Title
Decarbonizing the US Energy System

Journal
Annual Review of Environment and Resources, 49(1)

ISSN
1543-5938

Authors
Hendrickson, Thomas P
Abhyankar, Nikit
Mohanty, Priyanka
et al.

Publication Date
2024-10-18

DOI
10.1146/annurev-environ-112321-091927

ANNUAL REVIEWS

Annual Review of Environment and Resources

Decarbonizing the US Energy System

Thomas P. Hendrickson,[1] Nikit Abhyankar,[1]
Priyanka Mohanty,[1] Kimberley K. Mayfield,[2]
Whitney Kirkendall,[2] Alexander J. Stanley,[2]
Stephen Stack,[3] Hung-Chia Yang,[1]
and Andrew J. Satchwell[1]

[1]Energy Analysis and Environmental Impacts Division, Lawrence Berkeley National Laboratory, Berkeley, California, USA; email: asatchwell@lbl.gov

[2]Energy Group, Lawrence Livermore National Laboratory, Livermore, California, USA

[3]Energy and Resources Group, University of California, Berkeley, California, USA

Annu. Rev. Environ. Resour. 2024. 49:163–89

First published as a Review in Advance on
August 27, 2024

The *Annual Review of Environment and Resources* is online at environ.annualreviews.org

https://doi.org/10.1146/annurev-environ-112321-091927

Keywords

decarbonization, technology adoption, equity and environmental justice, political economy

Abstract

Recent rapid and unexpected cost reductions in decarbonization technologies have accelerated the cost-effective decarbonization of the US economy, with greenhouse gas (GHG) emissions falling by 20% from 2005 to 2020. The literature on US economy-wide decarbonization focuses on maximizing long-term GHG emissions reduction strategies that rely mostly on renewable energy expansion, electrification, and efficiency improvements to achieve net-zero GHG emissions by 2050. While these studies provide a valuable foundation, further research is needed to properly support decarbonization policy development and implementation. In this review, we identify key decarbonization analysis gaps and opportunities, including issues related to cross-sectoral linkages, spatial and temporal granularity, consumer behavior, emerging technologies, equity and environmental justice, and political economy. We conclude by discussing the implications of these analysis gaps for US decarbonization pathways and how they relate to challenges facing major global emitters.

Contents

INTRODUCTION

Context

Decarbonization technologies have become increasingly affordable and advantageous in recent years as a result of both public and private sector initiatives. These include federal rulemaking [e.g., light- and heavy-duty vehicle fuel economy standards, high–global warming potential (GWP) chemical phase-down, power plant greenhouse gas (GHG) emissions limits], state and local programs (e.g., renewable portfolio standards, residential energy efficiency retrofit incentives), and corporate actions (e.g., power purchase agreements) (1, 2; see **https://www.epa.gov/climate-change/climate-change-regulatory-actions-and-initiatives**, **https://programs.dsireusa.org**). The economic and performance advantages of decarbonization technologies over fossil fuel–based alternatives are leading to increased adoption of energy-efficient appliances, renewable energy, and electric vehicles (EVs) (3, 4); expanded renewable energy integration, energy storage deployment, and grid flexibility (5, 6); and enhanced local benefits and community resilience through improved air quality and energy reliability (7, 8).

In response to these trends and to promote more aggressive deployment of decarbonization technologies, recent federal legislation has gone beyond agency rulemaking and nonbinding targets to generate clear pathways for economy-wide decarbonization. The Inflation Reduction Act (IRA), the most significant decarbonization legislation in US history, is estimated to reduce national GHG emissions to 40% below 2005 levels by 2030, primarily through the expansion of renewable and low-carbon energy (e.g., up to 90% clean electricity by 2030). In addition, the Infrastructure Investment and Jobs Act will bolster the IRA's goals through rehabilitation and replacement of critical infrastructure and enhanced resilience (9, 10). This progress, coupled with increased international urgency to meet 1.5°C goals through heightened climate action (11; see **https://ukcop26.org/cop26-goals/**), will accelerate decarbonization, but domestic and global disruptions to supply chains, research and development, and implementation threaten continued progress (12, 13).

Despite this ongoing progress, global energy demand is outpacing the growth of clean energy, leaving fossil fuels to close the gap. This energy demand is coming predominantly from rapidly developing economies like China and India. At the same time, Western countries are not reducing their fossil fuel consumption enough to meet stated climate goals. The International Energy Agency (IEA) has estimated that fossil fuel consumption will peak by the end of this decade, in both Western countries and countries like China, which leads the world in renewable installations (see **https://www.iea.org/reports/world-energy-outlook-2023**).

This review focuses on US decarbonization. US decarbonization research includes both economy-wide and sector-specific studies and models, most notably for the power sector. Studies have characterized GHG emissions sources and key pathways for reducing emissions, namely through clean electricity expansion, electrification, and energy efficiency improvements. This research, which forms a valuable foundation for decarbonization planning, nonetheless lacks the analytical depth necessary to support detailed decision-making and implementation both within and across sectors, regions, and timelines. This article provides a detailed review of recent decarbonization research and examines specific needs in the following areas:

- Cross-sectoral relationships: incorporating dependencies and interconnections between sectors.
- Modeling granularity: developing models that assess outcomes at finer scales of spatial and temporal resolution.
- Consumer adoption: utilizing improved behavioral realism in decarbonization analysis.
- Emerging technologies: identifying emerging technology research needs and roles within hard-to-abate sectors and broader decarbonization pathways.
- Equity and environmental justice (EJ): identifying strategies for creating equitable decarbonization that addresses environmental injustice.
- Political economy implications: assessing policy needs at the federal, state, and local levels to support implementation and continued decarbonization.

Beyond these areas, we discuss how recent research has connected US decarbonization challenges with global ones and how future research can support decision-making and implementation across nations. Importantly, we focus on US economy-wide decarbonization through technology development and deployment but do not discuss research on climate change impacts or adaptation. For reviews of climate change and adaptation research, see, for example, References 14 and 15.

OVERVIEW OF EXISTING RESEARCH

For our foundational review in this section, we select studies that incorporated an economy-wide or, at least, a power sector decarbonization scope where the assumptions and data sources were clear. We focus primarily on studies that modeled a range of decarbonization scenarios that projected emissions reductions by fuel or sector out to 2050. For studies that did not include projected scenarios, we incorporate insights from their authors.

Key Themes from Recent US Studies

A small but important number of US decarbonization studies have developed overarching pathways and supporting methodologies for high-level analyses to project GHG emissions and reductions over time from key decarbonization strategies. To achieve this goal, most of these studies established a historical GHG emissions inventory, and then researched and modeled pathways for achieving net-zero GHG emissions by 2050 to align with 1.5°C warming targets (16) for scopes ranging from energy-related GHG emissions to the full US economy (17–22).

These studies have generally found that economy-wide decarbonization through existing or emerging technologies and infrastructure can be achieved by 2050. Many examined net-zero

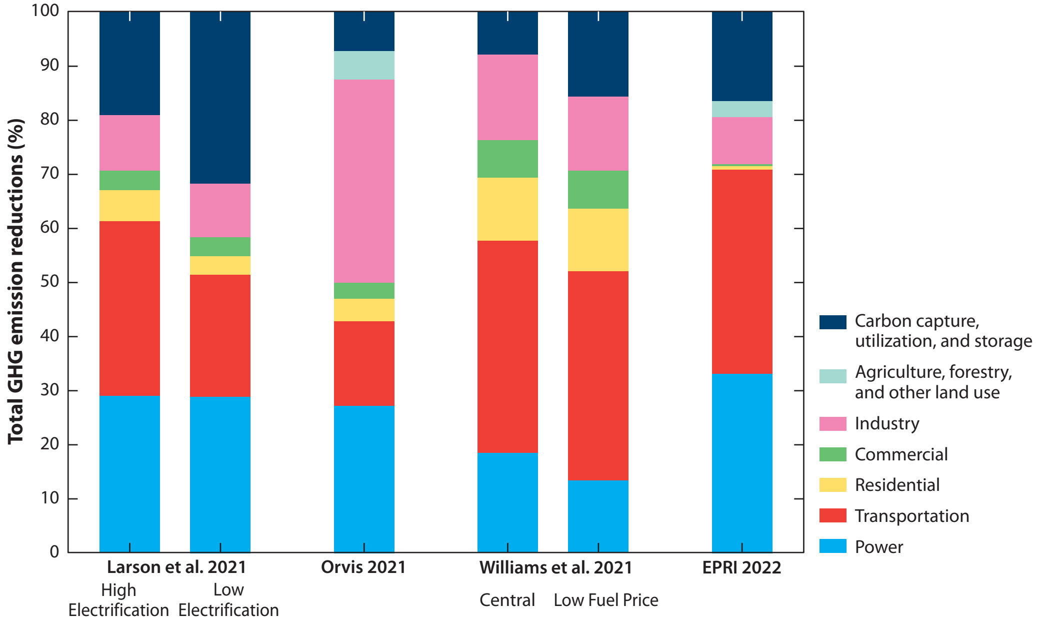


Figure 1

Summary analysis of four studies (18, 20, 22, 24) and the overall contributions to total net-zero or near net-zero GHG emissions reductions by 2050. Specific scenarios are noted for studies that used multiple scenarios. Abbreviations: EPRI, Electric Power Research Institute; GHG, greenhouse gas.

pathways through variations in technology scale-ups [e.g., levels of electrification or carbon capture utilization and storage (CCUS)], prices (e.g., for fossil fuels, renewable fuels, technology costs), energy demand, and policies (e.g., federal incentives, state renewable portfolio standards). Some studies modeled shorter time frames for critical milestones, such as reducing economy-wide GHG emissions by 50% below 2005 levels by 2030 (23). For analysis scoping, economy-wide studies generally categorized GHG emissions through four key sectors: power, industry, transportation, and buildings (often split into residential and commercial buildings). **Figure 1** shows a summary analysis of six studies that detailed economy-wide GHG emissions reductions through these sectors, including any GHG emissions sequestered through CCUS or the agriculture, forestry, and other land use sector.

Electric power sector. The electric power sector, which accounted for 25% of US GHG emissions in 2021 (25), is a significant focus of economy-wide decarbonization studies. Projected economy-wide GHG emissions reductions varied significantly on the basis of power sector drivers such as forecasted electricity generation mix, electrification of transportation and building end uses (increasing demand), and efficiency improvements (decreasing demand).

There is consensus that decarbonization will require a sharp rise in wind and solar generation; Electric Power Research Institute (EPRI) projections range from 36% to 71% (the lower end of the range is due to the assumption of higher levels of carbon capture with continued fossil fuel use) (26), and projections from other studies range from 78% to 98% in terms of maximum shares of solar and wind in total generation capacity in 2050 (18, 22, 24). Studies have projected that this renewable generation would need to be bolstered by energy storage capacity ranging from 80 to 750 GW by 2050 (18, 22, 24). Some studies examined the supporting transmission infrastructure requirements of increasing demands from electrification and a rapid growth in solar and wind power; they found that, by 2050, 1.4 to 5.1 times the current transmission capacity would be needed (17, 18, 22, 24).

Power sector models depend on interactions with other sectors to capture potential changes in electricity demand. Authors have modeled these interactions through scenario variations of scale-ups of electrification and efficiency technologies. Nadel & Ungar (21) focused solely on efficiency opportunities, finding that a high-end efficiency projection, even with aggressive scale-up of electrification technologies, would still result in a 28% reduction in electricity demand by 2050 when coupled with infrastructure improvements, conservation, and policy programs. While other studies have found significant overall energy savings, electricity demands increased in sectors with enhanced electrification (18, 23, 24).

Transportation sector. The transportation sector represents the largest share of US GHG emissions and accounted for 28% of total 2021 GHG emissions, with diesel and gasoline from passenger cars, light trucks, and medium-duty/heavy-duty (MDHD) vehicles making up 83% of transportation GHG emissions (25). Given the significant concentration of economy-wide GHG emissions in this subsector, research has found that maximizing efficiency and fuel switching through electrification of these vehicles are the greatest drivers of transportation decarbonization. In these models, electrification is most prominent in cars and light trucks, where EVs reach between 53% and 97% of total vehicle stocks by 2050, reducing overall energy demands by 52% to 71% (18, 22, 24).

Research is uncertain about the role of electrification in MDHD vehicles. EPRI (24) projected that MDHD vehicles would have similar electrification levels as cars and light trucks by 2050 (approximately 90% of total vehicles), whereas two other studies projected that EVs would make up only 30–52% of MDHD vehicles (18, 22). For studies with less MDHD electrification, hydrogen vehicles are more prominent, particularly for heavy-duty vehicles at 18–38% (18, 22). Larson et al. (18) modeled the infrastructure needed to support this rapid rise in EVs, finding that more than nine million public chargers would be needed between 2030 and 2050.

Less research on fuel switching exists in US decarbonization studies. Fuel switching is a decarbonization pathway for nonroad transportation modes that are challenging to electrify, namely aviation and cargo ships. Three studies found alternative fuel options and electrification to have significantly higher costs than fossil fuel options with carbon capture technology and largely projected that fossil fuels would continue to be used with efficiency gains (18, 22, 24).

Building sector. GHG emissions from the building sector, which result from on-site combustion of natural gas and petroleum, accounted for 10% of total US GHG emissions in 2021 (25). Studies in this area focus primarily on replacing on-site fossil fuel combustion with electrification of space and water heating, using appliances (e.g., for cooking and clothes drying) to drive emissions reductions through efficiency gains, and achieving a cleaner electricity mix (17–19, 22–24). With greater electrification (e.g., using heat pumps and electric resistance heat technologies), studies project that electricity's share of total building energy consumption will rise from 46% (residential) and 52% (commercial) to 70–88% and 70–92%, respectively, by 2050 (18, 22, 24).

US decarbonization research also emphasizes the continued need for appliance efficiency upgrades and building retrofits and weatherization. These can yield substantial energy conservation and provide benefits beyond GHG emissions reductions, including improved occupant comfort and productivity (17, 21).

Industrial sector. The industrial sector, responsible for 20% of 2020 US GHG emissions (25), presents unique challenges in that mitigation strategies with electrification that are suitable for other sectors are not readily available. This is partly due to the prevalence of chemical and high-temperature heating processes, for which few electric technology alternatives exist. To model emissions reductions, decarbonization research assessed efficiency improvements and fuel switching (e.g., using biomass, hydrogen, and/or electricity in place of fossil fuels) wherever feasible. Two studies projected that energy use in this sector would remain constant or increase due to expanded domestic industrial production, and that petroleum-based fuels could still meet up to 43–53% of industrial energy demand in 2050 (18, 22). In contrast, EPRI (24) projected constant or decreasing energy demands and a much greater opportunity for electrification, with electricity meeting 75–95% of the sector's total energy demand in 2050. Studies found that efficiency gains would come from electrification and overall productivity increases (17, 18, 21–24). In particular, research focused on mitigation opportunities in the high-emitting subsectors of cement and steel production, where electrification (steel) and carbon capture (cement) can be utilized (17, 18, 21, 24).

Industrial nonenergy GHG emissions are characterized by on-site processes and fugitive emissions of carbon dioxide (CO_2) and high-GWP materials (e.g., fluorinated gases); this category accounted for one-third of US industrial GHG emissions in 2020 (25). Recent models incorporate mitigation of these emissions through the assumed scale-up of carbon capture technology (17, 18, 23, 24) and fluorinated gas substitution with lower-GWP materials (18, 23).

Carbon capture utilization and storage, and carbon dioxide removal. CCUS focuses on capturing CO_2 emissions from large industrial sources such as power plants and storing them in long-lived products (e.g., cement) or deep underground (at depths of 2 km or more) to prevent their release into the atmosphere. In contrast, carbon dioxide removal (CDR) refers to technologies and approaches that remove CO_2 from the atmosphere. Recent decarbonization research includes scenarios with and without CCUS. In most scenarios, however, some form of CDR is necessary to achieve carbon neutrality due to persistent CO_2 emissions from the hardest-to-abate sectors (e.g., air travel, shipping, some industrial processes, and agriculture) (11, 18, 22, 24, 27).

Least-cost scenarios for rapid decarbonization of the US energy sector by 2035 rely minimally on CCUS implementation, instead sourcing electricity mostly from 70% to 90% renewables (primarily wind and solar) and only 10% to 30% CCUS-equipped traditional thermal power plants such as gas and biomass (18, 22, 27). Beyond electricity generation, the opportunity for CCUS lies in its ability to capture CO_2 emissions from hard-to-abate industries (e.g., steel, cement) and emerging biomass-based renewable solutions (e.g., ethanol, hydrogen). Studies assume that captured carbon will be either stored in geologic formations (17, 18, 22, 24) or utilized in synthetic fuel production and long-lived products (18, 22, 29).

The magnitude of CDR needed varies significantly on the basis of model assumptions for storage feasibility, synthetic fuel demands, technology costs, and support of infrastructure scale-up (e.g., carbon transportation and storage networks). The amount of CO_2 projected to be captured annually varies widely, from 65 to 1,800 million metric tons (MMT) CO_2, equivalent to approximately 1% to 30% of current GHG emissions (18, 22, 25). This estimate has led to a general finding that the United States will need at least 1 GT of CDR per year by 2050 (19). Some CDR studies included expansion of land sinks (e.g., from ecosystem protection and restoration) as an opportunity for enhanced carbon removal; currently, land sinks reduce total US GHG emissions by approximately 12% (25). The EPRI scenario (24) modeled a reduction in land sink carbon removal by 2050, while three other scenarios either maintained current levels or included the potential for a 25–50% enhancement in removals (18, 22, 23).

The bottom-up approach taken in a recent, national CDR report (28) demonstrated that 1 GT of CDR is feasible by 2050, but the collection of CDR methods implemented varies with the valuation of carbon (e.g., with a price of $40/MT of CO_2, soil management could sequester 186 MMT of CO_2, but at \$100/MT this increases to 936 MMT) and the prioritization of biomass for fuels versus CDR. For example, if biomass utilization is optimized for CDR, it results in 877 MMT of CDR at an average price (across all CDR methods analyzed) of \$86/MT of CO_2; if biomass utilization is optimized to meet sustainable aviation fuel goals (17.5 billion gallons), then only 712 MMT of CO_2 removal is forecasted, and the average national cost of 1 GT of removals increases to \$126/MT of CDR.

Costs. Almost all studies included a cost analysis—based on assumptions and data for fuel prices, technology costs, and economic policy mechanisms (e.g., carbon taxes)—that largely drove these variations in findings. Two studies included cost analyses incorporating all sectors and technologies to determine key modeling sensitivities. Specifically, Larson et al. (18) found that capital and fixed operating costs were highest in scenarios that incorporate more renewable energy and electrification, and Williams et al. (22) found that grid infrastructure and renewable power plants primarily drove annual power sector costs in most scenarios.

Decarbonization research has assessed historical trends and forecasted how costs for wind and solar power, the largest projected renewable energy sources in US decarbonization studies, will change over time. US solar installation costs have dropped by 71% in residential and 77% in nonresidential systems in the last 20 years, largely as a result of plummeting module costs in addition to declining balance of system costs (e.g., mounting hardware) and "soft" costs (e.g., permitting, interconnections) (30). The levelized cost of utility-scale solar generation in the United States has fallen by 85% over the last decade, even though system performance (i.e., capacity factor) has plateaued over the same period due to expansion into areas with less irradiance (31). Solar costs are projected to continue to decline (32), with soft costs driving the overall reduction (33).

Since 2010, installed costs for land-based wind in the United States have declined by more than 40%, primarily due to a 50% reduction in turbine prices that occurred between 2008 and 2020. Coupled with performance gains, this decrease has led to a reduction in levelized costs of more than 65% since 2008 (34). Levelized costs for offshore wind fell by 28% to 36% from 2014 to 2019, far outpacing projections from that time. This reduction was due to a combination of technical advancement in turbines, design efficiencies, and industry learning curves that worked to lower capital costs (35). In the future, costs for both land-based and offshore wind are projected to continue to decline, though less quickly than historical rates (32, 33, 35, 36).

In the remainder of this article, we review and summarize existing literature, assess gaps in decarbonization studies and planning efforts, and identify future research needs. Analysis gaps and research needs are organized by major themes. Although each is discussed separately, all must be considered together in constructing economy-wide decarbonization studies and implementation plans so that costs and benefits can be comprehensively assessed.

EMERGING ANALYSIS GAPS AND RESEARCH NEEDS

Cross-Sectoral Relationships

Cross-sectoral studies consider how the deployment of decarbonization technologies in one sector can affect one or many other sectors. The US economy-wide studies reviewed in the preceding section were very limited in their modeling of cross-sectoral relationships. Nevertheless, several studies did envision a shift away from fossil fuel–based technologies and estimated a corresponding dramatic increase in electricity demand, from roughly 4,000 TWh per year in 2022 to more than 12,000–16,000 TWh per year in 2050 (18, 27).

The absence of mature capabilities to identify and represent cross-sectoral linkages and relationships hinders the development of effective carbon mitigation pathways. Benefits of studying cross-sectoral relationships include increasing both the feasibility and effectiveness of decarbonization actions, as well as minimizing trade-offs among sectors (37). Cross-sectoral analysis can also provide detail on coordinated policy responses (38). Importantly, cross-sectoral analyses should complement but not replace sectoral studies, which can provide more detailed technology development and deployment approaches.

Barker et al. (39) identified three categories of cross-sectoral relationships, namely those that occur in parallel in more than one sector, create competition among sectors, or involve interactions between sectors. Recent examples of the first category include thin-film photovoltaic panels that are used in both grid and building applications (40) and sodium-ion batteries for both transportation and grid applications (41). Advances in CDR technologies (e.g., direct air capture, reforestation, biomass carbon removal and storage) can also address CO_2 emissions in multiple sectors in parallel (42). Competition among sectors often arises from a limited resource that can decarbonize several sectors—for example, using natural gas to (partially) decarbonize power and transportation due to its higher energy content (per unit mass) and lower carbon emissions compared with coal and oil (43).

Identifying complementary effects via cross-sectoral studies can inform policies that avoid unintended competition, particularly in terms of relationships between electrification of the building, transportation, and industrial sectors and the power sector (44). Although several studies reviewed in the preceding section represented some degree of coupling between the electrification of various sectors with power sector decarbonization, they missed some important complementary benefits. For example, electrification is a key pathway for building and industry sector decarbonization and can produce complementary cost reductions in the power sector when building electrification and efficiency are pursued in tandem (45). Furthermore, changing the timing of buildings' electricity consumption and EV charging can improve power system load factors, better integrate renewable energy sources by matching supply and demand, and reduce power sector decarbonization costs (46). To sufficiently explore sectoral interactions and relationships, decarbonization modeling tools and approaches should align temporal and spatial resolutions within and across sectors (44). For example, the temporal resolution of power system models should capture the hourly variability of renewable energy generation and the potential for EVs to provide load shifting.

Modeling Granularity

Several recent studies modeled outputs at aggregated, regional levels (18, 22), whose detail is limited by the vast computing power needed to expansively and accurately model economy-wide decarbonization. While these studies identified key drivers, needs, and barriers to decarbonization at a national level, we believe actual technology deployment will require more granular analyses, tools, and models at the community and even facility level. This geographic specificity must be coupled with a temporal specificity to inform decision-makers about how energy use and GHG emissions may change over both the short term and long term, with annual and cumulative projections accompanied by hourly and subhourly ones. Furthermore, these data will inform fuel mixes (including direct use and electricity generation), combustion technologies, local supply and demand (e.g., for energy, transportation, or materials), and other factors that shape local GHG emissions and associated impacts.

The need for analytical specificity applies to all aspects of decarbonization, but recent literature has focused only on prominent technologies and sectors. When evaluating the reduction potential of incremental renewable electricity and storage applications, researchers need marginal (not average) emissions factors that incorporate hourly demand and available supply, particularly at peak demand, when renewable sources may need to be supplemented by dispatchable sources (47–49). In particular, EV costs and GHG emissions are closely tied to local electricity mixes such that shifts between regions and charging times can negate emissions benefits from switching from internal combustion to EVs (48, 50–52). In life-cycle assessment and technoeconomic analysis—where researchers track environmental impacts and costs throughout system lifetimes and associated supply chains—the need for geographic and temporal specificity has given rise to so-called dynamic methodologies. These methodologies include hourly and daily models in place of annual averages, local or regional specificity in place of national data, and ranges of projections to better understand sensitivities and technology performance over time (7, 53).

Implementing and scaling up decarbonization technologies will require significant infrastructure construction across sectors. Economy-wide decarbonization has ignored local negative effects of this rapid build-out, including sharp increases in local pollution, increased heavy traffic, displaced housing, and other critical impacts. Characterizing related local impacts, as well as potential benefits, will require continued refinement of approaches to temporal and geographic analysis. Recent economy-wide studies have focused on build-out rates of transmission and pipeline networks (17, 18, 22) and discussed needs throughout the life cycle of technologies. For example, rapidly expanding infrastructure to support the mining and refining of critical materials, building facilities for the manufacture and production of key technologies, and enhancing material recovery and reuse are all needed to create a carbon-free economy. While decarbonization can significantly benefit communities (17), decision-makers must consider local impacts (e.g., air pollution, water discharges) when expanding this infrastructure to avoid compounding burdens that disproportionately affect disadvantaged populations (54, 55). Future research should consider scenarios for scaling up decarbonization infrastructure and opportunities for mitigating local adverse impacts while maximizing potential benefits. We further assess these needs in the section titled Equity and Environmental Justice.

Consumer Adoption

Accurately forecasting impacts related to the deployment of low-carbon end-use technologies and the implementation of actual and prospective policies requires behaviorally realistic models of consumer adoption. Most decarbonization studies, however, took a simplified approach that did not comprehensively model consumer behavior and only incorporated varying levels of technology adoption driven by mostly economic factors (22, 24, 56). A large body of literature documents the complex drivers of energy-related investment behavior (57, 58), but reviews of energy system models note that these models typically use simplified representations of consumers as perfectly rational utility maximizers (59). A growing number of researchers highlight the limitations of overly simplistic adoption frameworks and identify improved behavioral realism as a key frontier in energy system modeling research (59–61).

In our opinion, oversimplified behavioral modeling in energy system models, lacking realism in portraying diverse and often nonoptimal energy-related behaviors, can result in inaccurate representations of the complex decision-making processes of actors in the energy system. This approach may fail to capture the dynamic nature of energy transitions and social changes, leading to insufficient policy insights and limiting the predictive power of the model. Pfenninger et al. (60) and Fodstad et al. (61) highlighted a few modeling techniques that represent a more integrated approach in energy system modeling, allowing for a more comprehensive and nuanced understanding of the social and behavioral factors that influence energy consumption and production. These include techniques rooted in complex systems thinking, which captures collective social behavior rather than individual decision-making. Additionally, the integration of qualitative scenario analysis enables the modeling of nontechnical factors and long-term uncertainty, while techno-economic energy models incorporating broader social science theories enhance our understanding of the human and social dimensions in energy transitions.

Early approaches to incorporating theoretical and empirical findings into energy investment-related decision-making fall into two broad categories. The first is rooted in behavioral economics, where researchers identify how decision-making heuristics differ from perfect rationality and adjust methodologies to account for them. For example, McCollum et al. (62) incorporate heterogeneity in consumer characteristics and preferences as well as disutility costs associated with technology characteristics into the transportation-focused Transportation Energy & Mobility Pathway Options (TEMPO) model. Similarly, the European Union focused Price-Induced Market Equilibrium System (PRIMES) model incorporates nonmonetary preferences and risk premiums around unfamiliar technologies into an otherwise-conventional consumer adoption method (see **https://e3modelling.com/modelling-tools/primes**).

The second, less incremental approach focuses on incorporating holistic behavioral models of decision-making. Wilson & Dowlatabadi (57) outline the range of attitudinal, psychological, and social models used to explain energy-related behavior, and Alipour et al. (63) document 13 of these models used in the solar adoption literature. Rai & Robinson (64) provide a case study for building this type of model in the context of solar adoption. Existing work has focused on developing test versions of such methodologies, and further research should develop approaches to incorporating them into larger-scale energy system models.

As adoption modeling continues to evolve, we believe decarbonization researchers should incorporate scenario modeling with variations in adoption rates and patterns informed by more holistic behavioral models to better reflect consumer impacts on emissions reduction projections. Future research should also focus on validating the predictive capabilities of existing models. Data limitations make testing these predictive capabilities challenging and yield limited insight into model performance (64). However, such testing is essential to improve model accuracy and realism and should be incorporated in future research to create approaches to validating existing and prospective adoption methodologies.

Emerging Technologies and Analysis Needs

This review focuses on decarbonization technology development and deployment. Decarbonization research incorporates technologies that either are commercially available or have higher technology readiness levels (TRLs).[1] Emerging decarbonization technologies, particularly relevant for the hard-to-abate sectors, will be critical for future decarbonization of these sectors. In this section, we identify some of the most significant hard-to-abate sectoral technologies.

Studies have shown that offshore wind has significant potential for expansion in the United States as an established commercial technology. Research has found more than 4,000 GW of offshore wind potential, with nearly 1,000 GW having an annual capacity factor above 50%, which will be critical to easing pressure on onshore renewable resource deployment (65–68). Between 2014 and 2023, offshore wind resource costs fell by more than 57%—from $172/MWh in 2014 to $74/MWh in 2023—and by 2040 they are expected to drop by a further 32%, to $50/MWh, mainly due to turbine technology advances and economies of scale (69, 70).[2] Offshore wind's

---

[1] TRL is a scale commonly employed to evaluate the maturity and commercial viability of a technology. A low TRL suggests that the technology is in its early stages of development, while a high TRL signifies that the technology is prepared for commercial deployment. For further information, see **https://en.wikipedia.org/wiki/Technology_readiness_level**.

[2] Fixed-bottom class 1 wind sites, moderate-cost case.

energy generation profile has excellent correlation with peak electricity load and complementarity with solar generation (i.e., summer evening peaking on the West Coast and winter evening peaking on the East Coast) (71). High capacity factors, favorable generation profiles, and falling costs make this resource particularly suitable for green hydrogen production. Significant barriers to accelerated offshore wind deployment remain, most notably in supply-chain constraints relating to port infrastructure and vessel availability (72, 73).

The heavy industrial sector poses significant decarbonization challenges, insofar as nonenergy GHG emissions, including reduction processes and technological barriers to electrification, make this sector hard to abate. Currently, the adoption of electrified and green hydrogen–based heavy industrial processes in the United States is minimal, except for electric arc furnace–based steel production (74). However, global momentum for green hydrogen–based iron and steel manufacturing and for ammonia and fertilizer production is increasing, attributable to reduced costs for electrolyzers and hydrogen infrastructure, significant incentives offered by the IRA for green hydrogen production, and the technological maturity of direct reduced iron for steel production (74). In the cement sector, most studies (e.g., 75) have proposed a decarbonization pathway focused on material efficiency, switching fuel to natural gas, and CCUS, although the last of these includes significant technological uncertainty. Promising new research and lab-scale pilots have been conducted on electrifying cement production, with a specific focus on microwave heating-based cement production, which has demonstrated improved cementitious properties (76). However, we believe the main challenges to industrial decarbonization lie in achieving technology maturity through pilots and reducing costs through widespread deployment. Because of the rapidly improving economics of renewable energy resources, especially after the passage of the IRA, a substantial portion of the IRA's required green hydrogen could be generated near industrial plants (77). Even so, substantial investments in hydrogen pipeline, transportation, and storage infrastructure would still be necessary.

Maritime shipping, a critical infrastructure for global supply chains, relies primarily on bunker fuel, but opportunities for electrification are being explored. Owing to dramatic reductions in battery costs and advances in battery technology, including higher energy density and faster charging times, Kersey et al. (78) show that the electrification of intraregional trade routes shorter than 1,500 km is already economical, with minimal impact on ship carrying capacity. If environmental costs are also included, the economical range of electric ships increases to 5,000 km; if battery prices drop to $50/kWh, as most studies project will occur by the early 2030s, the economical range nearly doubles. These projections could cover more than 40% of global containership traffic, with a pathway to economically electrifying over 95% of all shipping routes in the world. Use of ammonia and hydrogen in shipping is considered another crucial decarbonization pathway, especially on longer routes (79, 80). However, electric ships would be more than three to four times as energy efficient than the hydrogen- and ammonia-powered ships, making them a more cost-effective decarbonization alternative, especially for short to medium shipping routes (78).

For inland supply chains, Popovich et al. (81) show that battery electric trains would be significantly more cost effective than electrifying them via extended catenary lines because most trains in the United States are already diesel electric (i.e., the engines have a diesel generator that generates electricity to drive an electric motor). Consequently, the incremental cost of adding a battery cart to existing trains along with associated additional charging infrastructure would be much lower than laying out the additional catenary network. Additionally, battery electric trains could serve as an important grid backup and resilience solution, especially during extreme weather events (82).

Hydrogen can support decarbonization beyond applications where electrification is difficult. Many studies have shown an important role for hydrogen in deep decarbonization of the power sector, especially in mitigating the last 5% of power sector GHG emissions by providing much-needed seasonal balancing for renewable energy integration. There are two main pathways for using hydrogen on the grid. First, green hydrogen can be used in retrofitted natural gas turbines or converted into synthetic methane for use in existing natural gas turbines. Most US decarbonization studies include these pathways (18, 27, 83). Second, Phadke et al. (84) assess the use of green hydrogen in fuel cells, which involves automobile fuel cells serving as peak generation resources that are much cheaper ($200–300/kW to manufacture) than both grid-based fuel cells (more than $1,000/kW), which are better suited to baseload operation, and new natural gas turbines ($600–800/kW). This second pathway requires further investigation.

Finally, transmission is one of the most critical bottlenecks to aggressively scaling renewable energy (18, 22, 85). While studies have identified a need to create more transmission capacity, they focused mostly on building new transmission lines, which requires acquiring new rights-of-way and thus overarching permitting reform (27, 86). However, using advanced conductors on existing lines or converting AC lines to high-voltage DC ones could cost-effectively increase the transmission capacity of existing corridors two- to fourfold, with a reduced need for permitting (87, 88). For example, Chojkiewicz et al. (89) show that reconductoring existing transmission lines using advanced conductors would enable four times greater transmission capacity by 2035—representing more than 80% of the transmission needed to reach a 90% clean grid and resulting in $180 billion in system cost savings by 2050.

Equity and Environmental Justice

Decarbonizing the US economy requires a multifaceted approach that addresses both social and economic equity, as well as EJ concerns. In economy-wide decarbonization research, Larson et al. (18) incorporated estimates for labor needs to support decarbonization technology and infrastructure, as well as health benefits. The National Academies of Sciences, Engineering, and Medicine qualitatively identified key policy and funding needs to maximize decarbonization benefits equitably across populations (17). Beyond US decarbonization studies, several peer-reviewed studies have provided valuable insights into the opportunities and challenges associated with this transition (90–94). By reviewing these findings, we identify actionable strategies for fostering an equitable decarbonization process that directly addresses long-standing environmental injustices.

Equity.

Energy burden and jobs are common topics in the literature on equitable US economy-wide decarbonization. Energy burden refers to the portion of household income devoted to energy expenses (e.g., electricity, heating, cooling, transportation). In the United States, energy burden ranges from 3% to 30% and is strongly correlated not only with socioeconomic status but also with minority and linguistic isolation status, indicating the presence of systemic challenges that warrant solutions beyond simply increasing funding availability (90). In a critical review of energy burden policies, Brown et al. (91) emphasized that most renewable energy technologies (e.g., rooftop solar, home battery systems) are inaccessible to low-income households and low- to moderate-income multifamily residences (e.g., rental apartments). Three ways to decrease energy burden in a decarbonizing economy and immediately benefit disproportionately affected households are the following:

1. Deploying state-led, community-level energy and storage projects for low- to moderate-income households.
2. Leveraging linguistically diverse, interdisciplinary community organizations to enroll residents in programs and communicate energy savings.
3. Valuing public health benefits alongside cost and carbon savings from energy efficiency upgrades (e.g., appliances, gas stoves) (91).

Another key equity challenge in decarbonizing the US economy is the number of (predominantly rural) counties whose economies and residents depend on traditional energy industries such as coal, oil, and gas (see **https://qwiexplorer.ces.census.gov**). **Figure 2** shows both the distribution and concentration of historical, annual fossil fuel job losses in the United States from 2015 to 2022.

Coal communities have been hit hardest in recent years, in terms of job losses from mine and power plant closures (92, 93). Job losses have led to economic crashes and public health crises, made worse by insufficient workforce transition planning and unfulfilled promises to return local jobs (92, 95). While deep decarbonization of the US economy will likely necessitate additional closures in these communities, recent innovative workforce modeling showed that the United States can meet its energy decarbonization needs without incurring inequitable job losses if it optimizes renewable energy deployment in locations with likely coal closures and adequate renewable resources. This workforce-based optimization would increase nationwide decarbonization costs by approximately 24% but decrease negative impacts on traditional energy communities (94).

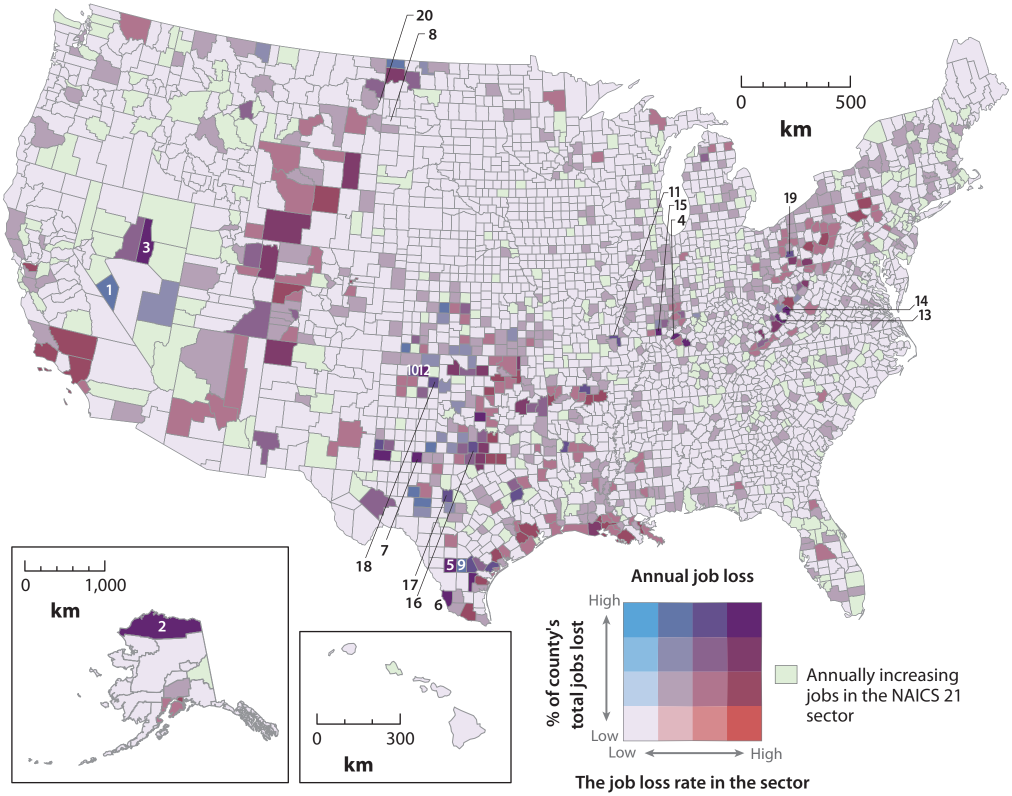
The above results, optimized for coal communities, do not consider workforce transitions in the oil and gas industry, which is already experiencing workforce declines in many US states and counties. Employment data from the Bureau of Labor and Statistics show spatially heterogeneous job losses from the mining, quarrying, and oil and gas extraction sector across the United States in recent years (see **https://qwiexplorer.ces.census.gov**) (**Figure 2**). To directly counteract these workforce job losses and avoid postindustrial decay, the IRA recently designated tax incentives for companies to set up job-creating operations in designated "energy communities" that have experienced workforce losses due to coal-related closures to support a just labor transition.

The just transition is an emerging field of study that addresses the socioeconomic and environmental challenges of decarbonization. Scholars have argued that such a transition is critical for garnering political support for green policies (96). Studies have examined the principles of a just transition, including the roles of government, the private sector, unions, and community organizations (97, 98), as well as case studies of successful and unsuccessful transitions in the United States and abroad (99–101). Other studies involving unions of the workforce serving the fossil fuel industry and workers have examined potential job crossovers between sunsetting fossil fuel industries and growing green energy industries (96).

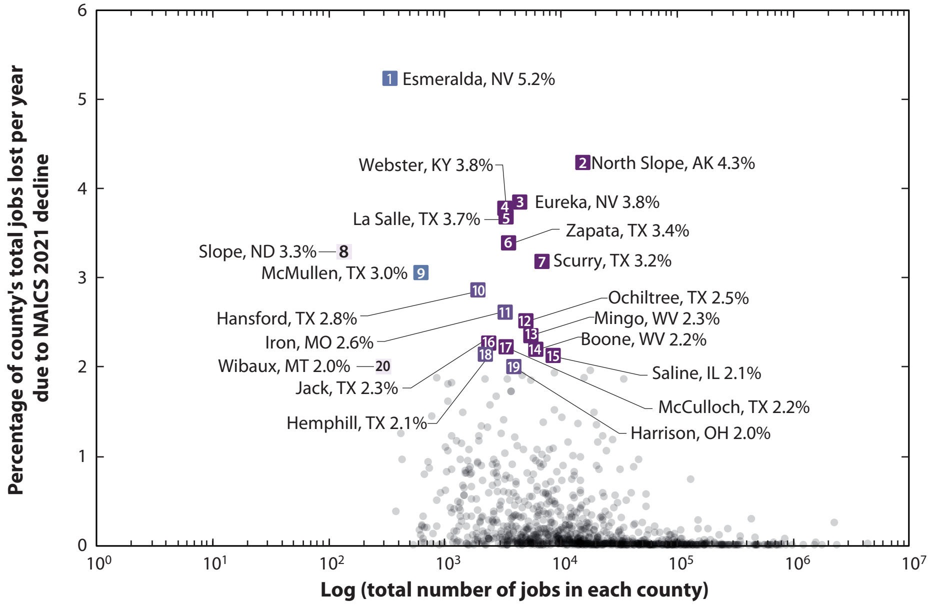
We conclude that further equity analyses that map skill transfers between existing occupations and new green energy industries and develop a comprehensive policy framework for transitioning affected workers while ensuring their economic stability could greatly benefit deep, just decarbonization progress in the United States. We find that such analyses have been done at a subnational level, but a national framework is lacking. We believe additional analyses that assess the economic impact of transitioning from predominantly unionized fossil fuel jobs to less-unionized green energy jobs could also improve our understanding of the socioeconomic and political impacts of this transition.

Environmental justice. The modern EJ movement emerged in the late twentieth century, driven by marginalized communities that had been disproportionately exposed to environmental hazards and pollution. Bullard (102) documented how African American neighborhoods and low-income communities were inequitably burdened by landfills, incinerators, chemical plants, and other environmentally hazardous facilities while simultaneously lacking the political power and economic resources to protect them from such risks. The modern EJ movement has expanded to include occupational health and safety efforts by labor groups, the Indigenous land rights movement, and social and economic justice movements (103).

a County-level annual job loss trends from the oil, gas, and mining sector from 2015 to 2021



b Counties with job markets heavily dependent on the NAICS 21 job sector



(Caption appears on following page)

Figure 2 (*Figure appears on preceding page*)

Geographic distribution of annual job loss trends from the oil, gas, and mining sector [North American Industry Classification System (NAICS) 21 sector] in the United States from 2015 to 2021, in comparison to the relative percentage impact that these annual job losses have had on each county's total job pool in 2015. Panel *a* shows a heat map of where these job losses are occurring with the greatest job inventory impact (*dark purple*). Panel *b* highlights the top 20 counties where these losses are most concentrated; all of them have been losing >2% of their jobs annually since 2015. These counties are also identified by number in the map in panel *a*. Each gray circular data point on the graph in panel *b* represents data from other counties with annual job losses from the NAICS 21 sector; counties with annual job gains are not included. Annual job loss rates were calculated as the slope of a linear regression ($R^2 > 0.4$) for NAICS 21 annual employment numbers; percentage of county jobs was calculated by dividing this annual job loss rate by the total number of jobs available across all sectors in each county in 2015. Figure adapted from figure 9-28 in Reference 28 and based on data from the US Census Bureau's Quarterly Workforce Indicators (QWI) Explorer (**https://qwiexplorer.ces.census.gov**).

As the United States pursues decarbonization, it faces three main EJ-related challenges: remediating past environmental injustices, avoiding environmental harm from decarbonization efforts, and maximizing cobenefits of policy implementation for disadvantaged communities (8). We believe that decarbonization studies must therefore incorporate these challenges to support policy design and implementation. A clear example of the need to incorporate EJ analyses into decarbonization strategies is found in electricity generation infrastructure. In the United States, Black and low-income households are exposed to ~0.2 μg/m^3 $PM_{2.5}$ pollution above the national average (which, in 2019, was 7.66 μg/m^3) (104). While decarbonization of electricity generation infrastructure is expected to reduce $PM_{2.5}$ exposure for all Americans, biomass plants (a key component in many net-zero scenarios) must include emissions controls for both SO_2 and $PM_{2.5}$ to avoid continued disproportionate air pollution impacts on Black and low-income communities (104).

Another area for combined decarbonization and EJ analyses is the heavy transportation sector (i.e., trucking and rail), whose $PM_{2.5}$ emissions cause 3,600 premature deaths per year; these deaths are predominantly in near-highway communities with higher percentages of low-income, Black/brown, and non–native English-speaking residents (105, 106). To have the greatest positive impact on public health in these overburdened near-highway communities, decarbonization policies for heavy transportation could target the replacement of superemitting older trucks, whose $PM_{2.5}$ emissions can be up to 7,000% higher than when they were new, with zero-emission trucks (105).

Although our review identifies several recommendations from existing literature, the dynamic nature of community socioeconomics and demographics requires continual updating of research needs to inform a just policy. Likewise, significant data gaps exist, especially for Hawai'i and Alaska, which have exceptionally diverse populations with limited inclusion in US studies, and low-income regions, which many studies describe as data poor relative to wealthier ones. As the United States pursues economy-wide decarbonization, filling these data gaps will be important for ensuring that policies are effective for all Americans.

In our opinion, the literature reviewed suggests that economy-wide decarbonization efforts would benefit from additional long-term studies on decarbonization and energy equity, which would be important for socioeconomically, linguistically, and demographically diverse communities across the United States where energy burdens are especially high. Such research would include evaluations of what policies have the greatest effect on annual energy savings, what outreach methods are most successful, and how communities perceive financial benefits from targeted programs. To support a just transition, social science studies of communities facing imminent fossil industry closures must assess what new industries those communities want to attract and how they perceive any new industries and their new quality of life. Finally, decarbonization research must leverage interdisciplinary studies that develop consequence comparisons of different decarbonization policies, alongside purposeful socioeconomic and demographic characterizations of the populations to be affected by those policy outcomes.

Political economy. Recent economy-wide decarbonization studies acknowledge that political economic dynamics will influence whether net-zero pathways can be successfully implemented (9, 11, 18). These studies note that factors such as overarching economic frameworks, quality of green jobs, and just transition policies will all influence the scale and speed of decarbonization. However, analyses specifically examining these dynamics are absent from the major cross-cutting decarbonization studies mentioned. Some studies examine broader issues, recognizing that climate policy writ large is a policy mix of economy-wide and sector- and technology-specific policies (107) accompanied by an array of political economy issues (108).

Decarbonization policy extends beyond interactions between industrial policy and environmental policy. The US debate on a Green New Deal has tied green industrial policy to social policy goals (109). Outside industrial policy, where most research and policy activity has occurred, there are other economic policies and frameworks that will be influenced by decarbonization efforts. Examples are climate goals featuring heavily in macroeconomic policies, including fiscal, financial, and monetary policies (110). The literature focuses primarily on economic efficiency and market frameworks for quantifying the benefits of decarbonization policy, best exemplified by the decades-long debates and analyses comparing a carbon tax to cap-and-trade systems as optimal choices for reducing emissions (111–113). In our view, researchers' focus on market mechanisms has come at the expense of seriously considering other interventions such as regulations, mandates, and subsidies.

In our opinion, economy-wide decarbonization studies could acknowledge and explain these dynamics. Furthermore, we believe that consideration must be given to trade-offs between economically efficient decarbonization policies and the requirements of achieving GHG emissions reductions in the time frames outlined by scientific literature. For example, overarching economic investment to jump-start green industries could become increasingly politically necessary if climate impacts worsen over time. China's decarbonization efforts, spurred by the impacts of air pollution from the burning of coal, resulted in a massive, government-led investment program to catalyze a green transition. The success of this investment—half of China's electric generating capacity is already nonfossil—depended on the political and economic circumstances shaping the country and directly contradicted a prior emphasis on market-driven approaches (114).

New frameworks have developed from the shift away from a focus on markets. The literature around the Green New Deal highlights the political economic necessity of a national mobilization in climate investment, on the scale of the New Deal and World War II, to achieve carbon neutrality in scientifically advised time frames (109, 115–117). This research on needed climate investment has opened a new field of political economic thinking around government's role in establishing an economic agenda for decarbonization in direct contrast to the market-driven literature of the past 40 years. Public sector enabling policies and regulations, coupled with new theories of degrowth, have risen to prominence in decarbonization debates. Degrowth as a concept was first articulated in the early 2000s by ecological economists and postdevelopment theorists who argued that a scale-down of both materials and energy is needed in the global economy, starting with wealthy nations (118–121). The current degrowth debate centers on measuring economic prosperity not by GDP or other growth indicators but rather by human wellness measures, including a planned reduction of throughput by high-income nations, redistribution of incomes, a shortened work week, and introduction of job guarantees and living wages along with an expansion of public goods (122). Such a reduction in consumption and total material output is supported by the latest Intergovernmental Panel on Climate Change report as a mechanism for achieving carbon neutrality (123).

The literature of the political economy of decarbonization is a growing field, and we believe that continued research is needed to compare economic approaches, establish economic metrics to define success, and identify the most relevant economic approaches in various political contexts as different climate policy implementation models take shape. Further research is also needed to compare alternative frameworks with business-as-usual ones in terms of their political effectiveness. Finally, we believe that analysis is needed to understand the present political and economic implications of future-impacting climate policy and the future climate impacts themselves, as well as how economic frameworks that focus on optimizing the present should be adapted for a set of problems that are inherently future-facing.

GLOBAL IMPLICATIONS

US Lessons Learned

US decarbonization research provides key insights into the greatest short- and long-term opportunities for emissions reductions, with high-level considerations for overcoming challenges (e.g., with infrastructure and hard-to-decarbonize sectors) and maximizing potential cobenefits. However, as highlighted above, achieving decarbonization is also a local issue that requires granular analysis incorporating costs and benefits in cross-sectoral relationships, community-level and hourly specificity, customer adoption patterns, equitable efficiency improvements and labor transitions, and maximizing benefits while minimizing impacts for historically burdened communities.

Figure 3 shows a summary of important decarbonization topics and how frequently studies included them. The most researched areas focus on power sector solutions and their interactions with related sectors. What is lacking are analyses incorporating hard-to-decarbonize sectors and subsectors, spatial variations, socioeconomic impacts, and implementation needs.

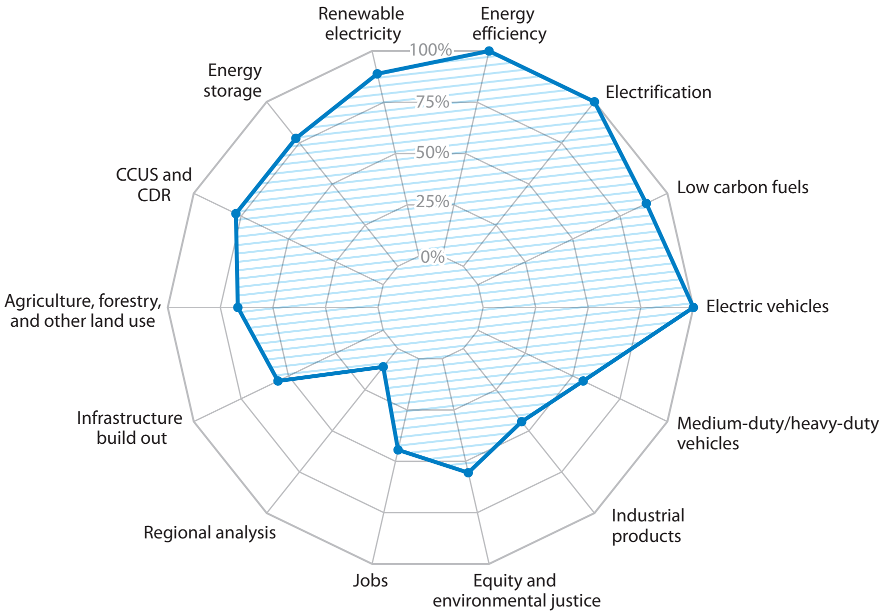


Figure 3

Summary of topic areas assessed in nine US economy-wide decarbonization studies (17–26) published as reports or in peer-reviewed journals since 2021. The radial distance from the center represents the total percentage of studies that addressed each topic (e.g., all nine studies addressed electrification, and only one study included a regional analysis). Electric vehicles denotes light-duty vehicles and/or unspecified modes. Electrification and low-carbon fuels pertain to nontransportation applications (i.e., buildings and industry). Abbreviations: CCUS, carbon capture utilization and storage; CDR, carbon dioxide removal.

These themes and research needs are not unique to the United States. Emission profiles, implementation barriers, and policy needs vary substantially among countries. In the following section, we examine how key lessons from US decarbonization can be applied internationally.

Key International Themes

Global energy demand is outpacing the growth of clean energy, which leaves fossil fuels to close the gap. This energy demand is coming predominantly from emerging economies like China and India, which are rapidly developing. At the same time, Western countries are not reducing their fossil fuel consumption enough to meet stated climate goals.

Additionally, rich countries like the United States, Canada, Japan, and the countries of Western Europe account for only 12% of the global population today but are responsible for 50% of all the planet-warming GHGs released from fossil fuels and industry over the past 170 years (124). At the same time, developing Global South countries that did little to contribute to historical emissions face the brunt of climate impacts, without the wealth to pay for adaptation. This disparity has raised debates at the annual Conference of Parties (COP) around loss and damage funds, financed by rich Western nations to support poorer countries in adapting to the impacts of climate change. A fund was recently announced at COP28 in 2023. However, the committed amount falls far short of what is needed to support the adaptation required (125). The IEA has estimated that fossil fuel consumption will peak by the end of this decade, in both Western countries and countries like China, the world's current largest emitter, which leads the world in renewable installations (see **https://www.iea.org/reports/world-energy-outlook-2023**). Below we present an overview of the current largest emitters, their sources of emissions, and the state of their decarbonization transition.

China relies on coal for roughly half of its energy needs, and coal-fired power plants and industrial activities contribute significantly to China's GHG emissions. At the same time, China has made significant progress in decarbonization, having achieved 50% non–fossil fuel electric generating capacity and established the world's largest EV industry (114). But China's continued expansion of coal-fired electric generating capacity poses a major challenge to domestic and global decarbonization. Recent studies have shown that achieving an 80% carbon-free electricity system in China by 2035 could reduce wholesale electricity costs from today's levels while maintaining system reliability, reducing deaths from air pollution, and increasing employment. In this scenario, wind and solar generating capacity would reach 3 TW and battery storage capacity would reach 0.4 TW by 2035, implying a rapid scale-up of these resources that will require changes in policy targets, markets and regulation, and land use policies (126, 127).

The European Union is the world's third-largest GHG emitter but has taken ambitious steps to combat climate change and reduce GHG emissions, committing to net-zero emissions by 2050. It has made significant progress toward this goal, with GHG emissions reductions already 30% below 1990 levels (128). This progress has been achieved in part through the addition of massive renewable installations and an increase in renewable generation, including hydro, from about 700 TWh annually to more than 1,600 TWh between 2000 and 2021 (129).

After the European Union, India is the fourth-largest emitter of GHGs globally. Like China, India depends heavily on coal for electricity generation, with approximately 70% of India's electricity coming from coal-fired power plants. The country also faces challenges in reducing GHG emissions from other sectors such as transportation and industry because of its high reliance on oil imports. But, more promisingly, India has achieved some of the lowest solar and wind prices anywhere in the world as a result of innovative policy design, and it continues to expand its renewable energy capacity. Both China and India have committed to achieving net-zero GHG emissions by 2060 and 2070, respectively, and India is expected to experience the largest energy demand growth of any country in the coming decade. India recently committed to achieve energy independence by

2047, and studies show that this goal can be met by expanding renewable energy usage across the power, transport, and industry sectors while reducing energy-related CO_2 emissions by 90% (130).

Russia is the fifth-largest global GHG emitter and has extensive oil, gas, and coal reserves. The country's GHG emissions stem primarily from the energy sector, including oil and gas extraction, production, and export. Russia has made some efforts to improve energy efficiency and increase its share of renewables, but these measures have been relatively limited. The country's vast natural resources play a significant role in its economy, making the transition to cleaner energy sources more complex (131).

Finally, Japan is a major global emitter with relatively high energy consumption and a high reliance on oil and gas imports due to its limited domestic energy resources. Historically, Japan has relied on coal and nuclear power, but after the Fukushima nuclear disaster it reduced its nuclear capacity by 33% (132). Japan faces challenges in reducing its dependence on fossil fuel imports and increasing the share of renewables. However, it has been investing in renewable energy sources, such as solar and offshore wind, to diversify its energy mix and decrease GHG emissions. A recent study has shown that Japan has the potential to achieve a 90% clean electricity share by 2035 with a strong policy framework and clean energy targets as a result of the rapidly decreasing costs of solar, offshore wind, and battery technology, which would eliminate its dependence on imported gas and coal (133).

Many studies highlight the importance of recognizing cobenefits of decarbonization as a driving force of the efforts and changes made. Internationally, cobenefits like reducing air pollution are drivers of climate policy, both because they have political salience and because they affect the entire populace. Another highlighted cobenefit of decarbonization is energy independence and security. Both Japan and India rely significantly on oil and gas imports (90%), and Japan also imports a large share of the coal used for its power generation mix (130, 133). The European Union has a significant import reliance on natural gas (128). Reducing import expenditure through clean energy deployment supports energy security and yields reverberating macroeconomic cobenefits, reducing the balance of payments and making countries less susceptible to inflationary shocks. It also has geopolitical implications, as observed for the European Union and its main source of natural gas, Russia. Studies also highlight other economic benefits that can be achieved from decarbonization, including job growth and the development of new, lucrative industries in green manufacturing, EVs, and renewable technologies. Finally, for Global South countries like India, the potential to leapfrog from a dominant coal mix to one heavily weighted toward renewables, skipping gas deployment, is salient to Indian policy makers and stands in stark contrast to places like the United States, European Union, and Japan, all of which rely heavily on natural gas in their transitions away from coal (130).

Studies also demonstrate the clear differences in challenges the United States faces with decarbonization compared with other countries. In growing economies like China, India, and Russia, economy-wide decarbonization will focus primarily on decarbonizing heavy industries like iron, steel, and cement because those countries have been among the world's top 10 producers of those materials. The European Union and United States, which have largely exported those industries, instead face challenges around decarbonizing the power sector and, especially in the United States, the transportation sector. Regarding transportation, in countries like India and China, heavy-duty trucks and buses consume the majority of oil (unlike in the United States, where passenger cars consume more than 60–70%); thus, decarbonization efforts will have a different focus (127, 130). Whereas places like the United States, European Union, Russia, and Japan will focus on retrofits of existing energy infrastructure, countries like India and China will see significant build-out of new infrastructure over the coming decades, providing a crucial opportunity to design energy systems optimized for renewable energy rather than fossil fuels.

However, if growth is coupled with increased fossil fuel use, as has been the case with new coal plant construction in China, the large investments and long lifetimes of new fossil fuel infrastructure will create greater barriers than retrofits (127).

CONCLUSION

Studies of US economy-wide decarbonization have mapped the overarching pathways and drivers for achieving net-zero GHG emissions by 2050, and recent federal legislation has created the foundational mechanisms for deep GHG emissions reductions via renewable energy, electrification, energy efficiency, and carbon capture through the next decade (9). However, implementation will require continued advances in research and development, policy making, and programs to support new technologies so that long-term decarbonization goals are sustainably and equitably achieved. This review has sought to inform such advances by offering guidance to researchers to identify emerging decarbonization implementation challenges and develop solutions for them, particularly as emissions reduction efforts move beyond "low-hanging fruit" and encounter the limits of existing technologies and increased socioeconomic barriers. This review has focused on technology development and deployment and does not address all decarbonization challenges, most notably the nexus of climate change adaptation and mitigation, where the supply, demand, and resilience of decarbonization technologies must adapt to new threats of climate change. While this article has addressed needs at the national, regional, local, sectoral, and subsectoral levels, it does not include specific steps for incorporating approaches into broader emissions reduction strategies (i.e., climate action plans) that can ultimately inform policy making and investment. Future research will need to develop methodologies and approaches that inform such decision-making analysis while retaining the level of detail we present here.

SUMMARY POINTS

1. Recent US decarbonization studies have found that economy-wide decarbonization through existing or emerging technologies and infrastructure can be achieved by 2050, and they have generally categorized greenhouse gas (GHG) emissions through four key sectors: power, industry, transportation, and buildings.
2. Greater analytical depth, particularly through examining cross-sectoral relationships and increasing modeling granularity, can inform policies to achieve economy-wide decarbonization that avoid unintended competition and are translatable to local communities.
3. Developing and utilizing behaviorally realistic models of consumer adoption are important to improve model accuracy and realism and should be used to validate the feasibility of decarbonization solutions from the consumer perspective.
4. To date, several important emerging technologies have been insufficiently considered as decarbonization solutions; these include offshore wind, electrification of the heavy industrial subsectors and maritime shipping, green hydrogen in fuel cells, and advanced conductors for electricity grid transmission.
5. Successfully achieving economy-wide decarbonization requires a multifaceted approach that addresses both social and economic equity and environmental justice (EJ) concerns, in addition to considering the political and economic feasibility of solutions.

6. US decarbonization studies offer insights for other countries as they seek to achieve economy-wide decarbonization, including the importance of cobenefits like reduced air pollution and lower electricity system infrastructure costs, greater domestic energy security, and the need to rapidly connect renewable energy to power grids.
7. Achieving economy-wide decarbonization is as much a national as a local issue that requires granular analysis incorporating costs and benefits in cross-sectoral relationships, community-level and hourly specificity, customer adoption patterns, equitable efficiency improvements and labor transitions, and maximizing benefits while minimizing impacts for historically burdened communities.

FUTURE ISSUES

1. Recent US decarbonization studies have successfully modeled net-zero GHG emissions pathways but are high level and lack the detail required to support decision-making and implementation.
2. Future research in US decarbonization should address the key issues we have identified in this review: cross-sectoral relationships, modeling granularity, customer adoption, emerging technologies and trends, equity and EJ, and political economy.
3. In applying decarbonization research, guidance is needed to incorporate these key issues into decarbonization planning analysis (i.e., climate action plans).
4. Future decarbonization research should consider the nexus between climate change adaptation and mitigation, where climate-driven hazards will affect decarbonization efforts (e.g., extreme heat increasing demands for cooling energy).

DISCLOSURE STATEMENT

P.M. is currently working as the executive director of a union-affiliated green training organization. The views and opinions of authors expressed herein do not necessarily state or reflect those of the US Government or any agency thereof, or the Regents of the University of California.

ACKNOWLEDGMENTS

The writing of this review was funded by the US Department of Energy under Lawrence Berkeley National Laboratory contract DE-AC02-05CH11231 and Lawrence Livermore National Laboratory contract DE-AC52-07NA27344. This manuscript has been authored by an author at Lawrence Berkeley National Laboratory under Contract No. DE-AC02-05CH11231 with the US Department of Energy. The US Government retains, and the publisher, by accepting the article for publication, acknowledges, that the US Government retains a non-exclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for US Government purposes.

LITERATURE CITED

1. Barbose GL. 2021. *U.S. renewables portfolio standards 2021 status update: early release*. Rep., Lawrence Berkeley Natl. Lab., Berkeley, CA. **https://live-etabiblio.pantheonsite.io/sites/default/files/rps_status_update-2021_early_release.pdf**

2. Kobus J, Nasrallah A, Guidera J. 2021. *The role of corporate renewable power purchase agreements in supporting US wind and solar deployment*. Res. Rep., Cent. Glob. Energy Policy, Columbia Univ., New York
3. IRENA (Int. Renew. Energy Agency). 2022. *Renewable power remains cost-competitive amid fossil fuel crisis*. Press Release, July 13, IRENA, Abu Dhabi, United Arab Emir. **https://www.irena.org/news/pressreleases/2022/Jul/Renewable-Power-Remains-Cost-Competitive-amid-Fossil-Fuel-Crisis**
4. Natl. Acad. Sci. Eng. Med. 2023. *Accelerating Decarbonization in the United States: Technology, Policy, and Societal Dimensions*. Washington, DC: Natl. Acad.
5. Satchwell A, Cowiestoll B, Hale E, Gerke B, Jadun P, et al. 2022. *Assessing the interactive impacts of energy efficiency and demand response on power system costs and emissions*. Rep., Lawrence Berkeley Natl. Lab., Berkeley, CA
6. Forrester S, Cappers P. 2021. *Opportunities and challenges to capturing distributed battery value via retail utility rates and programs*. Rep., Lawrence Berkeley Natl. Lab., Berkeley, CA
7. Luderer G, Pehl M, Arvesen A, Gibon T, Bodirsky BL, et al. 2019. Environmental co-benefits and adverse side-effects of alternative power sector decarbonization strategies. *Nat. Commun.* 10:5229
8. Spurlock CA, Elmallah S, Reames TG. 2022. Equitable deep decarbonization: a framework to facilitate energy justice–based multidisciplinary modeling. *Energy Res. Soc. Sci.* 92:102808
9. Jenkins JD, Mayfield EN, Farbes J, Jones R, Patankar N, et al. 2022. *Preliminary report: the climate and energy impacts of the Inflation Reduction Act of 2022*. Rep., Zero Lab, Princeton, NJ
10. White House. 2021. *Bipartisan Infrastructure Investment and Jobs Act*. Fact Sheet, White House, Washington, DC. **https://www.whitehouse.gov/briefing-room/statements-releases/2021/11/06/fact-sheet-the-bipartisan-infrastructure-deal**
11. Core Writ. Team, Lee H, Romero J, eds. 2023. Summary for policymakers. In *Climate Change 2023 Synthesis Report: Contribution of Working Groups I, II and III to the 6th Assessment Report of the Intergovernmental Panel on Climate Change*, pp. 1–34. Geneva: IPCC
12. Allam Z, Bibri SE, Sharpe SA. 2022. The rising impacts of the COVID-19 pandemic and the Russia–Ukraine war: energy transition, climate justice, global inequality, and supply chain disruption. *Resources* 11:99
13. Ryter J, Fu X, Bhuwalka K, Roth R, Olivetti EA. 2021. Emission impacts of China's solid waste import ban and COVID-19 in the copper supply chain. *Nat. Commun.* 12:3753
14. Nik VM, Perera ATD, Chen D. 2021. Towards climate resilient urban energy systems: a review. *Natl. Sci. Rev.* 8(3):nwaa134
15. Shi L, Moser S. 2021. Transformative climate adaptation in the United States: trends and prospects. *Science* 372(6549):abc8054
16. Masson-Delmotte V, Zhai P, Pörtner HO, Roberts D, Skea J, et al. 2018. *Global Warming of 1.5°C: An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*. Cambridge, UK/New York: Cambridge Univ. Press
17. Natl. Acad. Sci. Eng. Med. 2021. *Accelerating Decarbonization of the U.S. Energy System*. Washington, DC: Natl. Acad.
18. Larson E, Greig C, Jenkins J, Mayfield E, Pascale A, et al. 2021. *Net-zero America: potential pathways, infrastructure, and impacts*. Final Rep., Net-Zero Am. Proj., Princeton Univ., Princeton, NJ
19. US Dep. State, US Exec. Off. Pres. 2021. *The long-term strategy of the United States: pathways to net-zero greenhouse gas emissions by 2050*. Rep., US Dep. State, US Exec. Off. Pres., Washington, DC
20. Orvis R. 2021. *A 1.5 Celsius pathway to climate leadership for the United States*. Fact Sheet, Energy Innov., San Francisco, CA
21. Nadel S, Ungar L. 2019. *Halfway there: Energy efficiency can cut energy use and greenhouse gas emissions in half by 2050*. Res. Rep., Am. Counc. Energy-Effic. Econ., Washington, DC
22. Williams JH, Jones RA, Haley B, Kwok G, Hargreaves J, et al. 2021. Carbon-neutral pathways for the United States. *AGU Adv.* 2(1):e2020AV000284
23. Bistline J, Abhyankar N, Blanford G, Clarke L, Fakhry R, et al. 2022. Actions for reducing US emissions at least 50% by 2030. *Science* 376(6596):922–24

24. EPRI (Electr. Power Res. Inst.). 2022. *LCRI net-zero 2050: U.S. economy-wide deep decarbonization scenario analysis*. Rep., EPRI, Palo Alto, CA
25. EPA (US Environ. Prot. Agency). 2024. *Inventory of U.S. greenhouse gas emissions and sinks: 1990–2022*. Fact Sheet, EPA, Washington, DC. **https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks**
26. EPRI (Electr. Power Res. Inst.). 2021. *Powering decarbonization: strategies for net-zero CO_2 emissions*. Rep., EPRI, Palo Alto, CA
27. Denholm P, Brown P, Cole W, Mai T, Sergi B. 2022. *Examining supply-side options to achieve 100% clean electricity by 2035*. Tech. Rep. NREL/TP-6A40-81644, Natl. Renew. Energy Lab., Golden, CO
28. Pett-Ridge J, Kuebbing S, Mayer AC, Hovorka S, Pilorgé H, et al. 2023. *Roads to removal: options for carbon dioxide removal in the United States*. Tech. Rep. LLNL-TR-852901, Lawrence Berkeley Natl. Lab., Berkeley, CA
29. Hepburn C, Adlen E, Beddington J, Carter EA, Fuss S, et al. 2019. The technological and economic prospects for CO_2 utilization and removal. *Nature* 575(7781):87–97
30. Barbose G, Darghouth N, O'Shaughnessy E, Forrester S. 2022. *Tracking the sun: pricing and design trends for distributed photovoltaic systems in the United States, 2022 edition*. Rep., Lawrence Berkeley Natl. Lab., Berkeley, CA
31. Bolinger M, Seel J, Warner C, Robson D. 2022. *Utility-scale solar, 2022 edition*. Rep., Lawrence Berkeley Natl. Lab., Berkeley, CA
32. Phadke A, Pailwal U, Abhyankar N, McNair T, Paulos B, et al. 2020. *2035: the report*. Rep., Univ. Calif., Berkeley
33. Natl. Renew. Energy Lab. 2022. *2022 Electricity ATB technologies and data overview*. Fact Sheet, Natl. Renew. Energy Lab., Golden, CO. **https://atb.nrel.gov/electricity/2022/technologies#:~:text=The%202022%20Electricity%20ATB%20provides,both%20at%20present%20and%20with**
34. Bolinger M, Wiser R. 2022. *Land-based wind market report*. Rep., Lawrence Berkeley Natl. Lab., Berkeley, CA
35. Wiser R, Rand J, Seel J, Beiter P, Baker E, et al. 2021. Expert elicitation survey predicts 37% to 49% declines in wind energy costs by 2050. *Nat. Energy* 6(5):555–65
36. Musial W, Spitsen P, Duffy P, Beiter P, Marquis M, et al. 2022. *Offshore wind market report: 2022 edition*. Rep., US Dep. Energy, Washington, DC
37. Shukla PR, Skea J, Slade R, Al Khourdajie A, van Diemen R, et al. 2022. Summary for policymakers. In *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the 6th Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK/New York: Cambridge Univ. Press
38. Natl. Acad. Sci. Eng. Med. 2021. *Partnerships and Cross-Sector Collaboration Priorities to Support Climate Research and Policy: Proceedings of a Workshop—in Brief*. Washington, DC: Natl. Acad.
39. Barker T, Bashmakov I, Alharthi A, Amann M, Cifuentes L, et al. 2007. Mitigation from a cross-sectoral perspective. In *Climate Change 2007: Mitigation. Contribution of Working Group III to the 4th Assessment Report of the Intergovernmental Panel on Climate Change*, ed. B Metz, OR Davidson, PR Bosch, R Dave, LA Meyer, pp. 619–90. Cambridge, UK/New York: Cambridge Univ. Press
40. Aslam A, Ahmed N, Qureshi SA, Assadi M, Ahmed N. 2022. Advances in solar PV systems: a comprehensive review of PV performance, influencing factors, and mitigation techniques. *Energies*. 15(20):7595
41. IEA (Int. Energy Agency). 2023. *ETP clean energy technology guide*. Rep., IEA, Paris. **https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide**
42. Mulligan J, Rudee A, Lebling K, Levin K, Anderson J, Christensen B. 2020. *CarbonShot: federal policy options for carbon removal in the United States*. Work. Pap., World Resour. Inst., Washington, DC
43. Lee A, Zinaman O, Logan J. 2012. *Opportunities for synergy between natural gas and renewable energy in the electric power and transportation sectors*. Tech. Rep. NREL/TP-6A50-56324, Natl. Renew. Energy Lab., Golden, CO
44. Chang M, Thellufsen JZ, Zakeri B, Pickering B, Pfenninger S, et al. 2021. Trends in tools and approaches for modelling the energy transition. *Appl. Energy* 290:116731

45. Langevin J, Satre-Meloy A, Satchwell AJ, Hledik R, Olszewski J, et al. 2022. *The role of buildings in U.S. energy system decarbonization by mid-century*. Work. Pap., Lawrence Berkeley Natl. Lab., Berkeley, CA
46. Jenkins JD, Luke M, Thernstrom S. 2018. Getting to zero carbon emissions in the electric power sector. *Joule* 2(12):2498–510
47. Arent DJ, Green P, Abdullah Z, Barnes T, Bauer S, et al. 2022. Challenges and opportunities in decarbonizing the U.S. energy system. *Renew. Sustain. Energy Rev.* 169:112939
48. Graff Zivin JS, Kotchen MJ, Mansur ET. 2014. Spatial and temporal heterogeneity of marginal emissions: implications for electric cars and other electricity-shifting policies. *J. Econ. Behav. Organ.* 107:248–68
49. Thind MPS, Wilson EJ, Azevedo IL, Marshall JD. 2017. Marginal emissions factors for electricity generation in the midcontinent ISO. *Environ. Sci. Technol.* 51(24):14445–52
50. Yuksel T, Tamayao M-AM, Hendrickson C, Azevedo IML, Michalek JJ. 2016. Effect of regional grid mix, driving patterns and climate on the comparative carbon footprint of gasoline and plug-in electric vehicles in the United States. *Environ. Res. Lett.* 11:044007
51. Tamayao M-AM, Michalek JJ, Hendrickson C, Azevedo IML. 2015. Regional variability and uncertainty of electric vehicle life cycle CO_2 emissions across the United States. *Environ. Sci. Technol.* 49(14):8844–55
52. Powell S, Cezar GV, Min L, Azevedo IML, Rajagopal R. 2022. Charging infrastructure access and operation to reduce the grid impacts of deep electric vehicle adoption. *Nat. Energy* 7:932–45
53. Sohn J, Kalbar P, Goldstein B, Birkved M. 2020. Defining temporally dynamic life cycle assessment: a review. *Integr. Environ. Assess. Manag.* 16(3):314–23
54. Tessum CW, Paolella DA, Chambliss SE, Apte JS, Hill JD, Marshall JD. 2021. $PM_{2.5}$ polluters disproportionately and systemically affect people of color in the United States. *Sci. Adv.* 7(18):eab4491
55. Thind MPS, Tessum CW, Azevedo IL, Marshall JD. 2019. Fine particulate air pollution from electricity generation in the US: health impacts by race, income, and geography. *Environ. Sci. Technol.* 53(23):14010–19
56. Mai T, Jadun P, Logan J, McMillan C, Muratori M, et al. 2018. *Electrification futures study: scenarios of electric technology adoption and power consumption for the United States*. Tech. Rep. NREL/TP-6A20-71500, Natl. Renew. Energy Lab., Golden, CO
57. Wilson C, Dowlatabadi H. 2007. Models of decision making and residential energy use. *Annu. Rev. Environ. Resour.* 32:169–203
58. Kastner I, Stern PC. 2015. Examining the decision-making processes behind household energy investments: a review. *Energy Res. Soc. Sci.* 10:72–89
59. Muratori M, Jadun P, Bush B, Bielen D, Vimmerstedt L, et al. 2020. Future integrated mobility-energy systems: a modeling perspective. *Renew. Sustain. Energy Rev.* 119:109541
60. Pfenninger S, Hawkes A, Keirstead J. 2014. Energy systems modeling for twenty-first century energy challenges. *Renew. Sustain. Energy Rev.* 33:74–86
61. Fodstad M, Crespo del Granado P, Hellemo L, Knudsen BR, Pisciella P, et al. 2022. Next frontiers in energy system modelling: a review on challenges and the state of the art. *Renew. Sustain. Energy Rev.* 160:112246
62. McCollum DL, Wilson C, Pettifor H, Ramea K, Krey V, et al. 2017. Improving the behavioral realism of global integrated assessment models: an application to consumers' vehicle choices. *Transp. Res. D* 55(1):322–42
63. Alipour M, Salim H, Stewart RA, Sahin O. 2020. Predictors, taxonomy of predictors, and correlations of predictors with the decision behaviour of residential solar photovoltaics adoption: a review. *Renew. Sustain. Energy Rev.* 123:109749
64. Rai V, Robinson SA. 2015. Agent-based modeling of energy technology adoption: empirical integration of social, behavioral, economic, and environmental factors. *Environ. Model. Softw.* 70:163–77
65. Lopez A, Green R, Williams T, Lantz E, Buster G, Roberts B. 2022. *Offshore wind energy technical potential for the contiguous United States*. Slides, Natl. Renew. Energy Lab., Golden, CO
66. Musial W. 2022. *Offshore wind energy: technology above the water*. Tech. Rep. NREL/PR-5000-81227, Natl. Renew. Energy Lab., Golden, CO

67. Paliwal U, Abhyankar N, Wooley D, Phadke A. 2022. *The offshore report: California. Plummeting offshore wind costs can accelerate a diverse net-zero grid*. Work. Pap. 1, Cent. Environ. Pubic Policy, Goldman Sch. Public Policy, Univ. Calif., Berkeley
68. Costoya X, deCastro M, Carvalho D, Gómez-Gesteira M. 2020. On the suitability of offshore wind energy resource in the United States of America for the 21st century. *Appl. Energy.* 262:114537
69. Blair N, Cory K, Hand M, Parkhill L, Speer B, et al. 2015. *Annual technology baseline*. Fact Sheet, Natl. Renew. Energy Lab., Golden, CO. **https://www.nrel.gov/docs/fy15osti/64077.pdf**
70. Natl. Renew. Energy Lab. 2023. *Annual technology baseline—offshore wind*. Fact Sheet, Natl. Renew. Energy Lab., Golden, CO. **https://atb.nrel.gov/electricity/2023/offshore_wind**
71. Paliwal U, Abhyankar N, McNair T, Bennett JD, Wooley D, et al. 2023. *2035 and beyond: abundant, affordable offshore wind can accelerate our clean electricity future*. Rep., Goldman Sch. Public Policy, Univ. Calif., Berkeley. **https://gspp.berkeley.edu/research-and-impact/publications/the-2035-report-abundant-affordable-offshore-wind-can-accelerate-our-clean-electricity-future**
72. Shields M, Stefek J, Oteri F, Kreider M, Gill E, et al. 2023. *A supply chain road map for offshore wind energy in the United States*. Tech. Rep. NREL/TP-5000-84710, Natl. Renew. Energy Lab., Golden, CO
73. Shields M, Marsh R, Stefek J, Oteri F, Gould R, et al. 2022. *The demand for a domestic offshore wind energy supply chain*. Tech. Rep. NREL/TP-5000-81602, Natl. Renew. Energy Lab., Golden, CO
74. Cresko J, Rightor E, Carpenter A, Peretti K, Elliott N, et al. 2022. *DOE industrial decarbonization roadmap*. Fact Sheet, Off. Sci., US Dep. Energy
75. IEA (Int. Energy Agency). 2018. *Technology roadmap: low-carbon transition in the cement industry—analysis*. Rep., IEA, Paris. **https://www.iea.org/reports/technology-roadmap-low-carbon-transition-in-the-cement-industry**
76. Buttress A, Jones A, Kingman S. 2015. Microwave processing of cement and concrete materials—towards an industrial reality? *Cem. Concr. Res.* 68:112–23
77. EPRI. 2023. *Decarbonization of industrial clusters initiative gains global momentum*. Press Release, Jan. 19, EPRI, Palo Alto, CA. **https://www.epri.com/about/media-resources/press-release/3YGlJTSNw3AUM1U6VlGHjY**
78. Kersey J, Popovich ND, Phadke AA. 2022. Rapid battery cost declines accelerate the prospects of all-electric interregional container shipping. *Nat. Energy* 7(7):664–74
79. Hume D. 2021. *Ammonia as maritime fuel*. Rep., Pac. Northw. Natl. Lab., Richland, WA
80. Comer B, Georgeff E, Stolz D, Mao X, Osipova L. 2022. *Decarbonizing bulk carriers with hydrogen fuel cells and wind-assisted propulsion*. White Pap., Int. Counc. Clean Transp., Washington, DC
81. Popovich ND, Rajagopal D, Tasar E, Phadke A. 2021. Economic, environmental and grid-resilience benefits of converting diesel trains to battery-electric. *Nat. Energy* 6:1017–25
82. Moraski JW, Popovich ND, Phadke AA. 2023. Leveraging rail-based mobile energy storage to increase grid reliability in the face of climate uncertainty. *Nat. Energy* 8:736–46
83. Cole WJ, Greer D, Denholm P, Frazier AW, Machen S, et al. 2021. Quantifying the challenge of reaching a 100% renewable energy power system for the United States. *Joule* 5(7):1732–48
84. Phadke A, Aggarwal S, O'Boyle M, Gimon E, Abhyankar N. 2020. *Illustrative pathways to 100 percent zero carbon power by 2035 without increasing customer costs*. Fact Sheet, Energy Innov., San Francisco, CA
85. Energy Technol. Area. 2021. *Queued up: characteristics of power plants seeking transmission interconnection*. Rep./Data Set, Lawrence Berkeley Natl. Lab., Berkeley, CA. **https://emp.lbl.gov/queues**
86. Grid Deploy. Off., US Dep. Energy. 2023. *National Transmission Needs Study*. Rep., US Dep. Energy, Washington, DC. **https://www.energy.gov/sites/default/files/2023-12/National%20Transmission%20Needs%20Study%20-%20Final_2023.12.1.pdf**
87. Reed L, Dworkin M, Vaishnav P, Morgan MG. 2020. Expanding transmission capacity: examples of regulatory paths for five alternative strategies. *Electr. J.* 33(6):106770
88. Reed L, Morgan MG, Vaishnav P, Erian Armanios D. 2019. Converting existing transmission corridors to HVDC is an overlooked option for increasing transmission capacity. *PNAS* 116(28):13879–84
89. Chojkiewicz E, Paliwal U, Abhyankar N, Baker C, O'Connell R, et al. 2023. *Accelerating transmission expansion by using advanced conductors in existing right-of-way*. Work. Pap. 343, Energy Inst. Haas, Univ. Calif., Berkeley

90. Shen Z, Chen C, Zhou H, Fefferman N, Shrestha S. 2023. Community vulnerability is the key determinant of diverse energy burdens in the United States. *Energy Res. Soc. Sci.* 97:102949
91. Brown MA, Soni A, Lapsa MV, Southworth K, Cox M. 2020. High energy burden and low-income energy affordability: conclusions from a literature review. *Prog. Energy* 2:042003
92. Carley S, Evans TP, Konisky DM. 2018. Adaptation, culture, and the energy transition in American coal country. *Energy Res. Soc. Sci.* 37:133–39
93. Roemer KF, Haggerty JH. 2021. Coal communities and the U.S. energy transition: a policy corridors assessment. *Energy Policy* 151:112112
94. Vanatta M, Craig MT, Rathod B, Florez J, Bromley-Dulfano I, Smith D. 2022. The costs of replacing coal plant jobs with local instead of distant wind and solar jobs across the United States. *iScience* 25(8):104817
95. Young T, Baka J, He Z, Bhattacharyya S, Lei Z. 2023. Mining, loss, and despair: exploring energy transitions and opioid use in an Appalachian coal community. *Energy Res. Soc. Sci*. 99:103046
96. Cha JM, Pastor M, Moreno C, Phillips M. 2021. *Just transition/transition to justice: power, policy and possibilities*. Rep., Equity Res. Inst., Univ. South. Calif., Los Angeles
97. Newell P, Mulvaney D. 2013. The political economy of the 'just transition.' *Geogr. J.* 179(2):132–40
98. Caldecott B, Sartor O, Spencer T. 2017. *Lessons from previous 'coal transitions' high-level summary for decision-makers*. Rep., Inst. Sustain. Dev. Int. Relat., Paris
99. Sheldon P, Junankar R, Pontello de Rosa A. 2018. *The Ruhr or Appalachia? Deciding the future of Australia's coal power workers and communities*. Rep., Ind. Relat. Res. Cent., Univ. N. S. W. Bus. Sch., Sydney
100. Strambo C, Burton J, Atteridge A. 2019. *The end of coal? Planning a "just transition" in South Africa*. Rep., Stockholm Environ. Inst., Stockholm
101. Hirsch T, Matthess M, Füngfgelt F, eds. 2017. *Guiding principles & lessons learnt for a just energy transition in the Global South*. Study, Friedrich Ebert Found., Bonn, Ger.
102. Bullard RD. 2000. *Dumping in Dixie: Race, Class, and Environmental Quality*. London: Routledge
103. Faber DR, McCarthy D. 2012. Neo-liberalism, globalization and the struggle for ecological democracy: linking sustainability and environmental justice. In *Just Sustainabilities*, ed. RD Bullard, J Agyeman, B Evans, pp. 38–53. London: Routledge
104. Goforth T, Nock D. 2022. Air pollution disparities and equality assessments of US national decarbonization strategies. *Nat. Commun.* 13:7488
105. Pan S, Roy A, Choi Y, Sun S, Gao HO. 2019. The air quality and health impacts of projected long-haul truck and rail freight transportation in the United States in 2050. *Environ. Int.* 130:104922
106. Boehmer TK, Foster SL, Henry JR, Woghiren-Akinnifesi EL, Yip FY, 2013. Residential proximity to major highways—United States, 2010. *Morb. Mortal. Wkly. Rep. Suppl.* 62(3):46–50
107. Rogge KS, Reichardt K. 2016. Policy mixes for sustainability transitions: an extended concept and framework for analysis. *Res. Policy* 45(8):1620–35
108. Meckling J. 2021. Making industrial policy work for decarbonization. *Glob. Environ. Politics* 21(4):134–47
109. Hockett RC, Gunn-Wright R. 2019. *The Green New Deal: mobilizing for a just, prosperous, and sustainable economy*. Res. Pap. 19-09, Cornell Leg. Stud., Ithaca, NY
110. Krogstrup S, Oman W. 2019. *Macroeconomic and financial policies for climate change mitigation*. Work. Pap. 19-185, Int. Monet. Fund, Washington, DC
111. Goulder LH, Schein AR. 2013. Carbon taxes versus cap and trade: a critical review. *Clim. Change Econ.* 4(3):1350010
112. Stavins RN. 2008. Addressing climate change with a comprehensive US cap-and-trade system on JSTOR. *Oxford Rev. Econ. Policy* 24(2):298–321
113. He Y, Wang L, Wang J. 2012. Cap-and-trade versus carbon taxes: a quantitative comparison from a generation expansion planning perspective. *Comput. Ind. Eng.* 63(3):708–16
114. Biber E, Kelsey N, Meckling J. 2016. The political economy of decarbonization: a research agenda. *Brooklyn Law Rev*. 82(2):8
115. Bossie A, Mason JW. 2020. *The public role in economic transformation: lessons from World War II*. Work. Pap., Roosevelt Inst., New York
116. Foord D. 2020. Mobilization models for electric power grid decarbonization. *Acad. Manag. Annu. Meet. Proc.* 2020(1):21034

117. Chomsky N, Pollin R. 2020. *Climate Crisis and the Global Green New Deal: The Political Economy of Saving the Planet*. London: Verso
118. Victor PA. 2012. Growth, degrowth and climate change: a scenario analysis. *Ecol. Econ.* 84:206–12
119. Alier JM. 2009. Socially sustainable economic de-growth. *Dev. Change* 40(6):1099–119
120. Kallis G. 2011. In defence of degrowth. *Ecol. Econ*. 70(5):873–80
121. Kallis G, Kerschner C, Martinez-Alier J. 2012. The economics of degrowth. *Ecol. Econ.* 84:172–80
122. Hickel J. 2020. *Less Is More: How Degrowth Will Save the World*. New York: Random House
123. Roy J, Tschakert P, Waisman H. 2018. Sustainable development, poverty eradication and reducing inequalities. See Ref. 16, pp. 445–538
124. Popovich N, Plumer B. 2021. Who has the most historical responsibility for climate change? *New York Times*, Novemb. 12
125. Reed B. 2023. $700M pledged to loss and damage fund at COP28 covers less than 0.2% needed. *The Guardian*, Dec. 6
126. Lin J, Abhyankar N, He G, Liu X, Yin S. 2022. Large balancing areas and dispersed renewable investment enhance grid flexibility in a renewable-dominant power system in China. *iScience* 25(2):103749
127. Liu Z, Deng Z, He G, Wang H, Zhang X, et al. 2021. Challenges and opportunities for carbon neutrality in China. *Nat. Rev. Earth Environ.* 3(2):141–55
128. EEA (Eur. Environ. Agency). 2023. *EEA greenhouse gases—data viewer*. Data Vis., EEA, Copenhagen. **https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer**
129. IEA (Int. Energy Agency). 2020. Europe. *International Energy Agency.* **https://www.iea.org/regions/europe**
130. Abhyankar N, Mohanty P, Deorah S, Karali N, Paliwal U, et al. 2023. India's path towards energy independence and a clean future: harnessing India's renewable edge for cost-effective energy independence by 2047. *Electr. J.* 36(5):107273
131. IEA (Int. Energy Agency). 2022. Russia. *International Energy Agency.* **https://www.iea.org/countries/russia**
132. IEA (Int. Energy Agency). 2022. *Assessing the effects of economic recoveries on global energy demand and CO_2 emissions in 2021*. Rep., IEA, Paris. **https://iea.blob.core.windows.net/assets/d0031107-401d-4a2f-a48b-9eed19457335/GlobalEnergyReview2021.pdf**
133. Shiraishi K, Park WY, Abhyankar N, Paliwal U, Khanna N, et al. 2023. *The 2035 Japan report: Plummeting costs of solar, wind, and batteries can accelerate Japan's clean and independent electricity future*. Rep., Lawrence Berkeley Natl. Lab., Berkeley, CA