping and more general demand flexibility will determine the degree to which the demand side will electrify more energy services and accommodate more clean energy resources.

While the policies undertaken (or not) are key to determining the level and mechanisms of decarbonization, it is important to note that the studies explored here are generally not comparing policies needed to decarbonize but, again, are simply exploring the lowest cost path(s) to achieve certain decarbonization targets, subject to various technical and economic constraints.

Electrification Challenges

The decarbonization studies identify seven major challenges associated with expanding electrification: (1) the pace of transition, (2) technology advancements, (3) siting issues, (4) cost, (5) supply chains, (6) human capital/jobs, and (7) public support.

1. The starting point and pace for electrification and transition to clean electricity has a significant impact on the cumulative amount of carbon emitted. A slower pace and later start lead to more emissions. These changes are dependent on the mobilization of capital, including divestment and new investment decisions. Princeton notes that the biggest challenge here is scale and rate of infrastructure change.

2. A second constraint is the rate of technological advancements. Some studies rely on technologies that have not yet fully matured or declined in cost to be economically viable currently. The studies indicate that it is important to make progress in the maturation, scale, cost, and performance improvements in needed technologies, such as advanced nuclear (small modular reactors [SMRs] and molten salt reactors [MSRs]), advanced geothermal, carbon capture for power and industry, hydrogen production and combustion, ultracheap long-duration energy storage, synthesis of fuels, carbon-free alternatives for steel, high-yield bioenergy, and direct air capture. These advancements will be particularly important for sectors of the economy that will be harder to fully electrify, including aviation, heavy-duty vehicles (HDVs), and industrial applications that require high-temperature heat and chemical feedstocks.

3. A third constraint is siting. Restrictive siting requirements for transmission infrastructure and renewables facilities can constrain the feasible scale and pace at which the electricity sector can decarbonize. For example, siting delays for carbon storage can constrain the decarbonization of hard-to-abate industries or other

lingering fossil fuel uses.

4. A fourth constraint is cost. Most net-zero strategies are capital intensive at the system and individual levels, even if the lifetime costs are lower. Consumers may need assistance with the upfront cost of technologies integral to electrifying demand, such as heat pumps and electric vehicles. Economy-wide decarbonization studies that rely heavily on electrification estimate costs that range from $2 trillion of clean energy investment to $28 trillion in total system costs for an electrified net-zero economy (Berkeley 2035, VCE, and Princeton). More information is needed, though, to assess the total cost of achieving maximum electrification on a path to a net-zero economy. However, while these costs exceed the reference scenarios in the studies examined in this report, the benefits outweigh the additional costs across studies, in line with others such as those in the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) Working Group III (WGIII) (Riahi et al. 2022).

5. A fifth constraint is the capacity of supply chains to rapidly develop for new industries and resiliently hold pace alongside a quickly electrifying economy. The geopolitical security of supply chains is increasingly important.

6. A sixth constraint is in the human capital and skill sets needed to fill the jobs required for a net-zero economy. The electricity supply sector needs skilled renewable energy and construction workers to make the transition. Similarly, the demand sectors will need technicians, manufacturing workers, and maintenance workers. It is also notable that there may be pockets of unemployment due to transition away from fossil fuels, indicating that a sector of the workforce would benefit from targeted reskilling to reduce some of the acute social costs of the transition.

7. Finally, a lack of public support can constrain the ability to transition to a clean energy economy. Public support is required for land use changes, for the uptake of electrifying technologies, and for many of the needed policy changes required to reach net zero. Such changes include redirecting fossil fuel subsidies to low-carbon technologies and streamlining clean infrastructure permitting. Historically, tax credits, such as the production tax credit and investment tax credit (ITC), have played a role in incentivizing the development of wind and solar. Similar policies may be required to sustain and accelerate development of low-carbon energy technologies in the future, including but not limited to incentives for energy storage and hydrogen, as well as changes to policies governing the design of electricity markets. Demand changes will require cultural acceptance, increasing familiarity with new technologies and behaviors, and financial incentives to convince consumers to shift away from solutions they have historically used but that might be more carbon intensive than modern alternatives. Some technology changes will encounter agency issues, such as landlord-tenant incentive mismatches that will require policy interventions.

Understanding these constraints is key to identifying approaches that can overcome them.

Decarbonization Topics for Further Consideration

Additional decarbonization topics are worth acknowledging even though they are not directly related to electrification, which is the focus of this report:

1. Some technology, policy, and infrastructure changes can enable energy-saving behavior changes, such as using videoconferencing to reduce the need to fly. Additional considerations include zoning for sustainability, climate resilience, and environmental justice (Velasco and Cohen 2022), as well as expanding public transit, investing in alternative transportation systems such as expanded and connected bike lanes, and improving the walkability of cities (Zagow 2022).

2. Deploying carbon management strategies such as CCUS, direct air capture (DAC), and expanding land sinks as a natural form of carbon sequestration may be needed to reach full decarbonization, as the eight electrification strategies mentioned above significantly reduce emissions but still may not reach all the way to zero emissions. For example, carbon capture can be added to industries that cannot otherwise economically decarbonize and/or be paired with biomass as a net negative carbon technology. In these scenarios, infrastructure to transport and store carbon is needed to meet this new demand, but these technologies have constraints stemming from cost, geology, capture rates, injection rates, site porosity, storage volume, energy availability, technology readiness, and land use. Deployed carbon management strategies are not primary methods of carbon reduction and are not used to extend the life of expensive carbon-intensive processes such as coal generation. Instead, they are used when electrification, energy efficiency, and similar strategies have been cost maximized. IPCC decarbonization scenario analysis has seen a likely reduction in CCS penetration in the power sector between Assessment Report 5 (AR5) and the most recent assessment report (AR6), while carbon management is still expected to be required in the industrial and synthetic fuels sectors.

3. Planning around the transition to net zero will need to consider effects on disadvantaged and marginalized communities to ensure they do not continue to be disproportionately harmed in the process. While the above strategies may achieve net zero, the studies and scenarios evaluated generally lack a complete discussion of who suffers as emissions continue. Capturing carbon from industrial facilities or power plants does not necessarily negate all of the forms of air pollution they produce and thus their effect on nearby communities. For example, studies have shown that people of color are currently exposed to higher levels of fine particulate matter (PM) compared to communities that are predominantly white (Tessum et al. 2019). The current studies also do not fully capture the complex conversation regarding energy poverty and potential tradeoffs with environmental impacts.[3]

Additional discussion regarding relevant decarbonization topics, including agricultural practices and effects on jobs, is provided in Appendix D.

Future Energy Needs

To understand the potential for expanding electrification in the economy, it is important to first understand the amount and type of energy that may be needed in the coming decades.

Primary and Final Energy

Primary energy is typically described as energy sources that naturally exist and can be harvested (e.g., oil, natural gas, and solar). In the context of this report, final energy will be defined as the forms of energy that are consumed to provide end-use services (e.g., gasoline, hydrogen, and electricity).

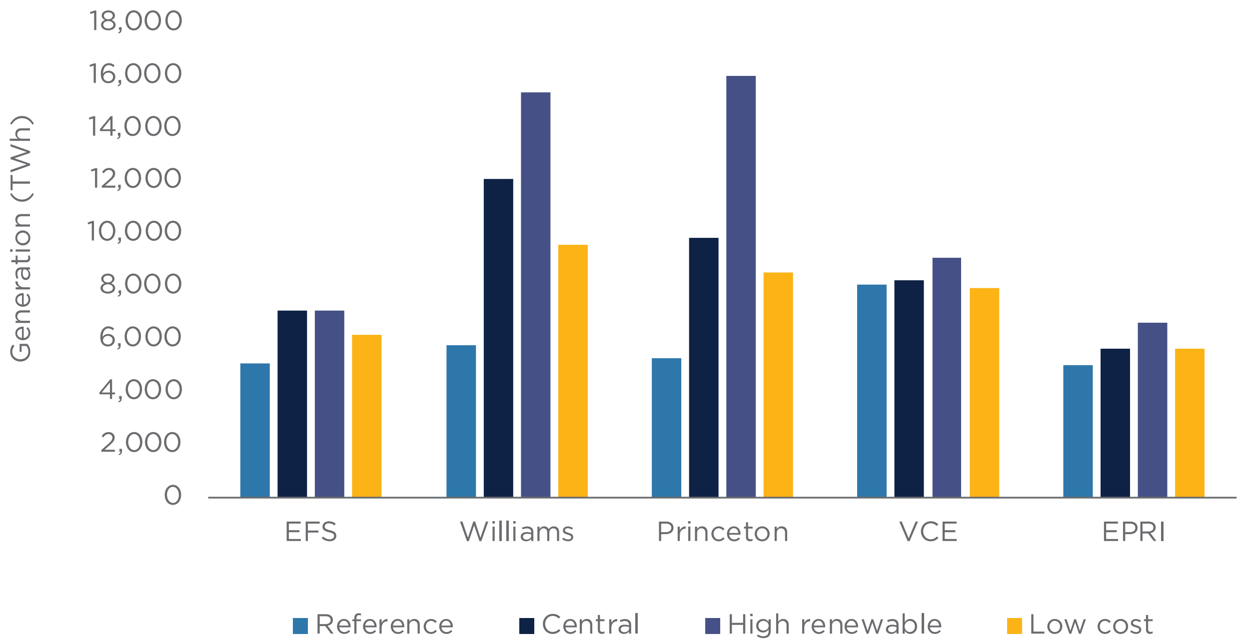
Projections of Future Energy Demand

Pathways toward decarbonization result in both a lower primary energy demand and final energy delivered. The reductions in both primary and final energy consumption are achieved through electrification, fuel switching, energy efficiency, modal shifts, and other demand reductions. Despite the reductions in primary demand and final energy delivered, the consumption of electricity is projected to increase. Using electricity for end uses is generally more efficient than using a nonelectric alternative (e.g., a best in class internal combustion engine may be up to 55 percent efficient, whereas a typical electric vehicle motor is 97 percent efficient), thus resulting in more electricity use but lower primary energy use. Delayed electrification slows this impact and yields less reduction in the cumulative sum of energy supply and energy delivered to end uses. Also, in net-zero analyses, less electrification means more energy supply is needed (e.g., increased consumption of gasoline).

In EFS, the use of natural gas for electricity also lowers primary energy demand due to generation efficiency gains compared with burning coal. Higher renewable energy scenarios result in small increases in primary energy. Bigger increases in primary energy occur when (1) renewables are constrained while the economy attempts to electrify, (2) when power plant retirements are constrained, (3) when transmission is constrained (and thus more curtailment of energy sources occurs), and (4) when less natural gas is available. Typically in international statistics, the input primary energy of wind, solar, or hydro is not measured and only the generated electricity is measured, biasing further the understanding of primary renewable energy versus primary fossil energy demand projections.

Despite similar scenarios modeled, the different studies examined in this report have noticeably different estimates of energy consumption in the coming decades. For example, the studies project that future electricity demand may vary between approximately 5,000 and 8,000 terawatt-hours (TWh) in 2050 in the reference cases (the US consumed almost 4,000 TWh in 2021), as shown in Figure 2. For electrification and high renewables scenarios, the studies show ranges of electricity generation from approximately 5,500 to 16,000 TWh. The wide range in estimated future demand for electricity elucidates the fact that underlying assumptions in the different models have important impacts on how the models estimate future energy needs. Consequently, these assumptions have a critical influence on the required adoption rates of different technologies and solutions to expand electrification and achieve a net-zero future. Thus, it is difficult to provide a simple side-by-side comparison of the different studies without discussing some of the nuanced results from each of the models. Additional details regarding the demand side considerations are provided in Chapter 3 and Appendix C. It should also be recognized that a comprehensive comparison of each assumption used in each of the studies would be intractable within the context of the goals of this report to summarize the primary findings. The authors refer the reader to each of the studies in question for more detailed discussion of the underlying assumptions.

Figure 2: Generation in 2050 across studies and scenarios



System Costs

Decarbonization strategies such as transmission expansion, renewable energy deployment, carbon management, and electrification retrofits are capital intensive with spending estimates in the trillions of dollars per year by 2050. However, there is wide variation between studies for how expensive reaching a net-zero economy will be; the studies used different metrics and thus were not wholly consistent in their costs reporting.

Princeton estimates that total system costs for a net zero economy reach $26 to $28 trillion from 2020 to 2050, an increase of $4 to $6 trillion over the reference scenario. Approximately $9.7 trillion is required cumulatively between 2020 and 2030. Annual cost varies between $1 and $2.2 trillion per year and increases as variable generation increases, as shown in Table 3. Similarly, compared to the reference scenario, Williams estimates total energy spending[4] to range from approximately $1.2 to $1.8 trillion per year by 2050, on par with Princeton. In contrast, VCE estimates that achieving net zero in the electric sector will vary between $2.5

and $3.2 trillion in total resource costs, which include capital, fixed and variable operations and maintenance, and fuel for electricity, hydrogen, and natural gas. Annual resource costs increase from approximately $320 billion in 2018 to between $372 and $496 billion in 2050 but vary lower and higher year to year depending on the scenario. For example, an increase in transmission installation pushes yearly costs to a maximum of $525 billion in 2035 in one VCE scenario, while the lowest cost scenario dips to $246 billion annually in 2030. Similarly, Berkeley calculates that a total investment of $1.7 trillion in clean energy by 2035 is needed to achieve the 90 percent clean energy goal. Table 3 shows a comparison of costs across the studies, including the EFS's nondecarbonized but electrified future costing $3.6–$3.9 trillion total from 2019 to 2050. The cost results from EFS were originally reported in 2016 dollars but have been converted to 2018 dollars here to help facilitate comparison with other studies. It is worth noting that for the majority of cases, the net cost relative to the reference is positive, meaning that a decarbonization pathway will cost more money than the reference scenario. The studies assert that the benefits of taking such action outweigh the cost; this conclusion is in line with IPCC AR6 WGIII as previously noted in the fourth electrification challenge. Additional work is warranted to assess whether the net cost relative to the reference case would remain positive if all system costs and externalities (e.g., nonlinear climate damages to economic productivity, adaptation costs, and health damages) were accounted for beyond the cost descriptions that are summarized in Table 3.

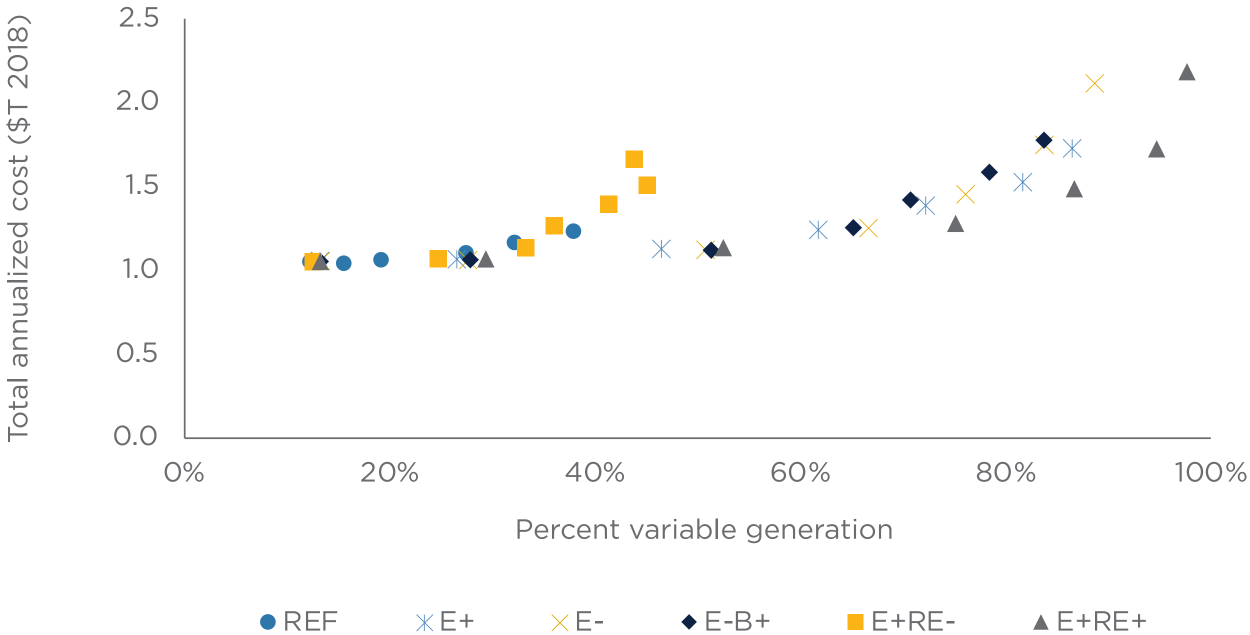
Table 3: Total, annual, and net costs for studies evaluated (2018, dollars)

Study	Cost category	Description	Total cost	Annualized cost	Net cost relative to reference
Princeton	Total system costs	Supply and demand side energy system costs, including capital and O&M	$26–$28T	$1–$2.2T	$4–$6T
Williams	Total energy spending	Supply side energy infrastructure, fuels, O&M, incremental cost of demand side equipment		$1.2–$1.8T	$53–$340B
VCE	Total resource cost	Electricity generation, hydrogen, and natural gas costs	$2.5–$3.2T	$246–$525B	$(–11)– $658B
Berkeley 2035	Clean energy investment	Supply side investment for 90% clean energy	$1.7T up to 2035		
EFS	Total cost	Transmission, nonfuel O&M, fuel costs, capital costs	$3.6–$3.9T		$491–$768B

Some of the capital-intensive strategies Princeton includes are the following: $7 billion investment in public charging infrastructure; $250 billion for energy efficiency that reduces energy intensity of transportation, industry, and buildings; $60 billion for new cement plants with carbon capture; $170–$230 billion for carbon dioxide (CO_2) pipeline infrastructure; and

$8 billion for new direct-reduced iron facilities that operate using hydrogen. An estimated $370 billion in total electricity distribution network investment is needed in the 2020s alone. The Princeton authors also expect that stakeholder engagement will require an additional $13B investment. Figure 3 shows the range of total cost for each scenario modeled in Princeton as the percentage of variable generation changes.

Figure 3: Total annualized cost compared to percent variable generation in electricity supply, estimated by Princeton



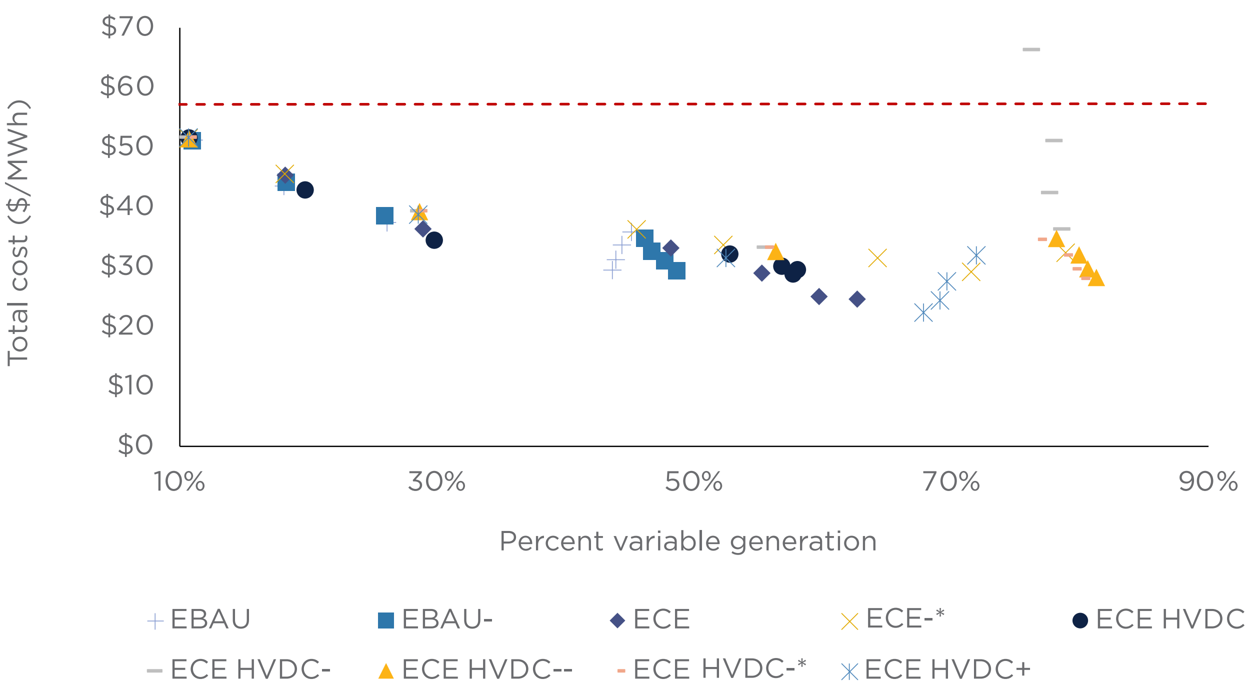
Note: For scenario abbreviations, see Table 2.

Future work could attempt to assess the potential carbon abatement value of each transition step in the models. This could be done using a metric such as levelized cost of carbon abatement. Unfortunately, this type of analysis cannot be completed using the information available in each of the studies in question due to the fact that multiple different investment decisions are made in each of the scenarios within each study. Furthermore, trying to isolate the influence of a single technology or transition step can obscure potential synergies that might only become evident with system-wide optimization models. As such, significant effort would be needed to attribute the value of carbon abatement to a single technology or transition step.

Decarbonization is more expensive for the energy sector overall when no externalities are considered but less expensive per unit of generation. However, when externalities or benefits are considered in the studies, decarbonization is less expensive than the reference scenario. Additionally, the need to install more transmission to accommodate distributed resources and additional renewable capacity (to compensate for variability in generation) increases total system costs. These capital-intensive strategies lead to an increase in fixed cost driven by increased generation and transmission deployments. However, there is a corresponding decrease in the variable cost of generation due to lower fuel use. Paired, these negatively correlated trends still result in an overall increase in cost, as shown in Figure 3 for Princeton. It is important to recognize that despite the apparent increase in costs, the studies currently under scrutiny did not use a consistent or comprehensive methodology to quantify the impact of all potential externalities associated with maintaining the status quo of a carbon-intensive economy. It has been shown in several studies that the climate and air quality costs associated with the status quo are quite substantial. For example, Driscoll et al. (2021) analyzed the costs and benefits, inclusive of local air quality improvements, for a target of 80 percent carbon-free electricity production by 2030 in the US and found a net present value of $1.43 trillion in net benefits (benefits less costs), the majority derived from air-quality-improvement-related reduced mortality.

The decline in variable costs of electricity for increased renewable energy deployments can be seen in the data from VCE in Figure 4, where the red dotted line is the initial cost per megawatt-hour (MWh) (i.e., average electricity cost in 2018). Increased flexible demands using off-peak electricity that reduce curtailments further reduce marginal costs.

Figure 4: Total variable and fixed generation cost per MWh compared to percent variable generation in electricity supply, estimated by VCE



Note: For scenario abbreviations, see Table 2.

However, some studies estimate that wholesale energy costs increase with a cleaner electricity system. Berkeley 2035 suggests these costs are about 12 percent higher by 2035 in the 90 percent clean energy scenario relative to the reference case but 10 percent lower than they were in 2020. Similarly, VCE estimates that electricity rates would increase between 9 percent and 41 percent relative to the economic business-as-usual scenario (EBAU) in all but one case (ECE HVDC-), despite being 12 percent to 30 percent lower than rates in 2018. Other studies do not directly quantify electricity rate changes.

Future Energy Infrastructure Needs

Electricity Generation

The electrification of most end uses is a major tenet of a net-zero economy. Deep electrification will increase demands on the electricity sector and thus require increased manufacturing and utilization of hardware to generate and distribute decarbonized electricity.

Decarbonization studies generally share a theme of rapidly eliminating coal, reducing or eliminating natural gas, and increasing renewable generation in the pursuit of expanded electrification. All studies evaluated in this report agree that there will be no deployment of any new coal capacity. However, decarbonization and nondecarbonization studies differ in how quickly coal and natural gas generation are phased out, if they are. Decarbonization studies eliminate coal generation by 2030 or 2035. Nondecarbonization studies see a reduction in coal use in scenarios with high renewable energy use, high natural gas use, emissions constraints, or high electrification, but they do not necessarily see coal generation disappear.

The decarbonization studies do allow for increased natural gas capacity as needed. This capacity is mainly combustion turbines that are used when the models are constrained in a way that it can only deploy renewables. However, most decarbonization scenarios do see natural gas generation decrease to almost zero by 2050. Increases in or continued natural gas use is paired with CCUS or some other carbon offset to achieve net zero.

In contrast, the nondecarbonization studies show an increased use of natural gas in both combined cycle and combustion turbines and continued use to 2050. In NREL's Interconnections Seam Study, there is variation across scenarios via the increased use of natural gas in more efficient combined cycles and a decreased use of combustion turbines. NREL's EFS sees increased electrification leading to more natural gas combined cycle (NGCC) generation. In some decarbonization scenarios, generators utilize hydrogen and natural gas fuel blends, particularly in high renewable energy scenarios. For example, in Princeton, higher blends of 60–100 percent hydrogen or synthetic gas are used, but Williams employs lower (less than 10 percent) blends of hydrogen in all scenarios except for the high renewable energy scenario. Hydrogen is only deployed at large scale when the modeling scenario requires decarbonization of the whole economy.

All electricity studies evaluated show a future heavily reliant on renewable generation (i.e., VRE accounts for 43–91 percent of generated electricity by 2050 in all studies, 47–91 percent in net zero studies), requiring a rapid expansion of clean energy capacity. Decarbonization studies expand these technologies further than nondecarbonization studies. Wind and solar generation significantly increase across all studies unless specifically constrained by factors such as land use, high renewable energy prices, or low natural gas prices. When land use is constrained, offshore wind generation and residential PV solar generation increase faster. However, concentrated solar power (CSP) does not increase in any study.[5]

Variable generation exceeds firm generation by 2040 in many net-zero scenarios. The studies show no new additions of hydroelectric capacity, and there are generally only minor changes to nuclear capacity, except VCE, which shows significant increases in advanced nuclear technologies in some scenarios. In general, hydroelectric and nuclear generation slightly decrease from current levels to 2050. However, in scenarios where renewables growth is more constrained by cost or land availability, nuclear generation increases; in scenarios where renewables growth is less constrained, nuclear generation decreases. Geothermal and biomass are generally used minimally, except in scenarios that favor expanded biomass, such as Princeton's E-B+ scenario. Energy storage capacity increases later in most studies and corresponds with high renewable or constrained gas scenarios. Table 4 summarizes these comparisons across studies.

Table 4: Changes in US fuel capacity and generation across studies

<table>
<tr><th>Fuel</th><th>Decarbonization studies</th><th>Nondecarbonization studies</th></tr>
<tr><td>Coal</td><td>• No capacity additions
• Generation eliminated by 2030–2035</td><td>• No capacity additions
• Generation reduced in scenarios with high renewables, high natural gas, emissions constraints, high electrification</td></tr>
<tr><td>Natural Gas</td><td>• Some capacity increase, expansion of NGCT
• Generation decrease to nearly zero in most cases
• Increases accompanied by CCUS or offset
(VCE: natural gas with CCUS noted as clean)</td><td>• Some capacity increase, expansion of NGCC and NGCTGeneration eliminated by 2030–2035
(Seams: variation in NGCC, decrease in NGCT generation; EFS: more electrification means more NGCC generation)</td></tr>
<tr><td>Hydrogen</td><td>• Used in CCGT capacity and generation blends
• More used in full RE scenarios
(Princeton: burning high (60–100%) blends of H_2 or synthetic gas; Williams: burning lower, less than 10%, blends of H2 except in high RE scenario)</td><td>Not used</td></tr>
<tr><td>Wind</td><td colspan="2">• Major installations in all studies
• Major generation increase, regardless of strategy (electrification, transmission, decarbonization) unless specifically constrained
• Mainly onshore wind unless land constrained
• Variable generation exceeds firm around 2030 in many net-zero scenarios</td></tr>
</table>

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Fuel	Decarbonization studies	Nondecarbonization studies
Solar	• Major installations in all studies • Major generation increase, regardless of strategy (electrification, transmission, decarbonization) unless specifically constrained • Mainly utility, some residential solar, no CSP	
Nuclear	• Generally, limited changes to capacity and generation, unless renewables constrained (in which case nuclear increases) or renewables growth is unlimited (decreases) (VCE: increases are SMR/MSR)	
Hydro	• No capacity additions, generation generally unchanged	
Geothermal	• Minimally used	
Biomass	• Generally minimal (higher under the biomass specific scenario, especially in the Princeton E-B+ [high biomass] scenario)	
Battery	• Increases with high renewables, constrained gas • Used as a firm resource • More use toward 2050	

Note: Wind, solar, nuclear, hydro, biomass, and battery capacity trends are similar in both decarbonization studies and nondecarbonization studies and are therefore appended into a single column. CCGT = combined cycle gas turbine, CSP = concentrated solar power, MSR = molton salt reactor, NGCC = natural gas combined cycle, NGCT = natural gas combustion turbine, SMR = small modular reactor.

While the studies and scenarios are similar early on, they begin to diverge from each other as they approach 2050. In Chapter 2: Supply Side, the authors further compare the generation profiles for the studies' reference scenarios (i.e., BAU cases), the main expanded electrification scenarios, the increased renewable energy scenarios, and the lowest cost scenarios for each of the studies that share the data.

Transmission

Increasing transmission is shown to be a critical strategy in enabling electrification in three ways. First, expanded transmission enables the use of lower cost energy sources that are often located further away from load. Second, it can decrease instances of electricity constraints and curtailments. Third, increased transmission availability reduces the amount of generation capacity needed to reliably meet demand, reducing total system costs. For example, increased interconnection between different regions in the US can help mitigate the variability of wind and solar resources in any given location with the potential to reduce the amount of generation capacity required in all locations. Both decarbonization and nondecarbonization studies agree that there is large value in significantly increasing transmission capacity in the US.

The required scale of transmission expansion is significant. Princeton estimates that $2.7 trillion in investment will be needed between 2020 and 2050. VCE includes an increase in total resource cost of 70 percent due in part to a 1,200 percent increase in transmission capacity over that currently installed. These investments are meant to increase connections between the Eastern Interconnection and Western Interconnection, including increased deployment of high-voltage direct current (HVDC) lines across the country. One of the primary goals of the transmission improvements in the decarbonization studies is to enable additional use of renewable electricity generation by accessing natural resources in regions with less land constraints. Additional details regarding transmission in the decarbonization studies is provided in Appendix A: Supply Side Considerations.

Technical Constraints

There are a few important caveats when interpreting and comparing results across the varying studies. When interpreting the results of macro-energy systems (MES) models, the level of operational realism of the power sector implemented in the variety of models can have considerable impact on the outcomes of the electrification and net-zero scenarios. The literature regarding net-zero scenarios suggests that the existing centralized and dispatchable power system will transition to a much more distributed network with levels of system inertia much lower than today (Gaffney et al. 2018; Brinkerink et al. 2022). Traditionally, inertia of rotating machinery has been a critical feature of the power grid to help stabilize the energy supply (e.g., frequency) as demand varies throughout the day. Thus, a variety of modeling innovation issues should be considered by the reader so as to accurately interpret the results of the studies: power grid inertia, ancillary services, and the seasonal and daily variability of renewable energy.

Solar does not provide conventional system inertia to the power grid, although some pilot demonstrations have yielded results showing that VRE supplies could provide some synthetic inertia to help maintain the reliability of the grid (Denholm 2020; Johnson 2019). Wind turbines also only provide very low inertia. In the absence of sufficient inertia, the electricity system can become unstable. To address this concern, a net-zero power system that is deeply electrified should be designed to include new ancillary service requirements for power system reliability, flexibility, inertia provision, and intraday and intraseasonal energy storage within the market design and the policy provision. These are necessary for the technical operation of the grid with higher resource variability and lower system inertia. While rapidly decarbonizing generation capacity, the transmission system and ancillary services of the grid need to be assessed as an enabler to achieve the race to net zero while ensuring a secure and resilient power sector.

The seasonal and daily VRE must also be incorporated into capacity and generation planning to ensure an accurate picture of resource capabilities, including curtailment and impact on firm resource deployment (e.g., nuclear power plants). The models and scenario studies reviewed in this report employ a variety of methods to include weather and the weather's impact on renewable energy resource potential, as well as methods to capture the impact of declining levels of firm power on the grid. For example, if a model allows VRE to have merit order flexibility (i.e., change the priority order of generation technologies entering and exiting the market) but does not model the dampening effects of operational ramp rates of firm power and minimum stable levels on their ability to quickly react to VRE fluctuations due to weather, then the importance of system flexibility, energy storage, and transmission is underestimated. If the costs of system integration and curtailment are underestimated, the role and costs of firm and flexible dispatchable natural gas and nuclear capacity expansion can thus also be underestimated. As a result, the pace of feasible net-zero electrification may be overestimated.

Market Constraints

In addition to adequately capturing technical constraints, models must be able to capture market constraints. However, the models employed in the net-zero scenario studies do not explicitly consider producer (utilities and independent power producers) and consumer behavior or market structures. This disparity between economic policy simulation and technology optimization modeling used in these studies may lead model outcomes to deviate from reality. For example, electricity provision in the US is broadly divided between regions with competitive wholesale markets with disaggregated electricity generators and load serving entities (LSEs) and regions with vertically integrated electric utilities that both operate generation facilities and directly sell electricity to end users. Profit-maximizing firms and publicly owned cooperatives operating in these different regions face very different market rules and have quite different business models, which in turn affect how they operate existing facilities and their capacity addition and retirement decisions. This inconsistency can lead to very different development patterns even as regulators in these regions push toward common goals of net-zero electricity provision.

Similarly, market structures, from purely competitive wholesale markets to those dominated by very few firms, can also affect the development path for an energy system. For example, Andres-Cerezo and Fabra (2021) show that incentives to operate and invest in energy storage depends on the degree of competition in the wholesale markets, with less competitive markets leading to a less efficient use and investment in storage. Furthermore, actual electricity markets typically operate dispatch behavior based on marginal costs of the generation facilities. This means that the market rate for electricity is not the average cost of generators supplying the grid but rather the marginal cost for the last generator that is dispatched. This dynamic means that a future grid with heavy penetration of near-zero-marginal-cost VRE and large capacities of relatively high-marginal-cost storage systems would likely yield very different seasonal price swings compared to what is currently experienced in most markets (Junge et al. 2022). This type of market granularity adds an additional layer of modeling complexity that the current studies did not thoroughly investigate.

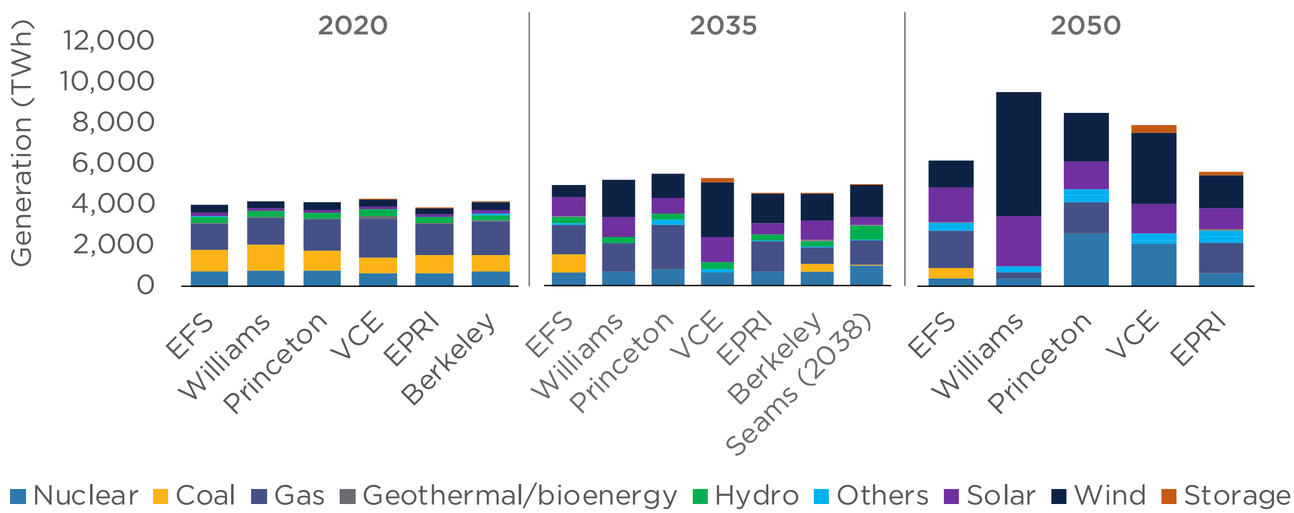
Additionally, MES models do not explicitly account for health impacts, instead approximating them on assumptions associated with policy and technology changes. Princeton estimates approximately 209,000 to 310,000 avoided deaths and $1.8–$2.7 trillion in net air quality benefits due to decarbonization, with the lowest savings in the delayed electrification (E-) scenario and the highest savings in the maximized renewable energy scenario (E+RE+). Berkeley 2035 also tracks avoided environmental costs, about 60 percent of which are due to reduced CO_2 emissions and the remainder to reduced exposure to PM2.5. Total estimated cost avoided is $1.2 trillion in health and environmental damages, including 85,000 premature deaths through 2050, compared to the reference scenario. Avoided deaths are primarily due to reduced exposure to PM2.5 by reductions in sulfur dioxide (SO_2) emissions from coal plants.

The ability of these MES models to represent outcomes under certain policies is also limited by the types of actors these models represent. Consider, for example, the proposed Clean Electricity Performance Plan (CEPP) under the Build Back Better Act, which sought to give awards or penalties to LSEs based on the amount of low-emitting electricity generation a given LSE procured. The MES models do not explicitly model the behavior of profit-maximizing LSEs and as such did not predict the type of CEPP-gaming actions that others voiced concerns about (Bushnell et al. 2021). These limitations should be kept in mind when one interprets the net-zero pathway operations and costs, as well as policy outcome predictions and benefits of these macro-energy models.

CHAPTER 2: SUPPLY SIDE

The total generation in 2035 for the least cost scenarios, shown in Figure 5, more closely resembles the total generation in the reference scenarios than the electrification and high renewable energy scenarios. The scenarios vary in expectations of generation in 2050. The Williams scenario shows increased generation over all other scenarios despite representing low demand, and EPRI's generation profile for net zero in 2050 is lower than EFS medium electrification scenario generation. Note that Berkeley 2035 and Seams carry their analyses through 2035 and 2038, respectively. Thus, their scenarios are only compared through 2035.

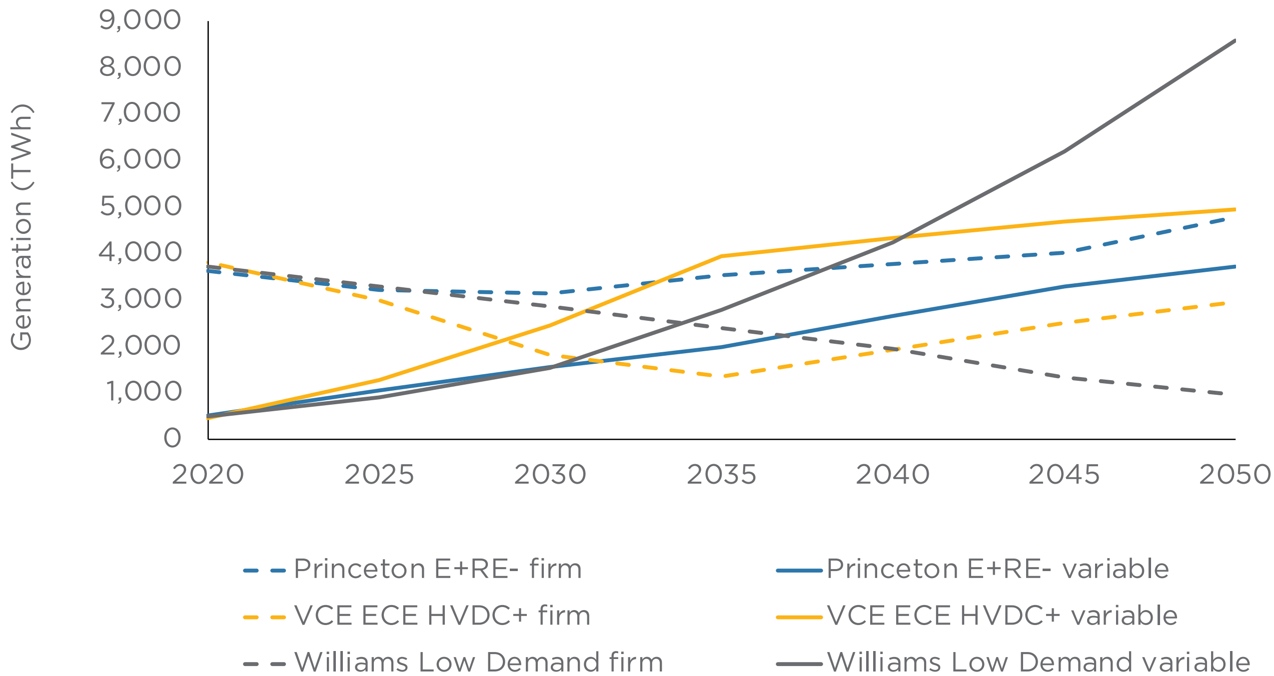
Figure 5: Generation estimated in lower-cost scenarios



Note: This figure is modified from Hausfather and Olson (2021) using the lower-cost scenarios rather than the central scenarios, different years (2035 instead of 2030 and 2040), and additional studies for comparison.

By 2035, coal generation is eliminated or nearly eliminated in all studies except EFS and Berkeley 2035. Natural gas use varies across the studies. Princeton relies on natural gas more than all other studies, and both Williams and Princeton rely on natural gas generation in 2035 more than in the electrification scenario. Williams significantly reduces natural gas use by 2050 as in the electrification scenario. Princeton and EPRI continue to use natural gas to 2050. VCE, on the other hand, nearly eliminates natural gas generation by 2035. Both Princeton and VCE expand nuclear generation after 2035. Variable generation exceeds firm generation prior to 2030 in VCE, prior to 2035 in Williams, and not at all in the other studies (Figure 6).

Figure 6: Firm and variable generation over time in lower-cost scenarios



Note: This figure is modified from Hausfather and Olson (2021) using the lower-cost scenarios rather than the central scenarios and additional studies for comparison. For scenario abbreviations, see Table 2.

The analyses indicate that net zero can be achieved at a lower cost with and without natural gas, as well as with and without increasing nuclear generation. However, all lower cost scenarios still eliminate coal by 2035 and expand renewable energy, though not as rapidly as in other scenarios.

In this analysis, the authors compare supply side electrification scenarios for US-centric net zero studies: Williams, Princeton, VCE, and EPRI. The 2020 starting point for each study varies by scenario but generally begins at 3,900–4,300 TWh of generation, 11–13 percent of which is variable renewable energy produced by wind and solar and 35–41 percent of which is nonfossil produced by nuclear, hydro, geothermal, and bioenergy, as well as wind and solar. By 2050, generation mixes vary across scenarios. Table 5 summarizes the total generation as well as the percent variable renewable and percent nonfossil generation. A deeper discussion of the trends and specific fuels used in each type of scenario as well as additional studies (EFS, Seams, and Berkeley 2035) is included in Appendix B: Comparing Supply Side Scenarios.

Table 5: Comparison of net-zero scenarios in Williams, Princeton, VCE, and EPRI from 2020 to 2050

Scenarios	2020			2050		
	Generation (TWh)	Fraction that is variable renewable	Fraction that is nonfossil	Generation (TWh)	Fraction that is variable renewable	Fraction that is nonfossil
Reference	3,900–4,300	11–12%	35–40%	5,000–8,000	30–62%	50–75%
Electrification	3,900–4,300	11–13%	37–41%	5,600–12,000	47–91%	73–100%
High renewables	3,900–4,300	11–13%	37–41%	6,600–16,000	76–98%	99–100%
Lowest cost	3,900–4,300	11–13%	37–40%	5,600–9,600	44–90%	73–100%

Reference Cases

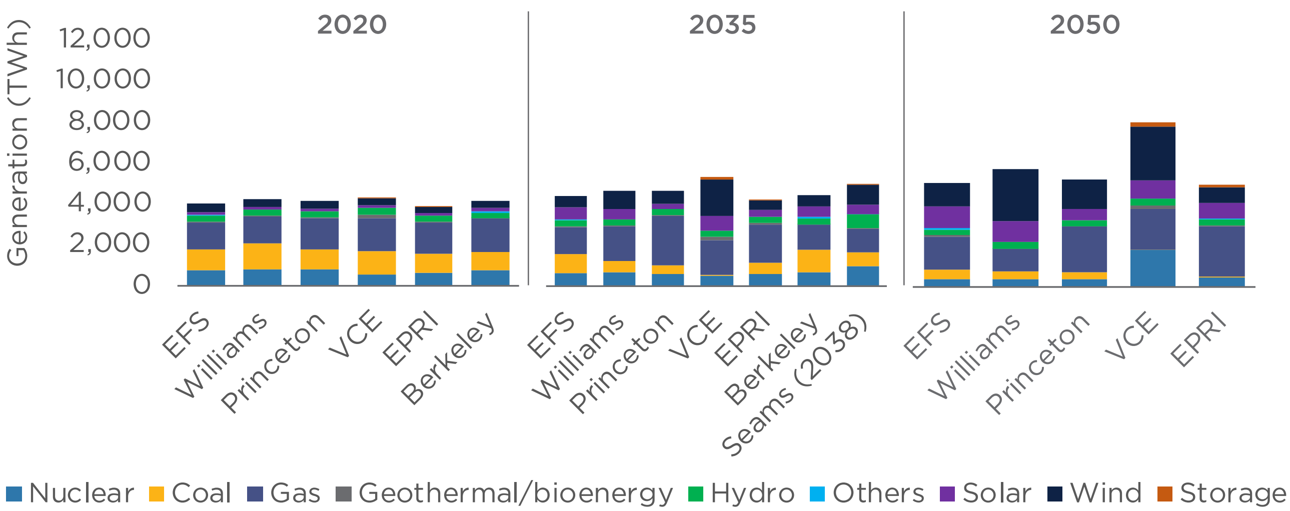
The reference or business-as-usual scenario for each study is not a net-zero scenario but serves as a reference point for each study for what generation might look like should no policy changes toward electrification and net zero be made. The reference scenarios compared here are Williams, Reference; Princeton, REF; VCE, EBAU; EPRI, Reference; EFS, Reference, Berkeley 2035, Baseline; and Seams, Base Case. The reference scenarios are critical for providing a basis of comparison for all other modeled scenarios. As such, particular emphasis is placed here on first describing the reference scenarios before considering alternatives.

Generation in the reference scenarios reaches 5,000–8,000 TWh in 2050 (which roughly represents a 30–100 percent increase in electricity consumption compared to 2020). Of the total consumption in the reference scenario, 30–62 percent is projected to be variable renewable energy in 2050 and 50–75 percent nonfossil resources. Variable generation exceeds firm generation only in one study. Use of natural gas continues to 2050 in most studies while coal generation decreases but continues to 2050 in two of the net-zero studies and is eliminated in the other two. Increases in renewable generation are delayed closer to 2050 in this scenario compared to others. In contrast, nuclear is projected to decline in most studies by 2050; however, VCE projects a significant increase in nuclear power over the same time frame for the reference case.

Breakdown of Reference and BAU Scenarios by Study

This section compares each of the studies' reference or business-as-usual scenarios. Depending on the year in which a study began, each of their 2020 total US generation values are around 4,000 TWh, as shown in Figure 7. The studies are generally consistent with each other at first due to limited feasible rates of change from current base year calibration—the generation consists mainly of natural gas, coal, and nuclear supplemented by renewable resources. VCE starts higher than other scenarios, and EPRI starts lower. In 2035, electricity generation increases slightly from 2020 to an average of 5,001 TWh. Coal generation decreases in most studies and is nearly eliminated in VCE. Berkeley 2035 is the only study to see an increase in coal generation, despite using the same modeling platform as EFS. Natural gas use increases in most scenarios but decreases in Berkeley 2035. Renewables increase in all scenarios with VCE seeing the largest increase by 2035.

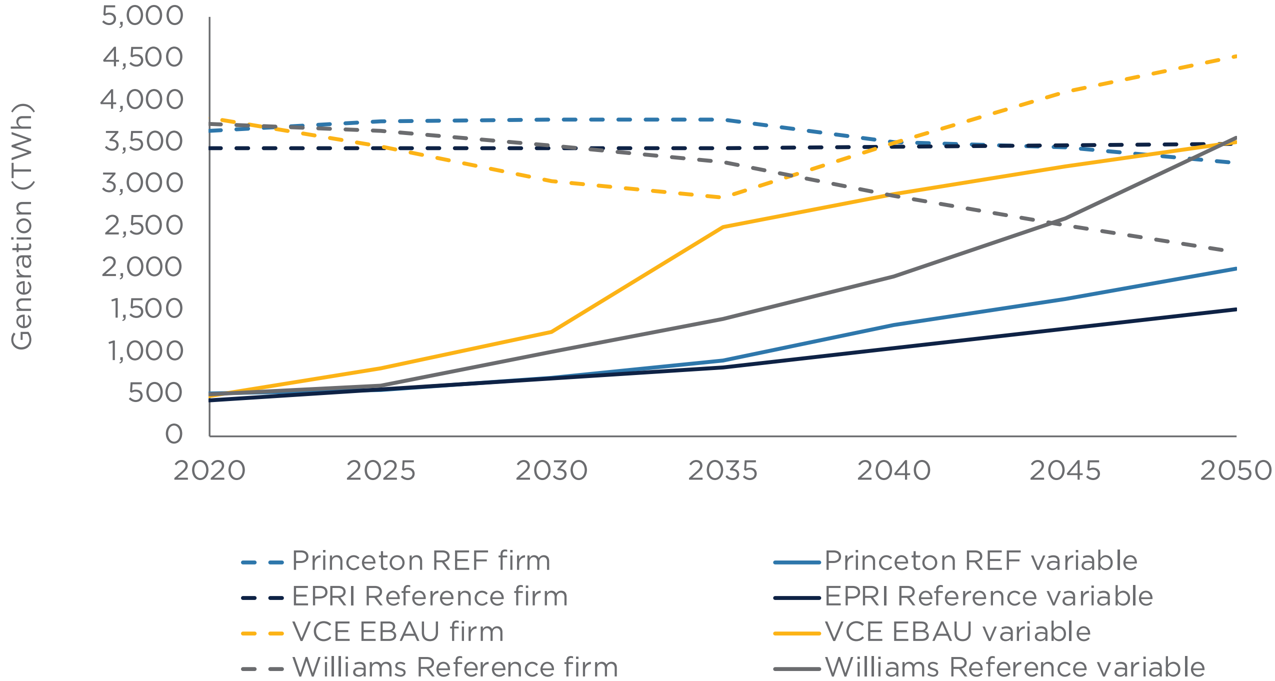
Figure 7: Generation estimated in reference/BAU scenarios



Note: This figure is modified from Hausfather and Olson (2021) using the reference scenarios rather than the central scenarios, different years (2035 instead of 2030 and 2040), and additional studies for comparison.

Through 2050, the trends generally continue. Coal decreases and is eliminated in the EPRI and VCE studies. However, natural gas use diverges and increases in some studies while decreasing in others but is not eliminated in any study. Solar and wind generation expand significantly between 2035 and 2050 in most studies and scenarios. Nuclear decreases in most studies but increases significantly in VCE. Additionally, VCE expects a much higher demand in 2050 in the BAU scenario compared to other studies. In most reference and business-as-usual scenarios, variable generation does not exceed firm generation, except for Williams, where variable generation exceeds firm generation prior to 2045 as natural gas decreases, nuclear decreases, and no firm generation is added to replace those changes, as shown in Figure 8.

Figure 8: Firm and variable generation over time in reference/BAU scenarios



Note: This figure is modified from Hausfather and Olson (2021) using the reference scenarios rather than the central scenarios and additional studies for comparison. For scenario abbreviations, see Table 2.

Electrification

The central electrification scenarios across studies lead to increased generation, mainly renewables, such that by 2050, generation reaches 5,600–12,000 TWh. Renewable generation increases rapidly, and 47–91 percent of 2050 generation is variable renewable generation. Nonfossil generation reaches 73–100 percent. Variable generation exceeds firm generation in three of the four net-zero studies. (The central electrification scenarios compared in this report are EFS, High; Williams, Central case; Princeton, E+; VCE, ECE; and EPRI, Net zero by 2050.)

High Renewables

The high renewable scenarios extend this trend further with high electrification and increased use of renewable energy. By 2050, the renewable scenarios reach 6,600–16,000 TWh of generation, 76–98 percent of which is variable renewable electricity and 99–100 percent of which is nonfossil. With a rapid transition to renewable energy, variable generation exceeds firm generation by 2030 in all scenarios. It is important to note this high variable renewable penetration is reached while also considering grid reliability constraints. Small decreases in firm generation are matched with much larger increases in renewable generation. (The high renewables scenarios compared here are Williams, 100% renewable primary energy; Princeton, E+RE+; VCE, ECE HVDC-; and EPRI, 100% renewable by 2050.)

Lowest Cost

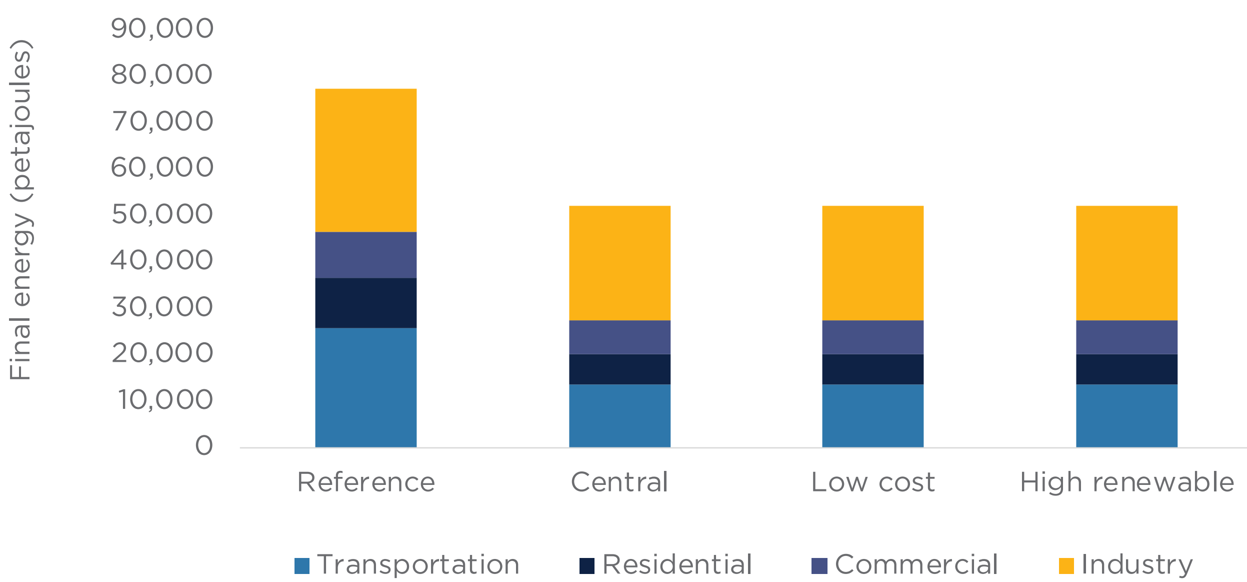
In contrast to the previous scenarios, there is large variation in how to achieve low-cost electrification on a path to net zero, including with or without natural gas or nuclear energy. Solar and wind increase but not as rapidly as the high electrification or high renewables scenarios. The lower rate of increase in renewables is due to the additional near-term costs of expanding transmission and expanding capacity to meet reliability needs. For the most part, the studies investigated herein support the claim that meeting the energy demands of the coldest and hottest days of the year with 100 percent VRE appears to be more expensive than a diversified portfolio. In Williams, the lowest cost scenario is the lowest demand scenario. Lowest cost scenario generation reaches 5,600–9,600 TWh, made up of 44–90 percent variable renewable generation and 73–100 percent nonfossil resources. Variable generation exceeds firm in two of the four studies, suggesting that high levels of VRE penetration will play a critical role in achieving the lowest cost outcomes on the path to net zero. It is worth noting that coal is eliminated from the energy mix by 2035 in nearly all of the low-cost scenarios. (The low-cost scenarios compared here are Williams, Low demand; Princeton, E+RE-; and VCE, ECE HVDC+.)

CHAPTER 3: DEMAND SIDE

The following conclusions regarding changes to electricity demand are all drawn from surveying the aforementioned studies that also included strategies to electrify the economy: Princeton, Williams, and EFS. Adjusting energy demand through increased electrification and energy efficiency is key to decarbonization. The considered studies mainly expand electrification across the residential, commercial, and transportation sectors, while the industrial sector was assumed harder to electrify. Flexible demands that allow for demand shifting throughout the day or demand response to reduce demand during periods of peak load play a key role in ensuring reliability of a highly electrified economy paired with a decarbonized grid.

The transition to more efficient technologies also reduces the total final energy needed. While energy efficiency and conservation alone cannot achieve net zero, they should be paired with electrification and other decarbonization strategies to minimize the need for additional infrastructure while also keeping the system as affordable as possible. Similarly, while electrification alone has efficiency benefits, it will not achieve net zero by itself; it must be paired with a net-zero electricity sector (e.g., electric vehicles can improve fuel efficiency, but to achieve net zero the vehicles must receive their electricity from zero-carbon sources). Projections of energy demand by sector in 2050, based on different scenarios in the Princeton study, are provided in Figure 9. Additional detailed discussion regarding demand side dynamics for electrification is provided in Appendix C.

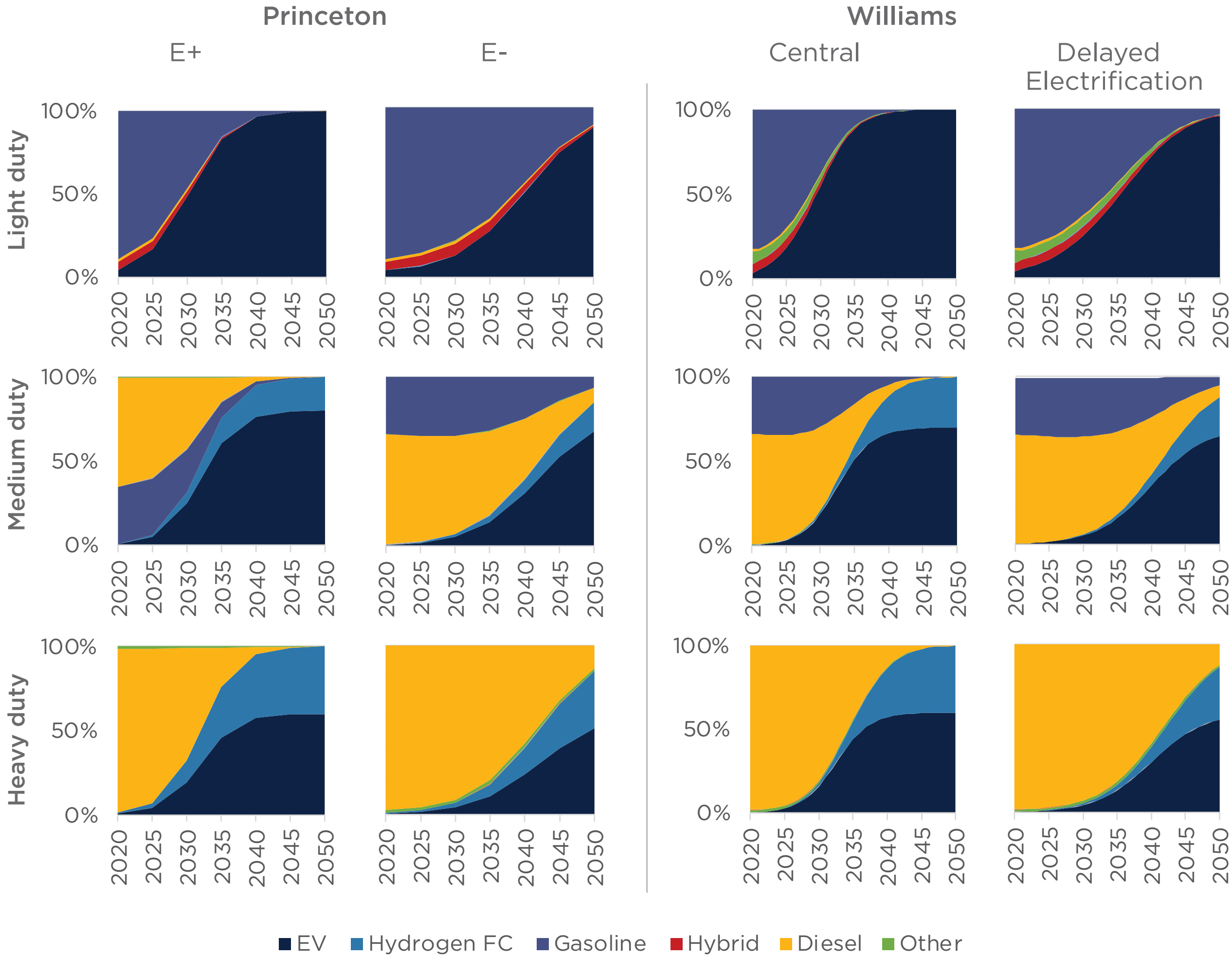
Figure 9: Final energy demand by sector in 2050, estimated by Princeton



Transportation Demand

The studies show that decarbonizing transportation involves relying heavily on EVs across all vehicle types, as well as utilizing some hydrogen vehicles. However, a minority of vehicles still consume diesel or gasoline by 2050, as shown in Figure 10.

Figure 10: Transportation sales in Princeton and Williams



Note: The E+ and Central scenarios are the high electrification scenarios for Princeton and Williams. The E- and Delayed Electrification scenarios both delay the adoption of electrification technologies. "Diesel" includes Reference TDI Light-Duty, Reference Diesel Heavy-Duty Vehicle, and Reference Medium - Duty Diesel Vehicle; "EV" includes Electric Light-Duty - 200 mile range, Electric Light-Duty - Long Range, Electric Heavy Duty Vehicle, and Battery Electric Medium-Duty Vehicle; "Gasoline" includes Reference Gasoline Light-Duty, Reference Gasoline Heavy-Duty Vehicle, and Reference Medium-Duty Gasoline Vehicle; Hybrid includes Diesel - Electric Hybrid Light-Duty, Electric - Gasoline Hybrid Light-Duty, PHEV - 25 mile range - Light Duty, PHEV - 50 mile range - Light Duty, Diesel Hybrid Heavy-Duty Vehicle, Hybrid Diesel Medium-Duty Vehicle, and Hybrid Gasoline Medium-Duty Vehicle; "Hydrogen FC" includes Hydrogen Fuel-Cell Light-Duty, Hydrogen FCV Heavy-Duty Vehicle, and Hydrogen Fuel Cell Medium-Duty Vehicle; and "Other" includes CNG Light-Duty, Propane ICE Light-Duty, Reference Flex Fuel Light-Duty, LNG Heavy-Duty Vehicle, Reference Propane Heavy-Duty Vehicle, Reference LPG Medium-Duty Vehicle, and Reference Medium-Duty CNG Vehicle.

Aggressive electrification of transportation requires a rapid expansion of electric vehicle sales across all vehicle types in the 2020s, as well as the need to expand charging infrastructure and electrify mass transit. In high electrification scenarios, battery EVs reach 100 percent of light-duty vehicle sales, and a combination of hydrogen and battery EVs reach 100 percent of medium- and heavy-duty trucks between 2040 and 2050. With increased sales, these vehicles reach 90–97 percent of total stock in highly electrified scenarios. In delayed electrification scenarios, these vehicles reach 85–90 percent of sales by 2050. While the majority of the envisioned EV sales are expected to be battery powered vehicles, some manufacturers continue to place focus on hydrogen fuel cell solutions. Additional breakthrough in fuel cell or hydrogen storage technology and/or greater adoption of hydrogen in other parts of the economy might lead to additional adoption of hydrogen, particularly for applications with rapid refueling needs.

Residential and Commercial Demand

Electrifying residential and commercial buildings is an important component for decarbonization in the studies. Ensuring technologies shift to the most efficient alternatives available helps reduce the timing and magnitude of peak demand, which reduces the total system costs. Electrifying residential and commercial demand includes relying mainly on electric appliances for cooking and heat pumps for climate control and water heating. Aggressive electrification requires rapid expansion in heat pump sales for space and water heating to over 50 percent of the market share in the 2020s in Williams and 100 percent of sales between 2030 and 2040 in both Princeton and Williams, leading to 95–100 percent of total stock by 2050. In delayed electrification scenarios, sales only approach 95–100 percent by 2050. Electric residential cooking follows a similar trajectory. However, in the commercial sector, some gas use continues through 2050 for cooking.

Ensuring the public is aware of the broader health and environmental damages of current energy infrastructure could encourage progress in electrifying residential and commercial buildings. An increasing body of evidence shows the health risk of indoor pollution from use of natural gas for cooking in buildings (Nicole 2014, Lee 2002, Hollowell 1980, Zhao 2021, Volkmer 1995) and of local outdoor air pollution from burning fossil fuels (Perera 2017, Kotcher et al. 2019, Perera et al. 2019, Kampa & Castanas 2008). Awareness of this topic could help accelerate the adoption of electric cooking solutions in the residential sector, for example.

Industrial Demand

The industrial sector is the slowest to electrify in the studies, but changes from other sectors ripple through. For example, the electrification of transportation reduces the demand for petroleum products, a major output of the industrial sector. Princeton estimates final energy demand for industry can be reduced by 5–6 exajoules (EJ) (1,400–2,000 TWh), a decrease of 17–20 percent from the Reference to the E+ and E- scenarios in 2050. While some industrial processes, such as iron and steel making can electrify, other hard-to-electrify industrial demands include processes that require high temperature heat (e.g., conventionally met by burning natural gas) and chemical feedstocks. To decarbonize these demands, the studies model that the industrial sector will transition to synthetic fuels (e.g., fuels derived from low-carbon hydrogen), deploy carbon capture, or both when electrification is not an option due to technical or economic constraints.

CHAPTER 4: RECOMMENDATIONS

Electrification

The pathway to net zero requires multiple economy-wide shifts to happen simultaneously, including a broad expansion of electricity production and consumption. The following recommendations include those made by the studies that dig into the transformative changes and their effects on the economy.[6]

Key recommendations across studies include (1) decarbonizing electricity, (2) electrifying end uses, (3) lowering energy demand including by reducing waste, and (4) increasing transmission, distribution, and energy storage infrastructure.

All the studies made clear that the electric sector needs to decarbonize. Coal requires retirement by the early 2030s, and wind and solar capacity must rapidly deploy early to become the largest source of electricity by about 2035. Decarbonizing electricity is a key component to decarbonizing other sectors of the economy. More transmission and distribution are needed to support lower costs as renewable energy expands and electricity loads grow. Increasing energy storage capacity adds firm supply that can be flexibly powered by renewable electricity at off-peak times and deployed during times of peak power demand—though it is not deployed in all study scenarios. In addition, some studies highlighted the opportunity to leverage the expansion of VRE to power useful energy services during off-peak periods, including the production of hydrogen.

When considering the logistical challenges to expand electrification, it is useful to consider the number of actors involved with each decision on the supply side and demand side. For example, there is less broad representation and involvement from the public with building, financing, and regulating utility scale electricity production. On the other hand, deployment of heat pumps, electric vehicles, and electric stoves ultimately requires uptake by individual consumers (i.e., millions of decision makers) and prosumers who have different decision criteria associated with cultural acceptance, familiarity, and financial costs. Deployment will also require an associated growing workforce to install and maintain the products. As a result, there may be an easier logistical path toward achieving the first key recommendation of decarbonizing electricity generation compared to achieving the second key recommendation of electrifying end uses.

Identifying how to effectively engage individuals is a critical step to achieving this second key recommendation of electrifying end uses (Revez et al. 2022, Mullaly et al. 2022). Consumer and installer incentives may be needed to increase uptake and ensure people at all income levels are able to afford the energy efficient technologies and retrofits needed to adjust from gas to electric heating, for example. These solutions and policies will need to be deployed at economy scale during the 2020s to meet most of the timelines described in the studies examined in this report.

Some of the studies also discussed opportunities to enable electrification and reduce the carbon intensity of cities through strategies intended to reduce energy demand, including investing in mass transit and increasing the ability for residents to walk or bike to their destination. While these solutions seem logical to meet the third key recommendation to lower energy demand, the MES models reviewed do not explicitly include metrics such as walkability in their analytical framework, instead modeling general assumptions of energy conservation. As a result, one must rely on other literature to substantiate the claims about the importance of improving the design of cities to expand electrification, reduce energy consumption, and minimize carbon emissions (Gaur et al. 2022, Grubler et al. 2018).

Expanded production and demand of electricity will also require expansion of the transmission and distribution network. Some of the studies estimated that over $1 trillion will be needed to deploy sufficient transmission infrastructure to achieve the required levels of electrification on a pathway to net zero. The expanded transmission system would enable greater use of solar and wind assets located in regions with good natural resources. Furthermore, a strengthened transmission and distribution system would reduce the amount of curtailment and congestion while also increasing the resilience of the energy infrastructure in the United States (Busby et al. 2021). Despite the apparent benefits of an improved transmission system, it is unclear whether the studies fully capture the project risks associated with transmission expansion, including environmental, legal, and financial challenges that can manifest with large scale infrastructure projects.

While many of the electrification strategies and technologies are readily available to be deployed, more innovations and research will be needed to develop new technologies at scale and reach the deployment pace required within the scenarios. Many of the studies, including VCE and Princeton, emphasize the importance of continuing to invest in maturing technologies, especially clean firm generation like advanced nuclear reactors (e.g., SMR and MSR) and advanced geothermal, in addition to carbon capture for power and industry, hydrogen production and combustion, inexpensive long-duration storage, synthesis of fuels, novel electricity-centric manufacturing methods for steel, high-yield bioenergy, and direct air capture. Active stakeholder involvement in electricity market design will also be required to adopt and integrate novel technologies as quickly as possible. A future grid that is heavily reliant upon VRE, energy storage, and other novel systems may require unique approaches to ensure that the market incentivizes sufficient assets to deliver the affordable and reliable electric grid that communities will expect.

Beyond Electrification

Electrification has significant potential to help decarbonize the economy. However, electrification alone is insufficient to achieve a net-zero future. More research is needed for the currently hard-to-eliminate emissions in aviation, long-distance transport, shipping, petrochemicals, and structural materials, as well as improved methods for reliable, cost-effective systems integration (Elsevier Analytical Services 2021). To address these applications that are hard to electrify due to technical or economic constraints, the net-zero studies recommend scaling up carbon management strategies through CCUS, DAC, and enhancing land sinks. A carbon transportation network would be required to move captured carbon for either useful purposes or permanent sequestration. Reducing demand for products such as raw steel can also help reduce the need for carbon capture. Additional discussion regarding decarbonization issues beyond electrification, including carbon management strategies, is provided in Appendix D.

Enhanced land sinks (e.g., forests and agricultural soils) are very likely needed to further offset carbon emissions.[7] Additionally, non-CO_2 emissions, particularly those that cannot be abated through electrification, must also be managed in order to reach net zero greenhouse gas (GHG). This recommendation includes refrigerant (a potent greenhouse gas) management and use of alternatives with low global warming potential. It also includes reducing methane (CH4) leaks and flares, for example, in current upstream oil and gas operations, at wastewater facilities, at landfills, and in industry.

Science, technology, engineering, and mathematical research needs to be better integrated with other fields such as social sciences, humanities, and policy to understand the broader implications of infrastructure design (Elsevier Analytical Services 2021). Employment opportunities will change as these sectors transform. Workers must be trained for the jobs required, and attention will need to be paid to communities that will experience high job losses.

Finally, transformative changes require public consent for land use changes, for uptake of electrifying technologies, and for any policy shifts required to reach net zero, such as redirecting fossil fuel subsidies to low-carbon technologies or streamlining clean infrastructure permitting. As discussed in Chapter 3, ensuring the public is aware of the broader health and environmental damages of current energy infrastructure could encourage progress in this area. Greater awareness of the health and environmental damages of existing energy infrastructure could help accelerate the adoption of electric cooking solutions, for example. Additionally, increasing the public's awareness of life cycle emissions impacts of different products (e.g., variations in manufacturing practices that result in greater emissions) will be critical to educating a population to achieve a net-zero system.

The studies discussed in this report show that there are paths to achieve net-zero carbon emissions. However, to reach this goal, significant, transformative change will be needed in every sector of the economy.

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APPENDIX A: SUPPLY SIDE CONSIDERATIONS

A.1 Transmission

Increased transmission is needed to match increasing generation, ensuring new resources can reach increased demands due to electrification. Seams, which focused on the grid and cost impacts of transmission, found that it will be cost effective to increase connections between the Eastern Interconnection and Western Interconnection in the US. A macrogrid of new generation HVDC lines connecting the nation, including running through Texas, is also an option but was found to not be the most cost-effective strategy evaluated. Instead, expanded, optimized B2B and HVDC connections between the Eastern Interconnection and Western Interconnection would be the most cost-effective strategy for the country through the end of the study (2038). The Seams analysis did not consider the impacts of higher electricity demand via expanded electrification or the increased renewable energy sources considered in the other decarbonization studies.

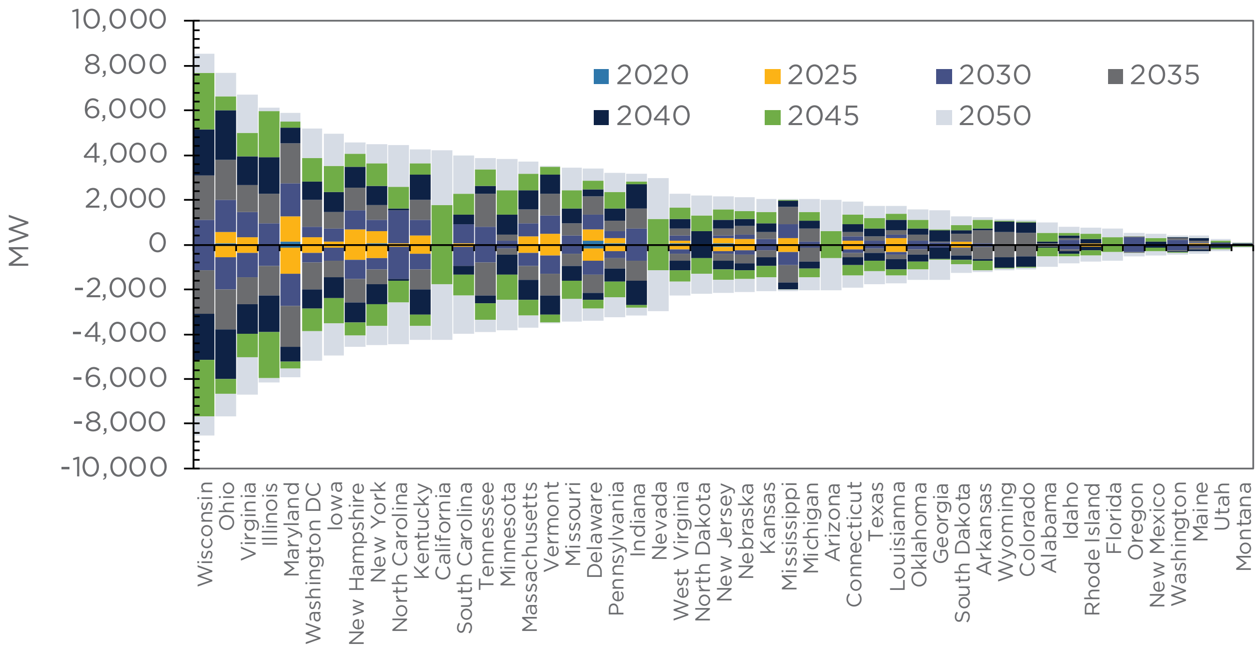
The studies show larger increases of transmission are needed to accommodate increases in renewables. However, both renewables and transmission are constrained by land availability. To account for future electrification and changes in electric supply, the decarbonization studies estimate large increases in HVDC connections across the country. Princeton estimates in the E+ scenario that a 60 percent increase in transmission is needed by 2030, and transmission will need to more than triple by 2050 to further connect more wind and solar energy to the grid. VCE models five HVDC macrogrid scenarios. The HVDC scenarios estimate an increase of 4.9 to 12.1 times the MW of installed transmission in use in 2018 by 2050, compared with a 60–70 percent increase for the BAU and aggressive electrification (ECE) scenarios. Berkeley 2035 also estimates that a large investment is needed for transmission, particularly within the Eastern Interconnection. While not a decarbonization study, Electrification Futures Study also estimates that more long-distance transmission will be needed with higher electrification, particularly in scenarios with less natural gas and more renewables.

While increasing transmission is necessary to enable decarbonization, it is not sufficient to achieve net-zero alone. Increasing transmission must occur alongside other strategies such as electrification of end uses and decarbonization of electricity generation to be fully effective.

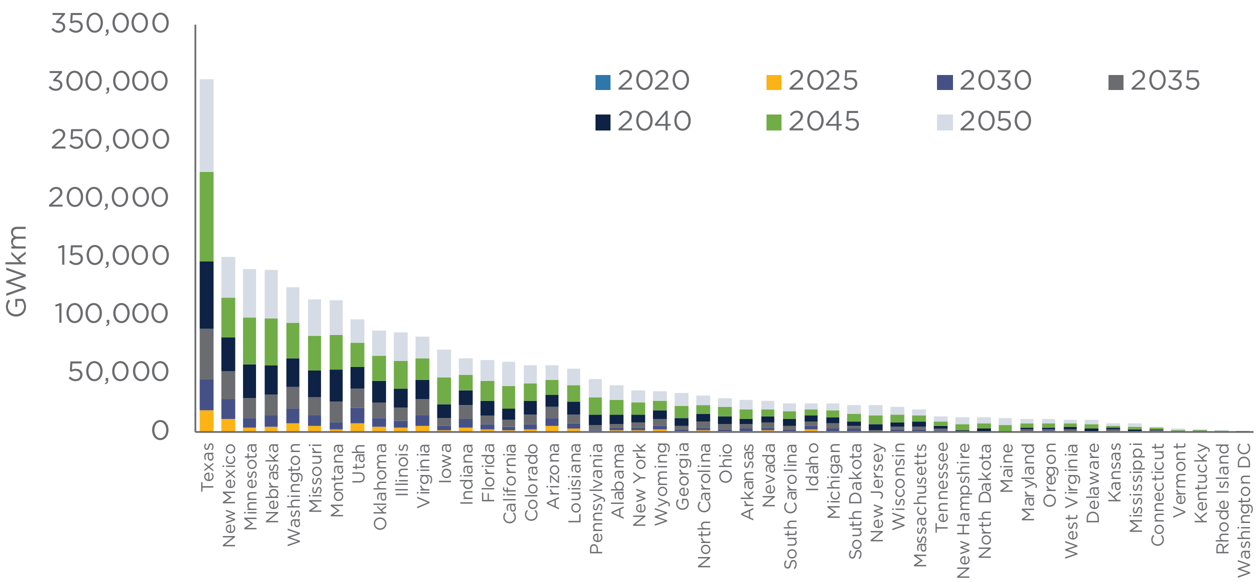
While studies agree large amounts of transmission are needed, the results disagree on location.[8] In three studies, the largest increases are in the Mid-Atlantic/Great Lakes and Texas. Berkeley 2035 expects transmission increases in Texas and large increases in the Eastern Interconnect. Williams estimates more transmission will be out of Louisiana and the Ozarks and the Mid-Atlantic/Great Lakes to other parts of the country with very little to or from Texas. VCE (ECE scenario) also estimates large transmission increases are needed for import and export in Mid-Atlantic and Great Lakes states. Princeton (E+ scenario) expects the largest increases in transmission needs in Texas, California, New Jersey, and New York. Figure 11 shows the transmission increases estimated in the VCE ECE scenario and Princeton E+ scenario. The top 10 states from each list are highlighted in the other one, e.g., because Texas is in the top 10 for Princeton (right side of Figure 11), it is highlighted in VCE's results (left side of Figure 11)

Figure 11: Comparison of transmission increases by state in VCE (ECE scenario) and Princeton (E+ scenario) transmission capacity

a. Added transmission capacity, exports and imports



b. Added HV transmission capacity for wind and solar



Note: Figure 11a compares additional transmission capacity to transmission capacity in 2018. Figure 11b compares additional wind and solar base spur intra-state transmission capacity to transmission capacity in 2020.

A.2 Energy System Reliability

Reliability is an important component of a viable electricity system. Electricity supply and demand must always be matched. Thus, increased demand that is met with increasing shares of variable energy supply presents challenges for grid operators. One way to enable a larger penetration of VRE sources while ensuring the reliability of the grid is to make the demand side more flexible in how it operates. This concept is often described as demand response, which describes a strategy in which a consumer of electricity can ramp up or down based on the needs of the grid. To maintain reliability, the considered studies rely heavily on more flexible loads such as direct air capture (DAC), electrolysis, and electric boilers that can respond to the variability of wind and solar. It is assumed that some portion of the load is able to strategically shift electricity use to balance variation in available renewable energy supply. For example, in Williams 100 percent RE and Princeton E+RE+ (increased renewable energy) scenarios, there is higher electricity demand for hydrogen electrolysis, but that demand is expected to be able to ramp up and down to not only produce the needed hydrogen to help decarbonize the economy but to also help mitigate the impacts of a changing electricity supply.

All study scenarios include generation resources that are less variable in nature compared with wind and solar. These energy assets are described as firm generation, including nuclear, natural gas with carbon capture, and/or natural gas plants burning high hydrogen blends. Some scenarios also increase battery storage or deploy advanced nuclear technologies. In the event that a given scenario has higher deployment rates of less firm generation sources, the studies generally compensate for intermittency by installing higher capacities of variable resources and associated high-voltage transmission.

Additionally, the models used by Princeton and Williams (RIO and EnergyPATHWAYS) and VCE's WIS:dom model account for reliability in scheduling power dispatch throughout the year. Williams notes that fuel and energy storage are tracked in the reliability analysis built into RIO. ReEDS, the capacity planning model used by Electrification Futures Study and Berkeley 2035, includes grid services meant to support reliable grid operations but does not reflect all aspects of grid reliability. Neither EFS nor Berkeley 2035 includes a full reliability assessment. However, the Berkeley 2035 authors did conduct scenario and sensitivity analyses to ensure that demand is met in all periods.

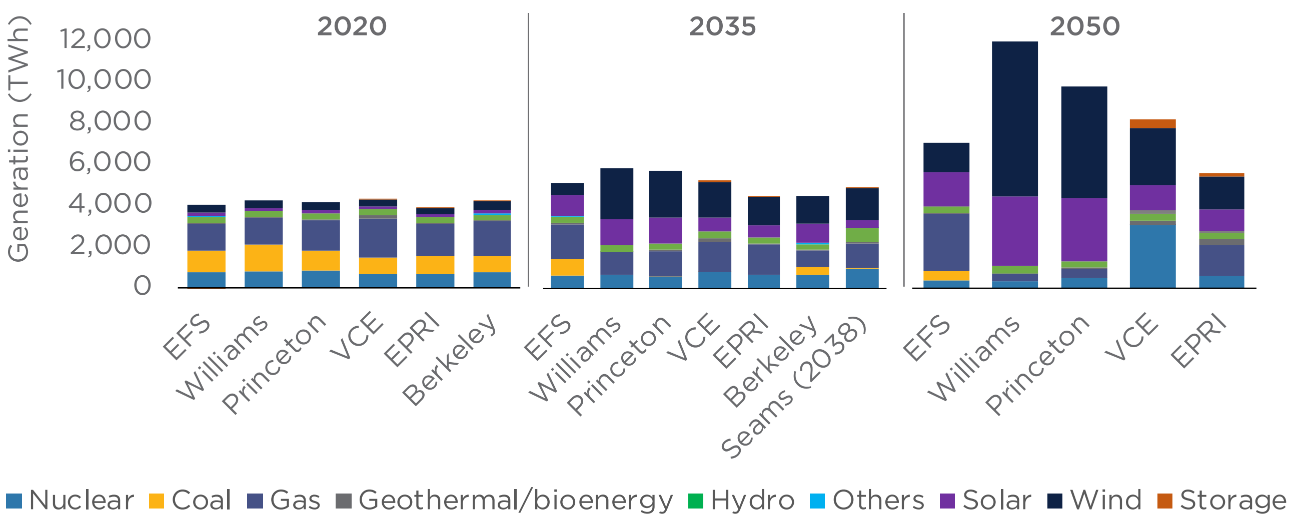
Grid reliability is also affected by weather and climate (Yalew et al. 2020). For example, freezing temperatures can inhibit generation at power plants as it did throughout the southern US in February 2021, and water supply constraints can limit hydroelectric and thermoelectric power supplies (Glazer et al. 2021, Busby et al. 2021). WIS:dom and ReEDS both include weather or climate constraints in modeling capacity available for generation.

APPENDIX B: COMPARING SUPPLY SIDE SCENARIOS

B.1 Central Electrification Scenarios

The central electrification scenarios compared in this report include the following: Electrification Futures Study, High electrification; Williams, Central; Princeton, E+; VCE, ECE; and EPRI, Net zero by 2050. Berkeley 2035 only has one scenario aside from the reference. That scenario is compared for 2035 in this section as well as the next two sections. The Seams scenario for increased HVDC and B2B connections (D2b), coupled with high variable generation, is compared here as well as in the next two sections. A comparison of generation in the electrification scenarios for the studies is shown in Figure 12.

Figure 12: Generation estimated in electrification scenarios



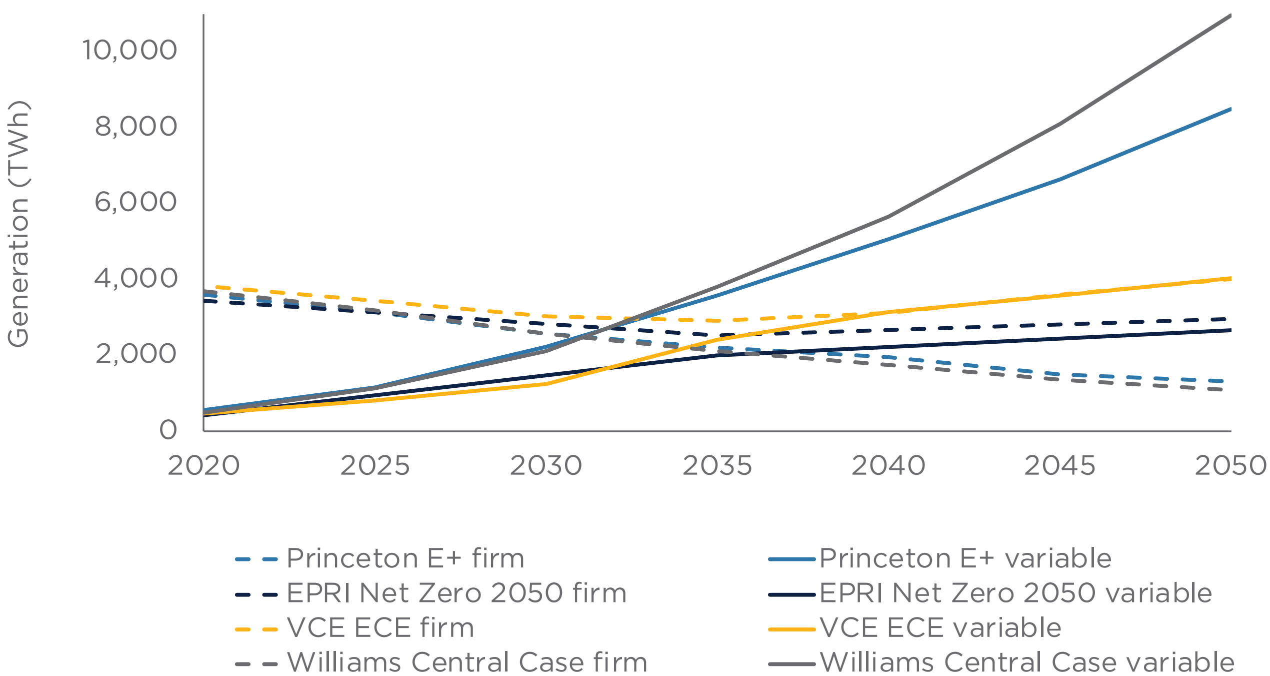
Note: This figure is modified from Hausfather and Olson (2021) using different years (2035 instead of 2030 and 2040) and additional studies for comparison.

Total generation in 2035 for the electrification scenarios (which are also net-zero scenarios, except for EFS and Seams) varies across studies more so than in the reference scenarios. Coal generation is eliminated or nearly eliminated in all net-zero studies, as well as in the Seams scenario by 2035. Coal is still used in Berkeley 2035 and Electrification Futures Study. Similarly, natural gas use decreases by 2035 and is eliminated or significantly reduced by 2050 in most net-zero studies but increases in Electrification Futures Study and EPRI's analysis. It is evident that the studies agree that when the goal is net zero, coal generation must be eliminated, and natural gas generation must decrease. However, when the goal is simply expanding clean energy as in Berkeley 2035, or electrification as in Electrification

Futures Study, coal is not necessarily eliminated, and natural gas use generally expands.

All studies show a large increase in wind and solar generation, and some also show expanded geothermal, bioenergy, and energy storage. Additionally, VCE shows significant expansion of nuclear generation. Deploying more renewable energy generation coincides with an increase in total generation in 2035 and much more so in 2050, as shown in Williams and Princeton. Decreases in firm coal and natural gas generation that is not replaced by nuclear or energy storage coincide with very large increases in renewable energy. Rather than significantly curtail renewable energy during periods of low demand, some studies employ increased levels of flexible loads, which also, in turn, increase total generation demands. In Williams and Princeton, variable generation exceeds firm generation in the early 2030s, and VCE does so by 2040, as shown in Figure 13. Variable generation does not exceed firm generation in Electrification Futures Study's or EPRI's analyses.

Figure 13: Firm and variable generation over time in electrification scenarios

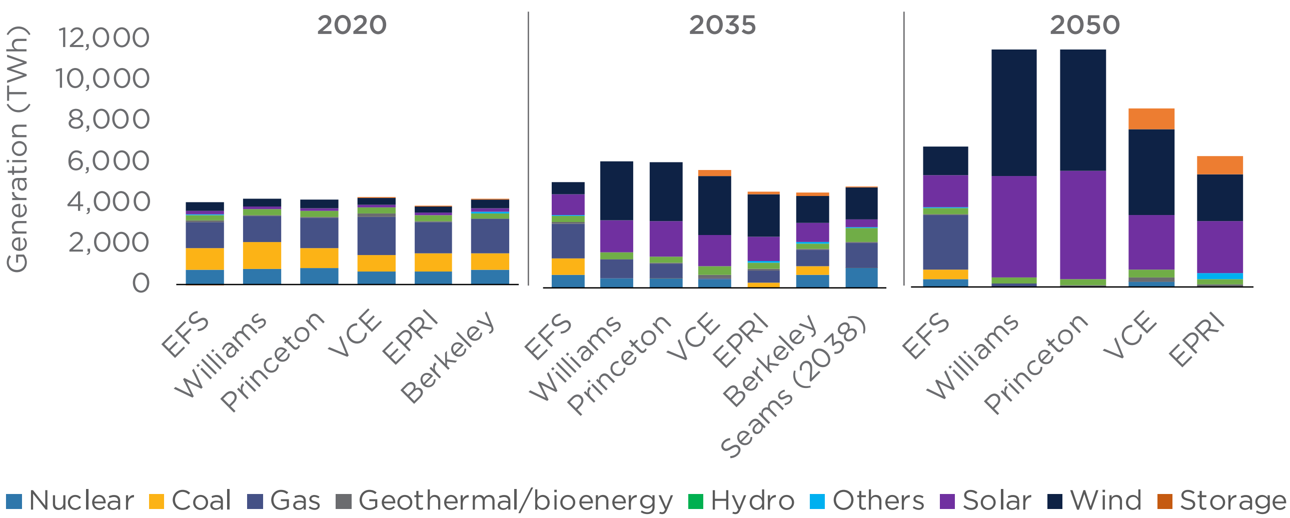


Note: This figure is modified from Hausfather and Olson (2021) using additional studies for comparison. For scenario abbreviations, see Table 2.

B.2 High Renewables Scenarios

The high renewables scenarios compared here are Williams, 100 percent renewable energy; Princeton, E+RE+; VCE, ECE HVDC-; and EPRI, 100 percent renewable by 2050). The EFS does not have a high renewable scenario; instead, the High electrification case is shown here for reference. The Berkeley 2035 standard scenario and the Seams D2b VG are used in this comparison as in the previous one. The studies are compared in Figure 14.

Figure 14: Generation estimated in high renewable energy scenarios



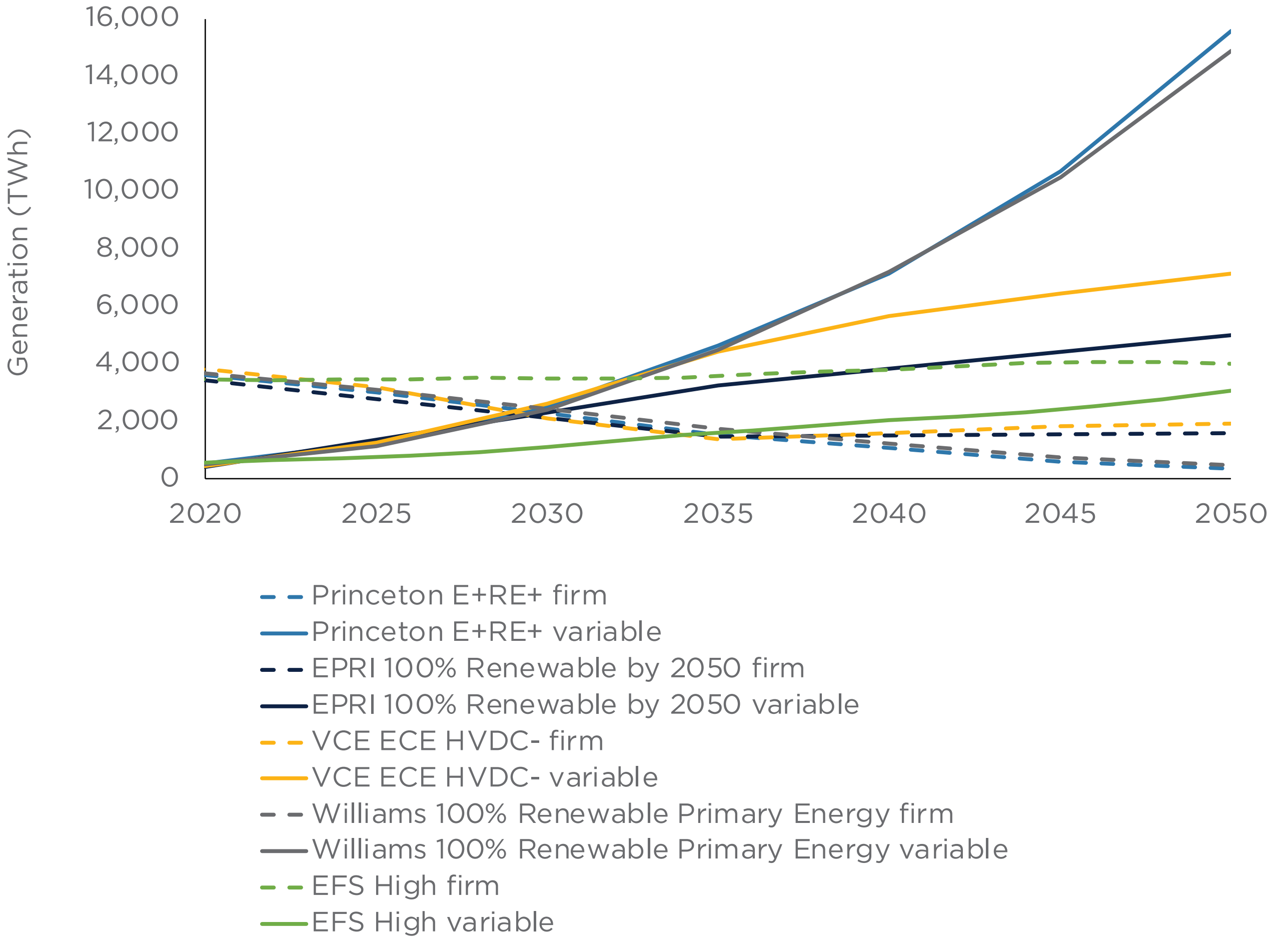
Note: This figure is modified from Hausfather and Olson (2021) using the high renewable scenarios rather than the central scenarios, different years (2035 instead of 2030 and 2040), and additional studies for comparison.

Total generation in 2035 again varies across studies as in the electrification scenarios. Coal generation is eliminated or nearly eliminated by 2035 in most net-zero studies. However, unlike in the electrification scenarios, coal is still used in the EPRI study. All studies decrease nuclear generation, and three of the four net-zero studies eliminate nuclear completely by 2050, as they have a 100 percent renewable energy goal. However, EPRI eliminates nuclear by 2035 and, in doing so, compensates by extending the life of coal generation beyond what occurs in the net-zero scenario. Also, as in the electrification scenarios, natural gas use decreases by 2035 and is eliminated or significantly reduced by 2050 in all net-zero studies. However, the reduction of natural gas generation in the high renewable energy scenarios is deeper than in the electrification scenarios in the previous section. When net-zero goals are accompanied by renewable energy expansion targets, reduction of coal and natural gas generation generally occurs more rapidly.

All studies show increased expansion of wind and solar generation in their high renewables scenarios over the electrification scenarios, with variable generation exceeding firm generation prior to 2030 in them all. Some studies also show expanded use of geothermal and bioenergy feedstocks for electricity generation. Geothermal presents one of the more unique sources of renewable power due to its firm, dispatchable nature. Additional advancements in geothermal technology could help lower its projected cost and allow it to be installed within a time frame to make it a larger contributor to the decarbonization effort prior to

2050. Energy storage is a bigger strategy in 2050 for VCE's and EPRI's analyses than it is in the electrification scenarios; both studies use energy storage to replace larger losses of firm generation. Decreases in firm generation are again matched with large increases in renewable generation as in the electrification scenarios. Deploying more renewable energy generation again coincides with an increase in total generation in 2035 and much more so in 2050, as shown in Williams and Princeton (see Figure 15). It is worth noting that none of the high renewable scenarios that implement least cost optimization achieve 100 percent renewable adoption across the electricity generation infrastructure.

Figure 15: Firm and variable generation over time in high renewable energy scenarios

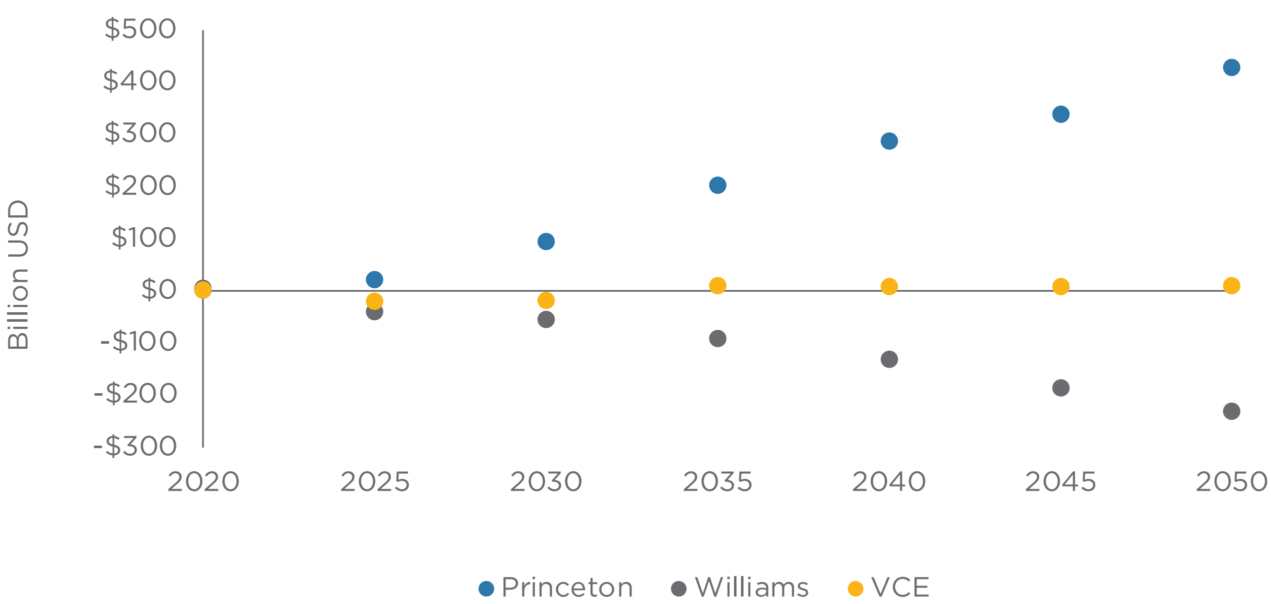


Note: This figure is modified from Hausfather and Olson (2021) using the high renewable energy scenarios rather than the central scenarios and additional studies for comparison. For scenario abbreviations, see Table 2.

B.3 Lower Cost Scenarios

There is large variation across studies in how to achieve net zero, particularly at least cost. As cost minimization models, each study minimizes cost within the constraints of the scenario. Thus, the studies evaluated here are the lower cost options among the set of scenarios in each study, given the assumed constraints on the model but not necessarily the lowest possible cost, in the absence of scenario specific constraints. The choices and assumptions authors made to build each scenario influence which scenario ends up with a lower cost within each study. Figure 16 shows one result of the variations in priorities and assumptions via a difference in annual cost between the lower cost scenario and the reference or BAU scenarios for Williams, Princeton, and VCE. The low-cost scenarios compared in this figure are Williams, Low demand; Princeton, E+RE-; and VCE, ECE HVDC+. It is critical to recognize that each of the studies are reporting costs in different ways; it is challenging, therefore, to draw conclusions between the studies if one only looks at reported costs. This potential source of confusion is being purposefully highlighted here, so the reader understands the complexity of comparing the reported costs in the different studies. In this section, the authors also include Electrification Futures Study, Medium electrification; and EPRI, Net zero by 2050. The Berkeley 2035 Baseline scenario and the Seams D2b VG are used in this comparison as in the previous two.

Figure 16: Difference in reported total annual cost between lower-cost scenario and reference/BAU



Note: This figure compares total annualized system costs in Princeton, total annual energy costs in Williams, and total annual resource costs in VCE. It should be recognized that there are differences in how each study reports costs, which leads to the wide discrepancy in the reported results in the figure.

While it is impossible to know the optimal path to achieve a net-zero economy, the pathway will almost certainly be influenced by relative cost. As such, one might be able to conclude that the lower cost scenarios from each of the studies might also be likely resilient paths to achieve the goal of eliminating emissions from the economy, depending on the assumptions inherent in the scenario, such as behavioral changes leading to energy conservation.

APPENDIX C: DEMAND SIDE CONSIDERATIONS

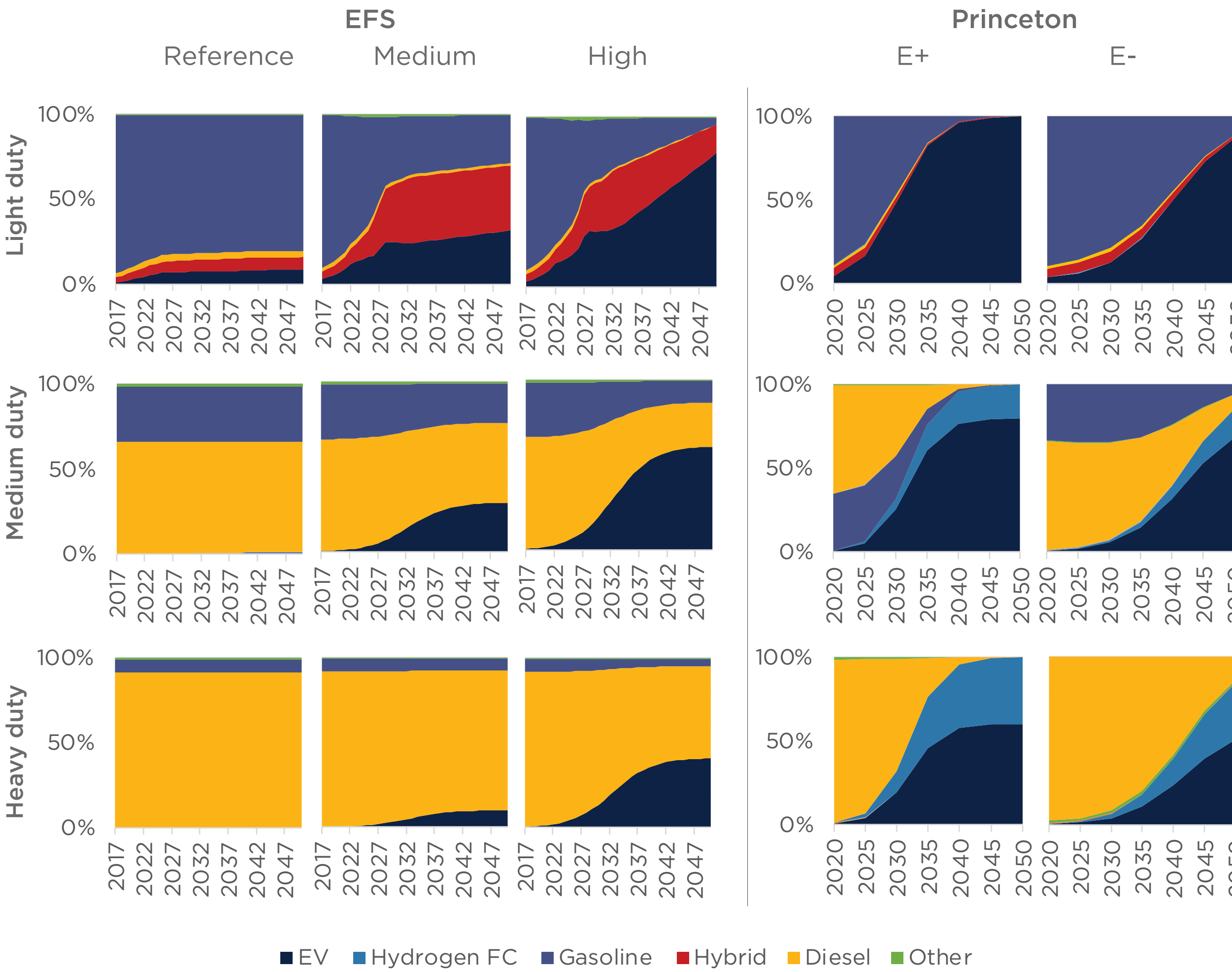
Three of the studies evaluated—Princeton, Williams, and EFS—discuss demand side strategies to reach net zero. Princeton and Williams both show technology trajectories and exhibit similar timing and magnitude of transitions across technologies and sectors. Princeton also notes that equipment replacements are assumed to occur at end of life to avoid stranded asset costs and reduce total replacements costs.

EFS also shows pathways to electrification across Reference, Medium, and High electrification scenarios, where the Reference scenario maintains existing policies, the Medium scenario is loosely consistent with favorable economic conditions, and the High scenario is more transformational. The greater efficiency of electric technologies in the High scenario yields reductions in final energy consumption up to 21 percent, relative to the Reference. However, these transitions are notably slower than in the decarbonization studies. NREL's high electrification scenario more closely mirrors the delayed electrification scenarios by Williams (Delayed electrification) and Princeton (E-) rather than the aggressive electrification scenarios (Central and E+, respectively). An example of this contrast is shown in Figure 17 using NREL's and Princeton's estimated transportation sales. Each of the three studies uses the same model, EnergyPATHWAYS, to represent future electricity consumption of all demand side sectors, but each of those studies incorporate different input assumptions.

C.1 Transportation Demand

In their aggressive electrification scenarios, Princeton and Williams (E+ and Central, respectively) both estimate that nearly all light-duty vehicle sales and a majority of medium-duty vehicle and heavy-duty vehicle sales will be electric early on. They also estimate that most of the operating vehicle stock will be electric by 2050. Some MDVs and HDVs are assumed to run on hydrogen, and a smaller minority still run on gasoline and diesel by 2050. A rapid increase in EV sales begins in the mid to late 2020s in both studies and across all vehicle classes. In the Williams Central case, EV LDVs expand to 50 percent of the market share of vehicle sales by 2030, LDV stock is approximately 75 percent EV by 2030 and reaches 100 percent between 2040 and 2050. Berkeley estimates a more rapid transition to electric vehicles, requiring EVs to be 100 percent of LDV sales by 2030 and 100 percent of MDV and HDV sales by 2035 (see Figure 17).

Figure 17: Transportation sales estimated in electrification scenarios in EFS and Princeton



Note: Note: "EV" includes Battery Electric, "Hybrid" includes Hybrid Electric and Plug-in Hybrid, "Diesel" includes Conventional Diesel, and "Gasoline" includes Conventional Gasoline.

The delayed electrification scenarios of the Princeton and Williams studies (E- and Delayed electrification) and NREL's High scenario estimate more gasoline use by LDVs and more diesel use by MDVs and HDVs in 2050. The greatest expansion in EV sales in these scenarios begins in the 2030s rather than in the 2020s and occurs at a slower pace. For example, Princeton estimates 17 percent of LDVs would be electric by 2030 in the aggressive electrification scenario, compared to 6 percent in the delayed electrification scenario.

It is worth noting that hydrogen has some characteristics that make it an appealing choice for the transportation sector (e.g., rapid fueling for high duty-cycle applications). Furthermore, if hydrogen is adopted widely across the economy to, for example, help decarbonize hard-to-abate sectors, then the production and use of hydrogen might decrease costs in ways that are not fully captured by the current studies. If that happens, hydrogen fuel cells might see wider adoption beyond just the heavy-duty trucking industry.

C.2 Residential and Commercial Demand

By 2050, Princeton and Williams estimate in their aggressive electrification scenarios (E+, Central) that the residential and commercial sectors will be nearly 100 percent electrified. Space heating and air conditioning needs are supplied mostly by heat pumps—air source heat pumps and ductless mini-split heat pumps for residential and only air source heat pumps for commercial in Williams—and some electric resistance heating. Cordwood stove and geothermal heat pumps are estimated to supply a small portion of residential heating needs. Fossil boilers and radiators, geothermal heat pumps, and natural gas are each estimated to supply a small portion of commercial space heating needs by 2050. This change to electrified heating may shift electric grid peak loads to winter rather than summer (White et al. 2021). Water heating needs are supplied mostly by air source heat pumps and some electric resistance. A small amount of commercial buildings rely on geothermal and residual natural gas use. Cooking needs are supplied by electric resistance appliances, which Princeton notes may include induction stoves. Commercial properties lag residential properties in cooking, in particular where natural gas use persists. Compared to Williams, Princeton estimates a higher level of commercial gas use continuing to 2050. The rapid transition to electrification in the residential and commercial sectors begins prior to 2030 in the two studies. Between 2030 and 2040, in the Princeton E+ and Williams Central scenarios, residential and commercial heating and residential cooking reach 100 percent of sales. By 2050, they reach 95–100 percent of total stock.

EFS high electrification scenario and the net-zero delayed electrification scenarios (Princeton, E-; Williams, delayed electrification) employ the same strategies as the aggressive electrification scenarios, but the transition rate is lower. Princeton E- and Williams delayed electrification scenarios estimate sales of residential and commercial heating and residential cooking approach approximately 95–100 percent by 2050 in the delayed electrification scenarios. Stock is slower to turn over due to delayed sales. By 2050, NREL estimates that residential electric technologies provide up to 61 percent of space heating, 52 percent of water heating, and 94 percent of cooking services in the commercial and residential building sectors combined. Use of gas for heating persists to 2050 in all three studies. By 2050, studies estimate there is still significant commercial sector gas use with delayed electrification. The greatest expansion in sales in these scenarios begins in the 2030s rather than in the 2020s. Williams notes that across all scenarios, heat pumps must reach over 50 percent of market share by 2030 to achieve the level of electrification required for net zero.

C.3 Industrial Demand

Reduction in demand for petroleum in transportation and infrastructure materials such as steel and concrete decrease total industrial energy demand. The electrification of some industrial processes, such as electric boilers and electric arc furnaces for steel production, provides additional gains. Conversely, industrial chemical demand for CCS and DAC technologies may significantly increase industrial final energy demand (Realmonte et al. 2019). Williams highlights that emissions of hard-to-electrify processes are captured or otherwise offset by negative emissions. Further decarbonization occurs due to switching fuels. Pipeline gas use shifts to renewable natural gas or synthetic fuels, and hydrogen is used for producing ammonia and other chemicals, as well as for processes like direct-reduced iron production. In Princeton, biomass is converted into pyrolysis oils used for petrochemical production. Princeton estimates final energy decreases by approximately 25 EJ by 2050 in the aggressive electrification scenario, a reduction of about 32 percent compared to the Reference scenario mainly due to lower demands for petroleum and pipeline gas and end-use efficiency of electric technologies compared to fossil alternatives. Some electrification changes are assumed to act as flexible demands, consuming abundant, mainly renewable energy at cheaper off-peak times and curtailing during electricity demand peaks.

EFS estimates additional changes to industrial heating, curing, and drying. By 2050, curing is dominated by infrared and ultraviolet heating, some natural gas, and minimal other fossil fuels. Drying is dominated by natural gas but infrared and ultraviolet heating are also utilized. Other process heat is supplied by a plurality of electric resistance, some industrial heat pumps, and minimal induction furnaces along with other fossil fuels. Some boilers switch to electricity, and space heating is dominated by air source heat pumps by 2050. The switch to electric processes is lower and slower in the industrial sector than in other sectors in EFS.

C.4 Demand Response Levels and Altered or Shifted Load

Large flexible demands are integral for enabling the expansion of VRE supply. The value of those flexible demands depends on three things: (1) When is the consumer of energy able to be flexible (e.g., can a manufacturing facility adjust its load during the middle of an afternoon)? (2) Where is the flexible demand located (e.g., is the manufacturing facility near congested transmission lines)? (3) What type of energy does the consumer need (e.g., high energy consumption for short durations versus lower energy consumption for long durations)? This flexibility in demand is particularly important for scenarios with higher levels of electrification. Princeton and Williams pair more renewables on the supply side with more flexible loads, such as electrolysis, electric boilers, DAC, and storage on the demand side. High renewables scenarios require expanded renewable fuels, increasing demand for flexible electrolysis during off-peak times. This hydrogen produced from electrolysis then provides for both industrial uses and firm supply, assuming sufficient storage for the excess hydrogen. Smart charging of electric vehicles and the automation of heat pump systems and water heating provide additional flexibility in demand. EFS does not incorporate the use of hydrogen or DAC, instead relying most highly on flexible loads in the transportation sector followed by the residential sector, industrial sector, and commercial sector in the High electrification scenario where flexible transportation loads are approximately 15 times larger than in the Reference scenario.

C.5 Energy Efficiency

Energy efficiency is assumed in technology upgrades brought on by electrification across all the studies. Choosing the most efficient end-use technologies decreases electricity demand and generation needs, with the potential to reduce total energy system costs. Princeton notes that additional changes could be made to improve building shells and shift transportation from single user vehicles to multioccupancy vehicles, transit, cycling, and walking and from on-road trucking to rail freight. Increasing fuel efficiency of internal combustion engines will also reduce energy demands and related carbon emissions in vehicles that continue to run on fuels. Energy efficiency is also key in helping the industrial sector decarbonize.

While electrification causes electricity demand to more than double by 2050, strategies such as electric drive trains in vehicles and electric heat pumps for heating in commercial and residential buildings reduce total final energy needed. On the other hand, Williams notes that slow consumer transition to electric vehicles and heat pumps in the Delayed electrification scenario increased fuel demand more than 25 percent relative to the Central scenario by 2050.

Williams also estimates further reductions in energy consumption in the Low demand scenario—the scenario that assumes high rates of energy conservation—reducing consumer demand for energy services such as driving and flying. These changes lower infrastructure requirements and reduce total costs but do not eliminate the need for electrification. Energy efficiency and conservation alone cannot achieve net zero. They must go together with electrification and other decarbonization strategies.

There is a growing body of literature in the energy economics field that empirically estimates the energy savings associated with efficiency upgrades and energy-focused building codes. A key takeaway of this literature is that many of the studies find the realized energy savings from energy efficiency and building codes are well below the engineering estimates (Christensen et al. 2021; Burlig et al. 2020; Fowlie et al. 2018; Allcott and Greenstone 2017; Zivin and Novan 2016; Levinson 2016). Furthermore, these studies provide evidence that at least for weatherization-related energy efficiency upgrades, the overestimated energy savings do not appear to be driven primarily by a rebound effect, meaning more energy use because it is now more affordable (Fowlie et al. 2018). However, the increased efficiency leads to lower costs per unit of energy service and thus a higher quantity of energy services consumed (Christensen et al. 2021; Fowlie et al. 2018). Thus, the assumed energy savings driven by the energy efficiency upgrades in the macro-energy models reviewed may be significantly overstated.

With respect to adoption rates, the economics literature has also described how information asymmetries and lack of cost salience can affect the incentives to invest in energy efficiency upgrades. For example, a long literature explores the "landlord-tenant problem," whereby asymmetric information between the landlords and tenants with regard to the level of energy efficiency of the rental unit leads to a disincentive for landlords to invest in energy efficiency (Blumstein et al. 1980; Jaffe and Stavins 1994; Gillingham et al. 2009; Allcott and Greenstone 2017; Davis 2011; Gillingham and Palmer 2020; Gerarden et al. 2017; Myers 2020). Furthermore, where energy bills are the responsibility of the tenant, the landlord lacks incentive to make efficiency upgrades while the tenant lacks agency to make property level efficiency upgrades. This dynamic regarding energy efficiency upgrades likely drives the observed reduced energy efficiency of rental units relative to owner-occupied units (Best et al. 2021; Gillingham et al. 2012). These studies indicate that increasing electrification and energy efficiency will likely face barriers beyond simply cost. As such, the level of energy efficiency and/or electrification shown by the macro-energy models using cost-minimizing strategies may be greatly overstated.

APPENDIX D: ADDITIONAL IMPORTANT DECARBONIZATION ISSUES

D.1 Agriculture

The agricultural sector is a source of non-CO_2 emissions such as nitrous oxide (N2O) from cultivated soils and manure management and methane from enteric fermentation in livestock, accounting for 10 percent of total US greenhouse gas emissions in 2019 (Environmental Protection Agency 2022). Greenhouse gas abatement in the agricultural sector is not a major strategy of most studies, but the Princeton and White House reports put some attention on this area. Princeton evaluates N_2O abatement using cost of CO_2 equivalent emissions to reduce emissions from croplands and livestock by approximately 0.06 gigatons (Gt) CO_2 emissions/year to 2050. The White House outlines mitigation strategies including more use of agricultural and management practices such as cover crops, rotational grazing, manure management, and improved nutrient management, as well as programs that increase productivity that also minimize land requirements. Additionally, the report puts forward advancements in feed additives to reduce methane from enteric sources, as well as replacing synthetic fibers with innovations in carbon-sequestering fiber as future emissions abatement strategies. Changes in diet, such as reduced consumption, including of meat and dairy when practical within health limitations, also have the potential to reduce the environmental impacts of agriculture (Hyland et al. 2017; Garnett 2011; Boehm et al. 2019; Scarborough et al. 2014).

D.2 Carbon Management

Unabated carbon elimination is the main goal of a net-zero future, but the rate at which the US economy decarbonizes varies across studies and scenarios. Some study scenarios show faster emissions declines, and some studies (Princeton, VCE, Williams, EPRI, and the White House) show scenarios that reach net zero. Studies that are not aimed at achieving net zero also show emissions reductions, but they don't get all the way to net zero. The latter do so by reducing fossil fuel use and/or replacing fossil fuels with renewable energy, electrification, transmission, and emissions constraints. While electrification alone has efficiency benefits, it will not achieve net zero by itself; it must also be paired with a net-zero electricity sector (e.g., electric vehicles can improve fuel efficiency, but to achieve net zero the vehicles must receive their electricity from decarbonized sources). Similarly, while transmission expansion allows further expansion of renewable energy generation, it alone does not reduce emissions. As Williams notes, binding emissions reduction policies is the necessary step to push renewable energy, electrification, and expanded transmission further. While electrification and transmission expansion are important improvements to the energy system that can help enable decarbonization, net zero is unlikely to be achieved without sufficient policy commitments.

Decarbonization study scenarios that achieve net-zero emissions employ multiple strategies (e.g., eliminating unabated use of fossil fuels by up to 2,700 TWh from 2020 to 2050 and increasing renewable energy, electrification, and expanding transmission) and fill in the remaining emissions reduction gaps via the use of zero carbon fuels[9] (e.g., green H_2), CCUS, direct air capture, and expanding land sinks. In general, the timeline of emissions reductions is faster with more rapid electrification and reduction of fossil fuels, while less CCUS is required to offset carbon emissions.

Most decarbonization and electrification studies report similar trends for timelines of emissions reductions, either on an economy-wide scale or across the electricity sector, as shown in Figure 1. The average rate of emissions reductions economy-wide from 2020 to 2030 is more rapid in the White House report than that of Princeton, Williams, and EPRI's net-zero 2035 scenario. Similarly, the rate of emissions reductions in the electricity sector from 2020 to 2030 in VCE's clean economy and clean energy by 2035 scenarios is more rapid than that of EPRI, Berkeley 2035, and EFS.

D.2.1 Carbon Management Strategies

Carbon can be captured, utilized, and sequestered in a variety of ways to help accelerate decarbonization, even in a scenario in which the economy continues to emit GHGs. These methods include land sinks, mineral weathering, forestry, DAC, and CCUS, which will be collectively described as carbon management strategies. These strategies help achieve net-zero emissions, but none of the studies under consideration deploy them as a primary solution to decarbonize. Instead, carbon management strategies are intended to supplement other broader pathways to decarbonize, including expanded electrification while reducing the impact of sectors in the economy that are otherwise hard to decarbonize. Overestimation of the capability of land sinks, DAC, and CCUS can lead to increased emissions (Realmonte et al. 2019).

The net-zero studies do not extend the life of carbon-intensive sectors that have viable alternatives. For example, none of the studies incorporate carbon capture with coal-fired electricity generation—consistent with global literature and the recent IPCC AR6 reports. Carbon management strategies are instead paired with carbon-intensive sectors that cannot be easily eliminated. For example, Princeton and Williams incorporate carbon capture in the hard-to-electrify cement and steel industries. Some studies, for example VCE and Berkeley 2035, attach carbon capture to continue natural gas generation, particularly when the scenario includes delays in natural gas reduction due to other constraints. In addition, constraining land use limits biomass, renewables, and transmission and can result in increased fossil fuel use. EFS meets its emission constraint with carbon capture attached to natural gas generation. Princeton pairs carbon capture with biomass generation or gasifying biomass to form hydrogen for a net negative emissions technology.

DAC and land sinks are used to offset any lingering fossil fuel use (e.g., the gas used for cooking in the commercial sector). Higher DAC compensates for lower electrification, constrained renewable energy, and low natural gas prices. DAC is an expensive technology, and inputs needed for its operation may be constrained by industrial capacity, limiting DAC scalability (Realmonte et al. 2019).

Captured carbon may be used for producing synthetic fuels, but sequestration is generally more favorable, unless a scenario requires more renewable energy or CCUS costs are low. Both utilization and storage of carbon require expansion of carbon transport infrastructure such as pipelines.

Land sinks, including carbon uptake in soils and trees, provide additional natural capture and storage in the Princeton, Williams, and White House studies. The White House points out opportunities in integrating trees into urban areas and increasing and protecting forested areas, including efforts to reduce wildfires and restore fire-damaged land. However, Princeton notes that land availability will limit carbon capture and storage via land sinks. Additionally, climate change may limit availability of carbon sinks in the future. Friedlingstein et al. 2021 estimate climate change reduced land sinks by about 15 percent from 2011 to 2020. Furthermore, it is possible to overestimate land sink carbon offset capabilities (Song and Wang 2021; Gundersen et al. 2021; Randerson et al. 2009). Thus, care must be taken in the accounting for such benefits in practice.

D.2.2 Carbon Management Timeline

Decarbonization studies and scenarios employ varying amounts of the above strategies to achieve net zero either economy-wide or in the electricity sector. Princeton, Williams, the White House, and EPRI show economy-wide changes, while EPRI, VCE, Berkeley 2035, and EFS show electricity sector changes. In Princeton's study, geologic sequestration is required at varying levels to offset continued use of fossil fuels except in the increased renewable energy (E+RE+) scenario. More sequestration—over 1.5 billion metric tons by 2050—is required when renewables are constrained (E+RE-). This requirement is due to the expansion of natural gas compared to other electrification scenarios and the continued use of diesel and gasoline, as well as jet fuel and other residual petroleum. The delayed electrification (E-) and increased biomass with delayed electrification (E-B+) scenarios also rely on nearly the same amount of geologic sequestration due to slower transition away from primary fuel use and more use of diesel and gasoline compared to other electrification scenarios. The speed of electrification and choice of energy sources have large impacts. Decisions on siting, generation technology, pollution abatement, and electrification rate also impact air quality, such as the exposure to fine particulate matter, which often disproportionately impacts lower income populations.

In Williams, all cases reach net zero by 2050. The expanded renewable scenario (100 percent renewable primary energy) and the Net negative scenarios go further than net zero and reach negative emissions. Most cases emit a cumulative 79 $GtCO_2$ from 2020 to 2050, versus 138 $GtCO_2$ in the reference scenario. The 100 percent RE case reaches 75 $GtCO_2$, and the Net negative case still reaches 73 $GtCO_2$ cumulative emissions. The cumulative emissions are due mainly to the sustained use of oil and natural gas, as well as the lingering effect of burning coal through the 2030s and other industrial processes. Emissions are offset in each scenario by a combination of product sequestration and geologic sequestration. Product sequestration remains the largest offset strategy in all scenarios. Geologic sequestration is not used in the 100 percent RE scenario but is relied on in the Central, Low fuel price, and Delayed electrification scenarios due to expanded fossil fuel use, the Low land scenario due to constraints on renewable energy, and the Net negative scenario to accelerate the timeline to achieve net zero. In the study, achieving net zero while continuing fossil fuel use is not possible without carbon capture, specifically higher sequestration and lower utilization of carbon. More synthetic fuel use also requires carbon capture as it is the basis for fuel synthesis. Synthetic fuel use enables lower sequestration and higher utilization of carbon.

The White House report shows major emissions reductions due to transforming the energy sector through energy transition to hydrogen, low-carbon fuels, and electrification (approximately 2.5 $GtCO_2$); decarbonizing electricity with zero carbon generation and fossil fuels with carbon capture and storage (approximately 1.5 $GtCO_2$); and energy efficiency in transportation, buildings, and industry (approximately 1.25 $GtCO_2$) compared to 2005 when domestic emissions were at or near an all-time high. Additional reductions of less than 1 $GtCO_2$ each are attributed to land sinks, carbon removal technologies, and non-CO_2 reductions in fluorinated gases, N_2O, and CH_4. Emissions vary by scenario with electricity sector reductions occurring most rapidly, reducing approximately 0.75 to 1.25 $GtCO_2$ by 2030 and another approximately 0.25 to 0.5 $GtCO_2$ by 2040. Transportation sector emissions reductions occur most rapidly between 2030 and 2050, reducing by approximately 1.25 $GtCO_2$ over the two decades. Industrial and building sector emissions are reduced by approximately 0.5 to 1 $GtCO_2$ and 0.25 to 0.5 $GtCO_2$, respectively, by 2050. While the White House analysis uses an earlier start date than other studies, the absolute reductions across other economy-wide carbon reduction evaluations in Williams and Princeton are similar.

EPRI shows emissions estimates for a select set of scenarios: the Net Zero 2035 scenario and the economy-wide carbon price with and without negative emissions. The Net Zero 2035 scenario achieves a reduction in the annual economy-wide emissions of over 4 $GtCO_2$ from 2005 to 2050, with the electric sector itself achieving approximately 1.5 $GtCO_2$ reduction in annual emissions by 2035. The economy-wide carbon price scenario without negative emissions achieves a more rapid reduction of approximately 1 $GtCO_2$ in the electric sector by 2025. However, the reduction immediately slows, and overall electricity sector CO_2 reduction is slightly less than those of the Net Zero 2035 scenario. When negative emissions are included, the rapid reduction of 1 $GtCO_2$ is instead followed by continued abatement for a total reduction of approximately 2 $GtCO_2$ in the electric sector and nearly 5 $GtCO_2$ economy-wide.

VCE evaluated the emissions impact from energy sector changes on CO_2, carbon monoxide, SO_2, nitrogen oxides (NO_X), CH_4, N_2O, volatile organic compounds (VOCs), and particulate matter at 2.5 and 10 micrometers (PM2.5 and PM10, respectively). VCE compared the emissions impact based on projected reductions to the starting year, 2018. The fastest and largest reductions occur in PM2.5, PM10, and N2O, and the slowest reductions are in CO_2 and CH4 across their scenarios. In the EBAU scenario, reductions plateau by 2035, ranging from 40–100 percent of the 2018 value for each pollutant. In EBAU–, a scenario that delays economy-wide decarbonization changes compared to EBAU, reductions peak by 2035, but pollution increases by 2050 for five pollutants. The four expanded transmission scenarios that prioritize both 100 percent clean economy by 2050 and clean electricity by 2035 (ECE HVDC--, ECE HVDC*, ECE HVDC-, ECE HVDC+) show 100 percent reduction of all pollutants by 2035. The scenarios that prioritize 100 percent clean economy but do not include clean electricity by 2035 (ECE*, ECE, and ECE HVDC) show major emissions reductions by 2030–2035, but they do not achieve 100 percent reductions until 2050.

In Berkeley 2035, the 90 percent clean scenario reduces CO_2 emissions by 1.3 $GtCO_2$ from 2020 to 2035, compared with the reference case, an 88 percent reduction. It also reduces PM2.5 exposure and NO_X and SO_2 emissions by 96 percent and 99 percent, respectively. It should be noted that Berkeley assumes greater use of coal in the reference scenario than any other study and thus shows increased comparative benefits due to its removal.

EFS shows reductions in CO_2, SO_2, and NO_X emissions in the high electrification scenario compared to reference, with the greatest reductions in transportation sector CO_2 and NO_X emissions. In the high electrification scenario, total CO_2 is reduced by approximately 1.5 billion metric tons from 2018 to 2050. However, the electricity sector shows increased CO_2 emissions due to electrification without transition from fossil fuels. No pollutant is reduced to zero across scenarios. NREL's Seams does not show emissions reductions. They are incorporated into costs but not explicitly stated.

D.3 Jobs

The models suggest decarbonization will lead to job growth that exceeds the job losses associated with the energy transition. Job growth is expected mainly in the solar, transmission and distribution, wind, and energy storage industries. The highest change in induced and direct jobs is expected in 2035. The studies differ in the scale of job growth, with VCE expecting more jobs than Princeton. Princeton estimates that the supply side energy workforce expands by over 30 percent between 2020 and 2030 for an annual average of approximately three million jobs and then nearly triples by 2050. The number of jobs in the supply side energy sector grows from approximately 1.5 percent of the labor force in 2020 to 2–4.5 percent by 2050, depending on the scenario. Wages also increase by $30–$40 billion over the reference scenario for a total of approximately $180–$190 billion in wages between 2020 and 2030. Princeton expects most states to see energy-related employment growth. However, states with high shares of current labor force employment in upstream fossil fuels do not necessarily see energy-related employment growth. Scenarios that rely on more renewables or alternative technologies see more job increases than the others. Coal jobs decrease in all scenarios, but natural gas jobs increase when natural gas capacity increases. Nuclear jobs increase when advanced nuclear capacity increases. In Berkeley's 90 percent clean scenario, energy sector–related employment increases by approximately 8.5 million net job years to approximately 29 million job years total from 2020 to 2035, a two-thirds increase over the reference scenario. Despite declines in the fossil fuel industry, each of the relevant studies projects that job growth is expected to exceed jobs lost across the economy.

With all macro-energy models, formulation of job "creation" and "loss" must be evaluated. In its simplest form, jobs are typically added (or reduced) in MES models at a constant rate per unit of physical capital installed. For example, jobs will be "created" at a certain rate per kilowatt of solar capacity installed. This abstracts from the way job creation is considered from the economics perspective in several key ways that can lead to an overstatement of the job additions in the MES models discussed. In a very simplistic framing, dynamic macroeconomic models show increased productivity leads to an expansion of the economy and thus an expansion in employment. To assume that increased investments to enable electrification and clean energy will yield increased productivity is to assume that the lower levels of investment in energy infrastructure under the business-as-usual case is due to some market failure that disincentivizes firms and individuals from making the investments seen under a net-zero path. While some of these market failures likely exist (e.g., the landlord-tenant problem), it's unlikely that correcting all these market failures incentivizes the level of investments needed to be on a net-zero path. Second, the assumption of a constant rate of job addition per unit of installed capital does not account for any labor market equilibrium effects. For example, policies that promote the expansion of renewable energy capacity (e.g., the ITC) increase the demand for skilled labor that is needed to meet that expansion goal. This increase in labor demand increases wages for skilled labor, which increases costs in other industries that also require skilled labor, lowering the quantity demanded in these sectors and creating essentially a job shuffling of sorts, where jobs decrease in the nonclean energy sector and increase in the clean energy sector (Borenstein 2017).[10] Similarly, the financing of the policies to expand clean energy and/or increase electrification likely requires increases in taxes or increases in general energy costs. These tax and/or energy cost increases have their own general equilibrium effects that reduce demand in ways that likely lower employment in other sectors.

These general equilibrium effects, where the policies aimed at a specific sector create cost and price effects in other sectors, are more directly captured in the computable general equilibrium (CGE) models in economics than in the MES models discussed here. Many CGE models have been created to explore economy-wide labor and output effects of climate policy, particularly carbon taxes (see Wing 2009, for a review). While these CGE models include detailed linkages across multiple sectors in an economy, and potentially across many different regional economies, they often lack the detailed modeling of the energy and transportation sectors included in the MES models examined here. More accurately portraying the employment effects of the energy and environmental policies needed to reach the net-zero goals will require building links between these sectoral diverse CGE models that are rooted in microeconomic principles and the detailed energy sector representation found in many of the MES models (Glynn et al. 2015 “Global”; Glynn et al. 2015 “National”).

APPENDIX E: ABBREVIATIONS

CCGT: combined cycle gas turbine

CCUS: carbon capture, utilization, and sequestration

CSP: concentrated solar power

DER: distributed energy resources

H_2: hydrogen

LSE: load serving entities

MES: macro-energy system

MSR: molten salt reactor

NGCC: natural gas combined cycle

NGCT: natural gas combustion turbine

PV: photovoltaic

SMR: small modular reactor

VRE: variable renewable electricity

NOTES

1. Novel technologies (e.g., natural gas with carbon capture and sequestration, small modular reactors, molten salt reactors, and enhanced geothermal systems) are set to be 40 percent of a mature technology, but their installation dates are pushed into the future so that they cannot be installed before a set investment period.

2. Net zero, in this case, refers to removing, reducing, and offsetting carbon dioxide emissions under the control or territorial responsibility of the United States such that the effective total is zero (definition adapted from Grubb et al. 2022).

3. See Bednar and Reames (2020) for a more thorough description of the evaluation of and policy response to energy poverty in the US.

4. Per Williams, "Total energy spending includes all investments in supply side energy infrastructure, fuels, and operations and maintenance, and incremental costs of demand side equipment relative to their equivalent reference investment in the Reference scenario."

5. Thus, all references to "solar" in this study are referring to solar PV.

6. Additional studies on specific policy or research changes have recommendations that concur with the prior studies that were the focus of this report, including: Hultman et al. 2021, Lempert et al. 2019, Davis et al. 2018, Kennedy et al. 2021, and Elsevier Analytical Services 2021.

7. Lempert et al. (2019) recommends incentives for afforestation or reforestation and "carbon farming" practices that increase sequestration in soils.

8. Modeled locations are scenarios, not recommend locations for installation.

9. Fuel, here and elsewhere in this manuscript, refers to a combustible substance used as an energy source. It does not refer to energy sources generally. Thus, a zero-carbon fuel here would not refer to solar or wind.

10. One may argue that such job shuffling described here can only result in scenarios where there is no unemployment. Currently, the US is in such a period of low unemployment, so the scenario is relevant. Additionally, even in periods of high unemployment, skilled labor unemployment rates often are lower than the economy at large. In periods of considerable slackness in the labor market, economists generally agree that some stimuli, including energy investments, is warranted. However, as those periods are transitory, it is unlikely that slack labor conditions will persist over the period needed to reach net-zero goals.

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