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REPORT

CLEAN ENERGY NOW FOR A SAFER CLIMATE FUTURE:

PATHWAYS TO NET ZERO IN THE UNITED STATES BY 2050

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ABBREVIATIONS AND ACRONYMS

AEO	Annual Energy Outlook
AIM	American Innovation and Manufacturing Act
ATB	Annual Technology Baseline
BECCS	Bioenergy with carbon capture and sequestration
CCS	Carbon capture and sequestration
CDR	Carbon dioxide removal
CES	Clean energy standards
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DAC	Direct air capture
DOI	U.S. Department of the Interior
EERS	Energy efficiency resource standards
EIA	U.S. Energy Information Administration
EJ	Exajoules
EPA	U.S. Environmental Protection Agency
EV	Electric vehicle
GDP	Gross domestic product
GHG	Greenhouse gas
Gt	Gigatons
GW	Gigawatt
HDV	Heavy-duty vehicle
HFC	Hydrofluorocarbon
H_2	Hydrogen
IIJA	Investment, Infrastructure, and Jobs Act
IPCC	Intergovernmental Panel on Climate Change
IRA	Inflation Reduction Act of 2022
ISO	Independent system operator
kWh	Kilowatt-hour
LDV	Light-duty vehicle
MMT	Million metric tons
NDC	Nationally determined contribution
NEMS	National Energy Modeling System
NERC	North American Electric Reliability Corporation
NOx	Nitrogen oxides
NREL	National Renewable Energy Laboratory
N_2O	Nitrous oxide
PM	Particulate matter
RD&D	Research, development, and demonstration
ReEDS	Regional Energy Deployment System Model
RIO	Regional Investment and Operations Platform
RPS	Renewable portfolio standards
RTO	Regional transmission organization
SMR	Small modular reactor
TWh	Terawatt-hour
USDA	U.S. Department of Agriculture
VMT	Vehicle-miles traveled

EXECUTIVE SUMMARY

To align with global efforts to limit warming to 1.5 degrees Celsius, the United States faces the monumental yet achievable task of cutting greenhouse gas (GHG) emissions to net zero no later than 2050. Even with last year's historic climate legislation, the Inflation Reduction Act, the country is not on track to reach its climate goals. Doing so will require critical choices about how and where to invest economic, political, and social capital in the coming decades.

Modeling by NRDC (Natural Resources Defense Council) and Evolved Energy Research (Evolved) offers guidance on how to prioritize these choices by estimating the technology, infrastructure, and cost requirements of different pathways to net zero.

This report finds that by deploying five crucial decarbonization strategies—clean power, energy efficiency, electrification, natural carbon solutions, and decarbonized fuels—achieving net zero GHG emissions in the United States can be technologically feasible and cost effective. NRDC's first four decarbonization strategies capture the highest priority actions for getting the United States on track to net zero within this crucial decade.

They also offer dramatic economic benefits: An average of about $9 billion a year in net energy system cost savings over the next three decades compared to a business-as-usual scenario. By 2050, those benefits increase to $35 billion a year, due to avoided expenses on fossil fuel infrastructure and the fuels themselves.

Furthermore, energy system savings represent only a fraction of the economic benefits of the clean energy transition. A net zero economy—built equitably and conscientiously—will deliver new, high-quality jobs, reduce health-harming air pollution, and mitigate the profound social, financial, and environmental costs of further climate warming.

By contrast, delaying climate progress comes at significant costs. Pathways where the United States stalls or fails to implement some of these first four strategies, and instead relies on more expensive technologies to "catch up" on emissions reductions down the road, ring up much higher cumulative costs.

When electrification progress is delayed until the mid-2030s, for example, total energy system spending is almost $1.3 trillion higher over the next three decades than in NRDC's core decarbonization scenario.

This report joins growing literature around net zero pathway analyses conducted by academic, government, and private institutions. By comparing tradeoffs between scenarios, NRDC's analysis offers a strategic lens for policymakers, providing recommendations and key milestones to inform critical policy and investment decisions. While other studies have already highlighted the role of clean power, electrification, and decarbonized fuels in reaching net zero, NRDC's analysis finds that two other well-demonstrated, but often overlooked, strategies can provide dramatic climate and economic benefits: Expanding energy efficiency and natural carbon sequestration as emissions-reducing resources.

Key Takeaways

NRDC and Evolved modeled least-cost pathways to achieving net zero emissions under varying technology and policy conditions. The analysis compared a "core" decarbonization scenario with a business-as-usual scenario, as well as four sensitivity scenarios: where electrification is delayed; where renewable development is constrained; where the land sink does not expand; and where fossil fuels are fully eliminated.

Each sensitivity scenario adjusts variables within one or more of the five decarbonization strategies to capture the impact of failure, delay, or uncertainty in their implementation. Comparing these pathways revealed:

The power sector represents the most impactful lever in the U.S. climate solutions toolbox. Transitioning to carbon-free electricity is the country's largest and most cost-effective opportunity to cut carbon pollution in this decade. It is also essential to unlocking the decarbonization of other sectors. As more vehicles, buildings and appliances switch from fossil fuels to electricity, they will only be as clean as the grid powering them. All modeled pathways to net zero by 2050 require a rapid shift to clean electricity, with the electricity grid relying on at least 80 percent zero-carbon resources by 2030 and nearly 100 percent by 2040.

Expanding this carbon-free grid will require a profound acceleration in renewable and transmission buildout. NRDC's core scenario sees over 1,000 GW of renewable capacity built by 2030—**about four times the pace of the past two years**. Interregional transmission capacity also doubles, then triples, then quadruples from today's levels in each subsequent decade leading to 2050. This translates to an annual growth rate of 9 percent in this decade, well beyond the historical 2 percent annual growth rate since 1978.

Energy efficiency must be paired with electrification to "right size" this buildout and minimize the transition costs of decarbonization. By pairing electrification with ambitious energy efficiency investments, the United States can avoid the unnecessary expense of overbuilding new physical energy infrastructure and ultimately reduce the costs passed on to American households. Among other measures, by 2030, all new buildings should have net zero building codes and all new appliances should adhere to high-efficiency standards. All new appliances and most new light-duty vehicles should be electric by 2030, and all new vehicles should be zero-emissions by 2040.

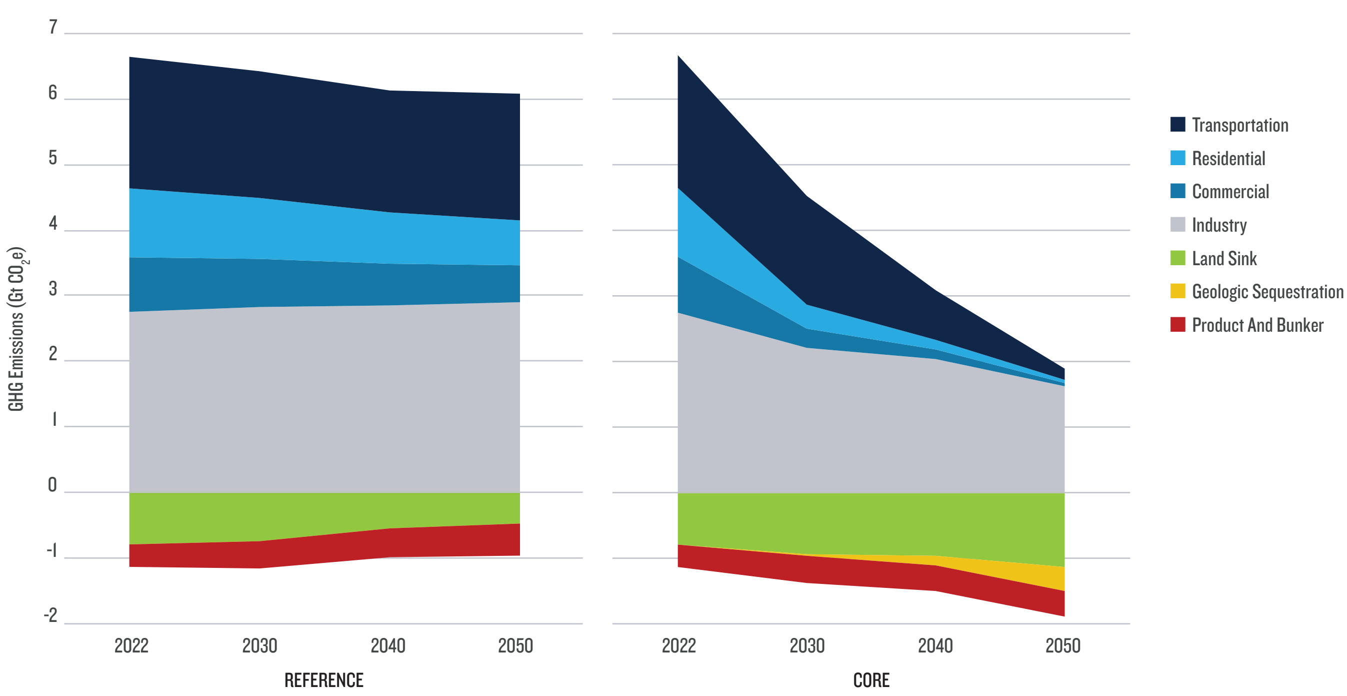
American forests, wetlands, and farmlands will play a critical role in naturally sequestering carbon and can reduce future reliance on more expensive carbon dioxide removal technologies. Under a business-as-usual scenario, the land sink is expected to decrease due to deforestation, development, and climate impacts. Preventing further decrease from today's levels, and instead expanding the land sink, will be essential to balancing any emissions remaining in the system in 2050, especially non-carbon dioxide emissions from agriculture and industry. Investments in reforestation, afforestation, and native ecosystem restoration should continue to expand the natural land sink through 2050.

Decarbonized fuels—such as electrolytic hydrogen, electrofuels, biofuels, and traditional fuels used with carbon capture—can provide targeted climate solutions for the hardest-to-abate end uses in the economy. The United States should invest in research, development, and demonstration for emerging decarbonized fuel technologies while recognizing that they are not a panacea. Decarbonized fuels should be used neither as a replacement for other decarbonization strategies nor for perpetuating reliance on fossil fuels. NRDC's sensitivity scenarios show that while decarbonized fuels have an important role to play, their widespread deployment at the expense of other decarbonization strategies represents more expensive and riskier pathways to net zero.

U.S. leaders must capitalize on the momentum of the Inflation Reduction Act and pursue today's highest-priority emissions reduction opportunities. In the near-term, federal policymakers must enact strong standards for power plants, vehicles, and appliances alongside robust protections of U.S. lands and freshwater to get the country on track to a net zero future. The sooner the United States reduces emissions from these sources, the cheaper and more predictable the clean energy transition will be.

These pathways all point to one clear finding: **This decade must see a profound transformation of the ways by which the United States produces and uses energy**. The longer the United States waits to make transformational climate progress, the fewer pathways remain viable and the more expensive the remaining pathways become. The window of opportunity to limit warming to 1.5 °C is rapidly closing, and immediate action is critical to ensuring a safe climate for us all.

Figure ES1: GHG Emissions by Sector, 2022 to 2050



I. INTRODUCTION

To align with global efforts to limit warming to 1.5 degrees Celsius, the United States faces the monumental, yet achievable, task of cutting greenhouse gas (GHG) emissions to net zero by 2050 or earlier. NRDC (Natural Resources Defense Council) partnered with Evolved Energy Research to model and compare pathways that achieve net zero by 2050 under different policy and technology conditions. The modeling aimed to estimate the technology and infrastructure requirements, social implications, and costs of the transition to a decarbonized economy.[1] This report uses the results of this modeling to identify the policy gaps, research and development priorities, and key milestones over the next three decades required to build the decarbonized, clean energy system of tomorrow.

WHAT IS "NET ZERO"?

The term "net zero" refers to a state of the global system in which greenhouse gases (GHGs) are either no longer released into the atmosphere (e.g., from the energy system, industrial processes, and working lands) or are otherwise removed from the atmosphere in equal measure through additional carbon sinks (e.g., sequestration in forests, soil, the ocean, or geological formations). The Intergovernmental Panel on Climate Change (IPCC) recommends that the world reach net zero GHG emissions by 2050 or earlier to limit increases in global average temperatures to 1.5 °C above preindustrial levels, a recommendation supported by the Paris Agreement as adopted by the U.N. Framework Convention on Climate Change in 2015.[2]

Reaching—and staying at—net zero will require the United States to drastically reduce GHG emissions from the tailpipes and smokestacks of its energy system. Then, any emissions still produced by the system must be balanced equally by durable and measurable carbon removal. If removed carbon reenters the atmosphere—for example, due to deforestation or improper artificial carbon storage—the system will no longer be at net zero.

Climate change is caused by the accumulation of GHGs in the atmosphere. Every year that the United States emits more GHG pollution than is removed by carbon sinks (i.e., every year that emissions are above net zero) contributes to incremental warming. While this report focuses on the long-term 2050 target, it is crucial to reduce net GHG emissions as quickly as possible to minimize overall warming.

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THE U.S. ROAD TO NET ZERO

The United States is the largest historical emitter of carbon pollution in the world, responsible for 20 percent of all CO_2 pollution released since 1850.[3] In the last 15 years, the country has made slow but meaningful progress in reducing its carbon footprint by shifting toward cleaner, renewable resources and more efficient technologies. However, it is still the world's second largest polluter, ranking behind only China.[4] Through their own industrialization, the United States and developed economies have played an outsize role in contributing to the climate crisis. Thus, they have the greatest obligation to repair and prevent climate harms. Furthermore, as a global leader, the United States has a unique responsibility to champion climate progress on the world stage and support developing economies working to achieve their own climate targets.

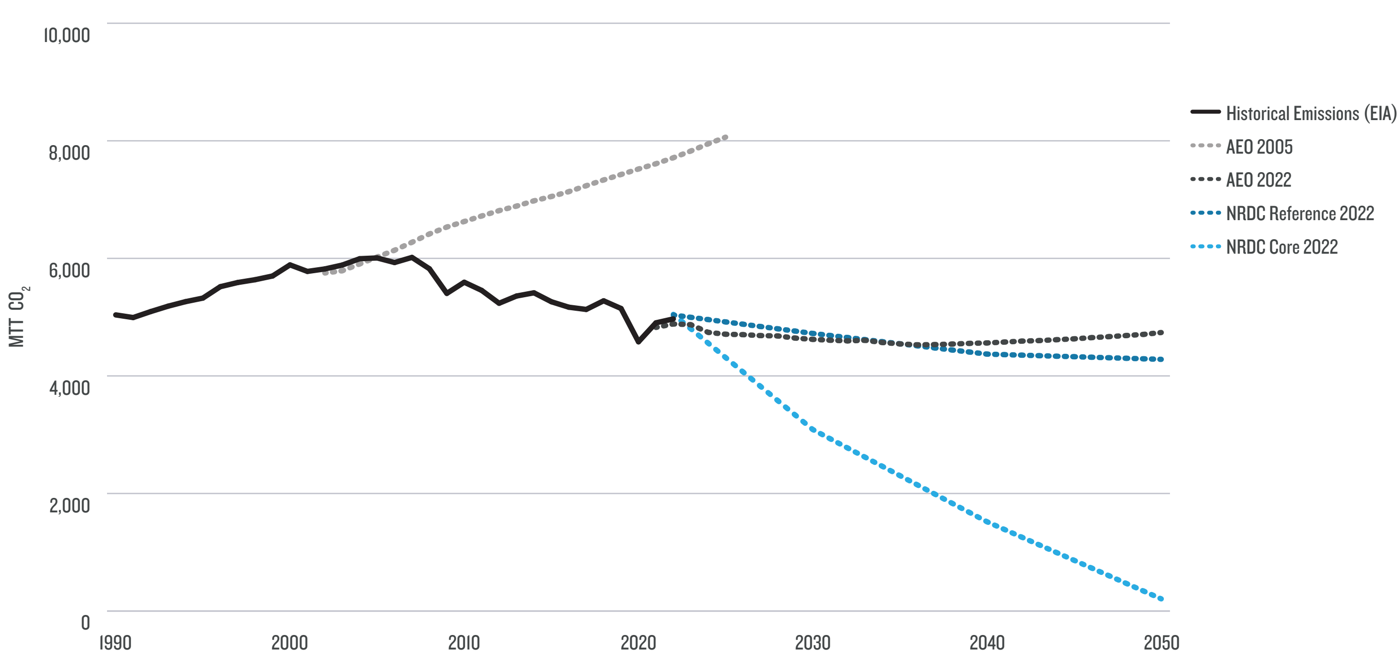
The United States has committed to following through on these responsibilities. As part of rejoining the Paris Agreement, the federal government established a target of reducing economy-wide GHG emissions by 50 to 52 percent by 2030, relative to 2005, as its nationally determined contribution (NDC).[5] This trajectory would put the country on track to reach net zero GHG emissions by 2050, a key contribution to limiting the global average temperature increase to 1.5 °C above preindustrial levels.[6]

Carbon emissions in the United States, as measured by the Energy Information Administration (EIA), have shown modest declines since their peak in 2007 (Figure 1). Both NRDC's Reference case and EIA's Annual Energy Outlook (AEO) predict that U.S. emissions, along their current trajectory, will level off over the next three decades. These projections show that, without further policy intervention, the United States is still far from achieving its NDC of 50 to 52 percent emissions reductions relative to 2005 levels, a target achieved by NRDC's Core modeling scenario.

While the United States has made progress toward reducing its climate footprint, the country must pursue steep and rapid emissions reductions across all sectors to reach net zero by 2050. U.S. leaders took a tremendous step toward this goal with the passage of the Inflation Reduction Act (IRA) of 2022 and the Investment, Infrastructure, and Jobs Act (IIJA) of 2021.[7] Together, these two pieces of federal legislation represent the most ambitious federal climate action in U.S. history. The legislation provides hundreds of billions of dollars to support the deployment of clean energy technologies, the expansion of the electric grid and charging infrastructure, the strengthening of the domestic clean energy supply chain and manufacturing, and funding for emerging technologies that can help address remaining challenges to full decarbonization. Analysis suggests that these federal investments will support the United States in cutting annual GHG emissions by up to 40 percent by 2030 relative to 2005 levels (details on the impact of the IRA can be found on page 32).[8]

While this progress is worth celebrating, it alone is not enough. **The United States is not yet on track to reach either the nation's commitment to halve GHG emissions by 2030 or to reach net zero emissions by 2050**. Successful implementation of these federal laws, coupled with new and updated federal regulations, state and local action, and utility reforms will be necessary to get the country on track to a net zero future.

Figure 1: Carbon Dioxide Emissions Trajectories of the U.S. (1990–2050)



WHAT IS GOOD FOR THE CLIMATE IS GOOD FOR AMERICANS

Climate change is not merely an environmental crisis. It also threatens public health, national security, and economic prosperity. Climate destabilization poses profound risks to the world's agricultural system and food supply. Sea level rise and natural disasters are already forcing millions of people around the world to flee their homes.[9] More intense and frequent extreme weather events—such as floods, droughts, and heat waves—threaten Americans' health, safety, and property. Studies estimate that the cost of climate change over the next 50 years could top $14.5 trillion *in the U.S. alone,* should society fail to keep warming below 1.5 °C.[10] The expense of climate change—both in monetary value and in human life—will far outweigh the modest costs of transitioning to a decarbonized energy system as projected by the modeling in this report.

By decarbonizing its energy system, the United States can avoid these damages, all while bolstering the domestic clean energy economy, securing energy independence, and saving lives threatened by health-harming air pollution.

CO-BENEFITS OF DECARBONIZATION

- **Decarbonization can protect Americans' wallets.** Energy decarbonization is not at odds with economic growth. Thanks to the falling costs of low-carbon technologies (e.g., wind and solar power) and the ever-improving efficiencies of vehicles and buildings, the carbon- and energy intensity of the U.S. economy has decreased even while U.S. gross domestic product has continued to grow.[11] These trends benefit American consumers; in 2021, average household spending on energy utilities (as a percentage of income) was less than half of what households were spending 40 years ago.[12] Moreover, investments in clean and efficient energy can help protect households from the price volatility that often afflicts the natural gas and oil markets.[13]
- **Decarbonization can lead to American energy independence.** Building out a domestic clean energy supply chain will reduce American dependence on foreign fuels, a vulnerability made salient by the European energy crisis following the Russian invasion of Ukraine. The only way to permanently protect Americans from the volatility of the global oil market—and soaring gas prices—is to reduce U.S. dependence on fossil fuels by transitioning to domestic clean energy sources and electrifying the economy.[14]
- **Decarbonization can improve Americans' health.** Fossil fuels not only contribute to a warming world, but also produce a myriad of other air and water pollution problems that impact the health of communities.[15] Exposure to the particulate matter and ozone-forming pollution, such as nitrogen oxides (NOx), caused by burning fossil fuels is known to cause premature death and is associated with chronic respiratory diseases such as asthma.[16] In 2018 alone, fossil fuel–related air pollution was responsible for the premature deaths of an estimated 350,000 Americans and 8.7 million people globally.[17] In the United States, these air pollutants are responsible for billions of dollars a year in public health costs stemming from emergency room visits, hospital admissions, lost work and school days, heart attacks, and premature deaths. Fossil fuel-related air pollution also has a disproportionate impact on low-income communities and communities of color.[18] Transitioning to zero-emissions energy resources will reduce the health-harming pollution produced by fossil fuel use, creating healthier and more livable communities for all.

II. MODELING PATHWAYS TO NET ZERO

NRDC modeled and compared a set of scenarios, or "pathways," in which the U.S. energy system succeeds in reducing its GHG emissions to net zero by 2050. This analysis (1) validates that existing clean energy technologies can cost-effectively achieve U.S. climate targets, (2) identifies where policy interventions are needed to keep the United States on track to reach these goals, and (3) underscores the implications of, and tradeoffs among, selected pathways. By comparing resource needs across scenarios, this report investigates questions such as: *What types of energy infrastructure will be needed, and at what scale? What are the consequences if clean energy progress stalls any longer? What are the environmental and economic impacts of the various pathways?*

FIVE STRATEGIES FOR EFFICIENT AND COST-EFFECTIVE DECARBONIZATION

NRDC's pathways efficiently and cost-effectively achieve net zero through five key decarbonization strategies: (1) clean power, (2) energy efficiency, (3) electrification, (4) natural carbon solutions, and (5) decarbonized fuels. NRDC's foundational decarbonization pathway depends on an aggressive, near-term deployment of strategies 1–4 and a measured, later-term deployment of strategy 5. As will be discussed further, each sensitivity scenario is the result of adjusting variables within one or more strategies to capture the impact of failure, delay, or uncertainty in implementing these five strategies over the next three decades.

1. **Clean Power:** Decarbonize the electricity grid by switching from fossil fuels to renewable and zero-carbon electricity resources, like wind, solar, and energy storage. Eliminating emissions from the power sector is key to the success of other decarbonization strategies given their reliance on direct electrification (e.g., transitioning from gasoline to electric vehicles [EVs]) or indirect electrification (e.g., creating renewable-powered, electrolytic hydrogen for use as a fossil fuel alternative).[a]

2. **Energy Efficiency:** Minimize energy waste and maximize cost savings by transitioning to higher-efficiency equipment, appliances, and vehicles; constructing new buildings from highly efficient materials; and retrofitting existing buildings to be more energy efficient. By maximizing energy efficiency measures first, the United States can "right-size" its energy systems and avoid additional costs from overbuilding energy infrastructure.

3. **Electrification:** Transition fossil-powered end uses, like gasoline cars and gas heaters, to electricity to reduce pollution and take advantage of an increasingly renewable-powered grid.

4. **Natural Carbon Solutions:** Protect and expand the land sink. These solutions include safeguarding the nation's carbon-critical mature and old-growth forests, recovering lost forests (especially lost old growth) via reforestation, protecting and restoring wetlands, and implementing sustainable agricultural practices to enhance soil carbon sequestration.

5. **Decarbonized Fuels:** Replace fossil fuel use in the remaining, hardest-to-electrify applications using verifiably carbon-neutral and carbon-negative fuels (e.g., electrolytic hydrogen, electrofuels, and biofuels), with the proper air pollution controls where appropriate. Use technological carbon dioxide removal technologies (including direct air capture and on-site carbon capture) to address remaining carbon pollution in the system (e.g., process emissions from cement production). Captured carbon can be used to produce carbon-neutral electrofuels.[b]

a This is otherwise known as "green" hydrogen.

b Electrofuels are synthetic, carbon-neutral hydrocarbons produced from electrolytic hydrogen and captured carbon.

The first four strategies—***clean power, energy efficiency, electrification, and natural carbon solutions***—represent the nearest-term opportunities for the United States to reduce climate-warming emissions. They have been proven time and time again to be the most cost-effective, efficient, and feasible solutions for reducing carbon pollution.[19] The most cost-effective net zero pathway modeled in this report depends on their immediate deployment. Given that dramatic GHG emissions reductions are needed within this decisive decade before 2030 to keep alive the hope of limiting warming to 1.5 °C, these strategies reflect the country's highest-priority solutions for getting on track to net zero.

Should the United States fail to deploy these first four strategies at scale, it will miss critical no-regrets opportunities to cost-effectively cut carbon pollution today. Without these early emissions reductions, the country will then need to rely on more expensive, earlier-stage, and riskier technologies to deliver very steep emissions reductions in future decades. If even those last-resort solutions fail to materialize at scale, a net zero future will very likely remain out of reach.

The last strategy—**decarbonized fuels**—provides more distant and targeted solutions that can address decarbonization challenges in the hardest-to-abate end uses in the economy (e.g., aviation, shipping, and energy-intensive industries), where direct electrification is cost-prohibitive or not technologically feasible. Decarbonized fuels include electrolytic hydrogen, electrofuels (which involve the use of with direct air capture), biofuels, and traditional fuels with carbon capture. Many of these technologies are not yet commercially viable and thus typically do not see much deployment in NRDC's modeling until the late 2030s and 2040s, with the next decade serving to support innovation and progress on these early-stage technologies.[c]

While this strategy can have an important function in the future clean energy system, the cost- and resource-intensive nature of these technologies means that they should be reserved only for applications where decarbonization via the first four strategies is not feasible. However, if action stalls during this decade—that is, if clean electricity, energy efficiency, electrification, and natural carbon solutions are not implemented quickly enough—the modeling finds that the U.S. energy system will likely have to rely more on these expensive strategies to address the emissions locked in by near-term business-as-usual. This more indiscriminate deployment of technological carbon dioxide removal, carbon capture, and carbon-neutral fuels will involve much higher system costs and, without proper technological and accounting guardrails, greater risks of climate failure.[20]

Decarbonized fuels are not without their own suite of health and ecological risks, and thus should not be used as a mechanism for indiscriminately justifying continued petrochemical use. In particular, NRDC does not support the use of decarbonized fuels to further the production of plastics and hazardous chemicals.

The five strategies identified in this analysis underpin the decarbonization of the U.S. energy system and will be necessary to secure a better climate future. They are, by design, high level and far-reaching. This report's modeling of technologies and policy mechanisms is not an exhaustive demonstration of how these strategies might be implemented. For example, energy efficiency can also be implemented outside of the scope of direct energy policy. Urban planning measures can reduce vehicle demand by promoting dense, mixed-use development. Policies that limit the production of plastics can reduce demand for, and thus the production of, fossil-derived and synthetic hydrocarbon feedstocks. Moreover, these strategies are not limited to governments and utilities. Corporations can transform their business models to drive down the overconsumption of carbon-intensive products. Individuals can accelerate the adoption of clean energy solutions by purchasing electric appliances and vehicles and upgrading the efficiency of their homes. This modeling proposes but one potential suite of solutions as benchmarks for where the United States should direct its attention and investments moving forward.

a. Scenario Design and Assumptions

NRDC's analysis used Evolved Energy Research's EnergyPATHWAYS model and Regional Investment and Operations Platform (RIO) to model least-cost solutions to achieving net zero emissions under varying policy and technology conditions.[21,d] These conditions adjust assumptions about the pace and availability of the strategies discussed above, capturing both demand- and supply-side energy resource impacts across scenarios. While the scenarios below follow different paths to net zero, they all rely on a profound transformation of the ways by which the United States produces and uses energy over the next decade. The window of opportunity to limit warming to 1.5 °C is rapidly narrowing, and immediate action is critical to the viability of any of the pathways examined below.

This analysis considers a reference scenario, a "Core" decarbonization scenario, and four sensitivity scenarios. Under the reference scenario, the United States does not attempt to meet any national emissions targets and instead follows a business-as-usual trajectory based on existing policies and best-available data on macroeconomic trends and technology costs. The Core decarbonization scenario is built from NRDC's foundational assumptions about the deployment potentials of the five decarbonization strategies based on a review of publicly available government research, other academic studies, and the success of state climate

c For the purposes of this report, "decarbonized fuels" is used as a catch-all term to refer to both carbon-neutral and carbon- negative fuels.

d Details about the EnergyPATHWAYS and RIO models can be found in Appendix B.

policies in leading states. The Core scenario, as well as the four sensitivity scenarios that branch from it, all meet projected U.S. energy demands while achieving a 53 percent reduction in GHG emissions by 2030 (relative to 2005 levels) and producing net zero emissions by 2050.[e]

The four sensitivity scenarios branch from the Core scenario by altering certain technological, economic, or policy assumptions related to one or more of the five strategies. For example, the Delayed Action case adjusts assumptions about the pace of electrification adoption. By comparing the decarbonization scenarios to the Reference scenario, this analysis identifies potential technology, infrastructure, and policy gaps between the current trajectory and a net zero future for the United States. The sensitivities then allow an assessment of trade-offs between different decarbonization pathways.

The scenarios and their assumptions are listed in table 1. This list is not exhaustive and represents only a subset of potential technological pathways; other analyses have identified additional pathways to achieving net zero emissions in the United States beyond those modeled here.[22] The sensitivity scenarios were chosen following a review of other net zero studies and input from NRDC experts; they are designed to highlight the complementary and competing dynamics among the five decarbonization strategies. No pathway is presented as ideal or best, and it is likely that the actual decarbonization pathway traced by the country will look different from any of these individual scenarios.

The scenarios all converge on one resounding finding: **This decade is crucial for making climate progress.** The longer the United States waits to make transformational climate progress, the fewer pathways remain viable, and the more expensive the remaining pathways become.

TABLE 1. SUMMARY OF SCENARIO DESCRIPTIONS
Full details of NRDC's modeling assumptions can be found in Appendix A.

Scenario	Purpose	Description
Reference (Business-as-Usual)	To understand the current U.S. trajectory absent further policy intervention beyond May 2022. Provides a shared baseline with which all other scenarios can be compared.	Assumes only national and state clean energy and emissions policies in place as of May 2022.[23] This case represents a business-as-usual projection of the incumbent energy system based on macroeconomic and expected technology cost and performance trends up to 2050.
Core	To provide a central, controlled decarbonization case from which all other scenarios can be built.	Constrained to net zero economy-wide GHG emissions by 2050 and a 53 percent reduction in GHG emissions (relative to 2005 levels) by 2030. Assumes aggressive but feasible electrification of end uses and energy efficiency improvements across the transportation, buildings, and industrial sectors. Power generation and remaining liquid fuel mix is optimized to achieve the GHG emissions constraints at the least cost possible. Land sink grows by about 70 percent, to −1,240 MMT CO_2 by 2050.
Delayed Action	To understand the consequences of stalled progress on the electrification of buildings, industry, and transportation.	Same assumptions as the Core scenario, except for a 15-year delay on all electrification rates (e.g., slower adoption of EVs and slower conversion to electric appliances for heating).
No Fossil Fuels	To understand the feasibility and impacts of a 100 percent fossil-free system by 2050 for both energy and nonenergy (e.g., feedstock) uses.	Same assumptions as the Core scenario, except all fossil fuel production and use (both energy and nonenergy) are barred by 2050.
Constrained Renewables	To understand the effects of limited or stalled renewable development, such as due to siting, permitting, or other interconnection challenges.	Same assumptions as the Core scenario, except annual solar and wind capacity builds are each constrained to 30 percent above their historical maximums.[24]
Low Land Sink	To understand the consequences of a smaller natural land sink than assumed in the Core case, due to uncertainty around carbon stock factors. These factors include climate impacts, development patterns (e.g., continued deforestation), and changes to forest and soil health.	Same assumptions as the Core scenario, except total land sink potential by 2050 is constrained to 850 MMT, as compared with 1,240 MMT in the Core case.
High Hydrogen[f]	To understand the infrastructure implications of a broader, less targeted deployment of hydrogen as a fuel than is considered in the Core scenario.	Assumes higher sales shares of hydrogen-fueled vehicles and building appliances than in the Core scenario. This scenario was based on an earlier Core case iteration, designed in 2021.

e All decarbonization scenarios exceed the U.S. climate target of achieving a 50–52 percent reduction in U.S. GHG emissions (relative to 2005 levels) by 2030.

f The High Hydrogen scenario was conducted on an earlier version of EnergyPATHWAYS. While it provides useful insights relevant to this report, NRDC does not include an apples-to-apples comparison with the other scenarios given differences between the EnergyPATHWAYS model versions used. The key findings of this run were discussed in "The Hidden Costs of Untargeted Hydrogen Deployment" on NRDC's Expert Blog, available at https://www.nrdc.org/experts/jacqueline-ennis/hidden-costs-untargeted-hydrogen-deployment.

b. Calculating the U.S. Carbon Budget

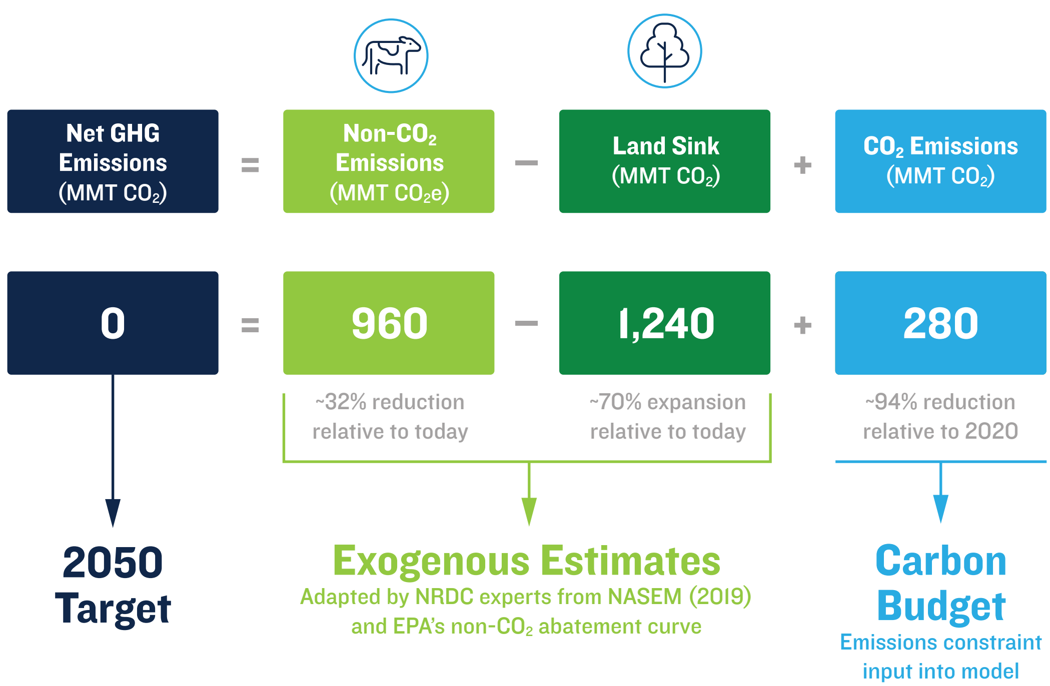
As previously discussed, "net zero" refers to a state of the global system in which GHGs are either no longer released into the atmosphere (e.g., from energy systems, industrial processes, and working lands) or otherwise removed from the atmosphere in equal measure through additional carbon sinks (e.g., carbon sequestered in forests, soil, the ocean, or geological formations). Limiting U.S. GHG emissions to net zero will require both drastic reductions in carbon pollution from smokestacks, tailpipes, buildings, and industrial facilities, and the long-term sequestration of CO_2 from the atmosphere and into sinks—particularly through protection and enhancement of the natural land sink.

The model required NRDC to calculate how much CO_2 the energy system will be able to "afford" to emit in 2050, based on how much carbon will be removed from the atmosphere at that time. Beyond emissions from the energy system, this number—the country's 2050 carbon budget—depends on other factors affecting the balance of GHG emissions in the atmospheric system. These include:

1. **Non-CO_2 emissions.** There are many greenhouse gases other than carbon dioxide, including methane (CH_4) and nitrous oxide (N_2O) from agriculture and oil and gas production, hydrofluorocarbons (HFCs) from refrigerants, and other fluorinated gases from industrial processes. These non-CO_2 emissions, which amount to about 20 percent of the country's GHG footprint, often have much higher warming potentials than CO_2, meaning that they generate a greater atmospheric warming effect per ton emitted.[25] Given the potency of these emissions, eliminating them in the near term can have an outsize impact on mitigating climate change. NRDC's experts estimate that, based on the U.S. Environmental Protection Agency's (EPA) non-CO_2 abatement curve and NRDC analysis of the agricultural sector, non-CO_2 emissions will decrease to around 960 million metric tons (MMT) CO_2e—around a 30 percent reduction relative to today's levels—by 2050.[26] Solutions to address these types of emissions have limited representation in this modeling, but they are equally important to reduce via policy measures and technological innovation.
2. **Natural carbon stocks.** Carbon is sequestered in soils, oceans, and biomass such as trees and algae. Using research from the National Academies of Science, Engineering and Medicine, NRDC estimated that these natural carbon stocks—collectively referred to as the "land sink"—could be affordably expanded by 500 MMT CO_2, or about 70 percent above today's levels, by 2050, amounting to a carbon sink of 1,240 MMT CO_2.[27] Because there is uncertainty around current quantifications of future land sink potential, NRDC's scenarios include a Low Land Sink sensitivity using the estimate of 850 MMT CO_2 used by Princeton University's *Net-Zero America* study.[28]

With these estimates, NRDC worked backwards to calculate the carbon budget for a given year (Figure 2). For example, in 2050 the model meets the net zero criteria by constraining the system to 280 MMT CO_2 by 2050, **or a 94 percent reduction from 2020 levels,**[29] in all decarbonization scenarios except the Low Land Sink (which has a budget of –70 MMT).

Figure 2: Calculating the Carbon Budget for Net Zero by 2050



C. Limitations and Scope of This Analysis

Given that EnergyPATHWAYS and RIO are energy system models, this report focuses on decarbonization solutions related to energy use. GHG emissions from outside the energy sector—including non-CO_2 emissions (e.g., methane and nitrous oxide) from sources such as agriculture, livestock, waste, industry, soil, and land management—were taken into account when developing the carbon budget constraint for the decarbonization scenarios (Figure 2). However, solutions designed specifically to address these nonenergy emissions have limited representation in the modeling. Thus, the solutions discussed in this analysis are not comprehensive; there is a broad portfolio of climate solutions outside the energy sector (and scope of this report) worth studying and implementing. These include, but are not limited to, policies that constrain the production of plastics, reduce vehicle-miles traveled (VMT) by supporting transit and bike infrastructure, and promote the use of sustainable building materials.

Additionally, the scenarios considered in this analysis are based on macroeconomic projections that approximate where the United States appears to be heading given current signals, trends, and available data. These business-as-usual assumptions do not reflect all NRDC priorities and positions, or what NRDC would consider ideal pathways. For example, NRDC is working toward the fundamental reform of the petrochemicals and plastics sector beyond decarbonization, acknowledging the need for the industry to halt its profound harms to people and the environment, which extend beyond GHG emissions.[30] NRDC is also working to ensure that the critical minerals used for new clean energy infrastructure are supplied via sustainable, circular, and safe practices. Even if they align with the net zero target, the growth trajectories of harmful and extractive industries need to be constrained beyond the scenarios modeled in this analysis to protect human and ecosystem health.

Achieving global net zero GHG emissions by 2050 is essential to limiting global warming to 1.5 °C by the end of this century. That said, while decarbonization is the focus of this report, carbon reduction should not be the sole metric by which climate and clean energy policies are measured. The energy system of the future should optimize for improved public health outcomes, conservation of biodiversity, and racial and socioeconomic equity both domestically and abroad. Solutions should be evaluated both on their ability to reduce carbon emissions and on their capacity to reduce the social and ecological harms of the current, fossil fuel–based energy system; the United States should be wary of merely replacing one set of harms with another. As discussed in the "Policy Implications" section of this report (page 32), decarbonization policies *can* support significant public health, equity, and economic benefits, but these benefits are not guaranteed without the right policy and technological guardrails. PSE Healthy Energy found that "decarbonization policies that fail to account for equity may result in prolonged exposure to health-harming pollutants and even increase energy and transportation costs for communities that are already disproportionately impacted by the current fossil fuel system."[31] The transition to net zero is needed to protect human life, economic prosperity, and ecological well-being and is an opportunity to design a healthier, more equitable, and more sustainable future for all.

III. KEY FINDINGS AND POLICY TAKEAWAYS OF NRDC'S MODELING

Strategy 1. Clean Power

Clean power is the key to rapid decarbonization.

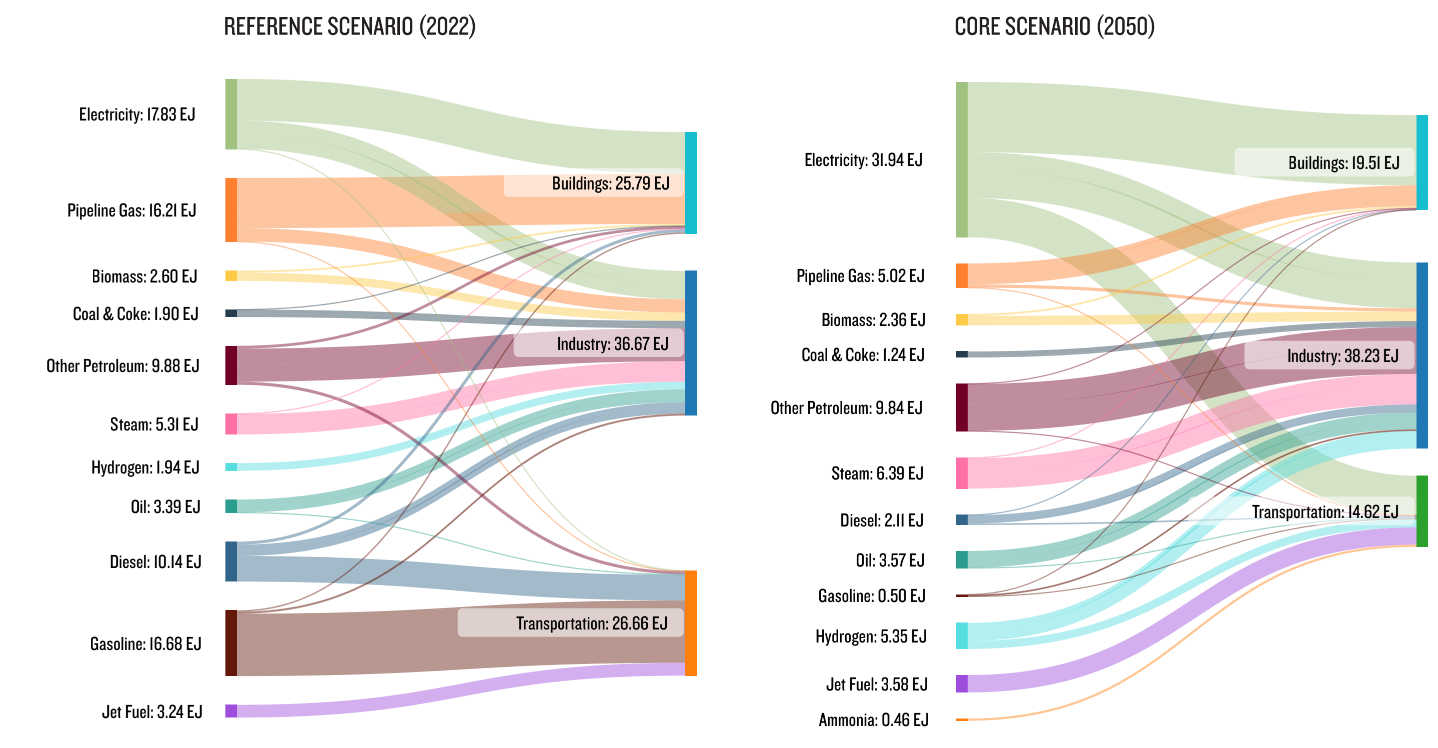
The power sector represents the most impactful lever in the U.S. climate solutions toolbox. Transitioning to carbon-free electricity is the country's largest and most cost-effective opportunity to cut carbon pollution in this decade. It is also an essential building block for the decarbonization of the other sectors: As more vehicles and buildings switch from fossil fuels to electricity, they will only be as clean as the grid powering them. Meeting these newly electrified loads while also transitioning away from coal and gas power plants will require an aggressive and sustained build-out of new clean power resources—as well as investments in transmission and grid services—over the next three decades. In parallel, reforms to existing utility and market structures can bolster the reliability, resiliency, and flexibility of the power grid as it transitions, expands, and modernizes.

1a) Model Finding: If electrification targets are met, electricity will become the primary energy carrier of the U.S. energy system.

Policy Takeaway: Cleaning up the grid should remain a top-line priority for near-term decarbonization policies.

When electrification targets are met under the Core scenario, electricity becomes the primary energy source of the United States, delivering almost 32 exajoules (EJ) across all economic sectors by 2050 (Figure 3). This demonstrates the importance of eliminating GHG emissions from the power sector as quickly as possible, so that carbon-free electricity can reduce emissions from other sectors as they electrify.

Figure 3: Fuel Use by Economic Sector: Reference (2022) and Core (2050) Scenarios



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1b) Model Finding: Wind and solar proliferation is the cheapest way to quickly decarbonize the electricity grid.

Policy Takeaway: Policies and reforms should responsibly enable the acceleration of wind and solar development.

All decarbonization scenarios modeled involve a steep ramp-up in zero-carbon generation from the 40 percent of the electricity mix that wind, solar, hydro, and nuclear power provide today. Across all net zero scenarios, renewable generation grows from around 20 percent today to 70–74 percent by 2030 and to 84–95 percent by 2050. By the end of this decade, the Core scenario achieves 86 percent zero-carbon electricity; by 2050 this share reaches 98 percent (Figure 4). In comparison, the Reference scenario reaches 54 percent zero-carbon by 2030 and 78 percent by 2050.

The energy system model selects the most cost-effective resource supply mix that can meet U.S. energy demand as well as the carbon emissions constraints. Across all decarbonization scenarios, wind and solar proliferate, dominating grid capacity within the next decade (Figure 5). Wind and solar are already the cheapest sources of new electricity today.[32] They also have shorter construction times than new carbon capture or nuclear plants.[33] These factors render wind and solar the most cost-effective solutions for replacing emitting resources and decarbonizing the grid as quickly as possible.

In the Core scenario, 573 gigawatts (GW) of wind and 472 GW of solar are installed by 2030, translating to an average build rate of about 100 GW of renewable capacity every year over the next decade (Figure 6). This implies an unprecedented acceleration in renewable deployment—about four times the pace of the past two years.[34] At the time of writing, the annual U. S. solar installation record was 15.5 GW and the wind installation record was 17.1 GW of wind, both set in 2021.[35] This gap—between today's pace of development and the accelerated pace necessary to transition to a net zero grid—highlights the need for a transformation of the U.S. renewable development process. Achieving this projected scale of build-out will involve larger investments in new projects. It will require resolutions to the permitting and siting challenges delaying renewable development today.[36] Finally, it will necessitate updates to utility planning, transmission planning, interconnection processes, and wholesale electricity markets to better support the widespread integration of new renewables. These reforms should also reflect the updated resilience and reliability needs of a highly renewable grid.

Figure 4: Annual Electricity Generation

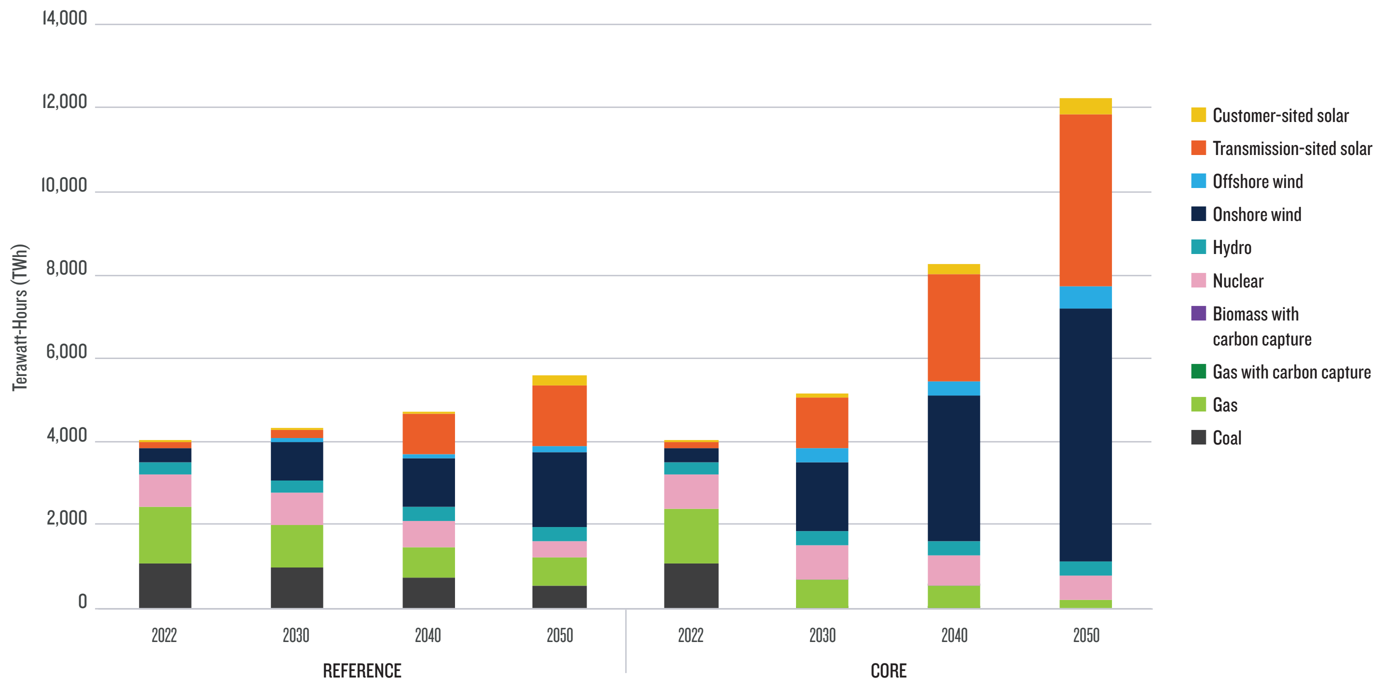


Figure 5: Electricity Capacity

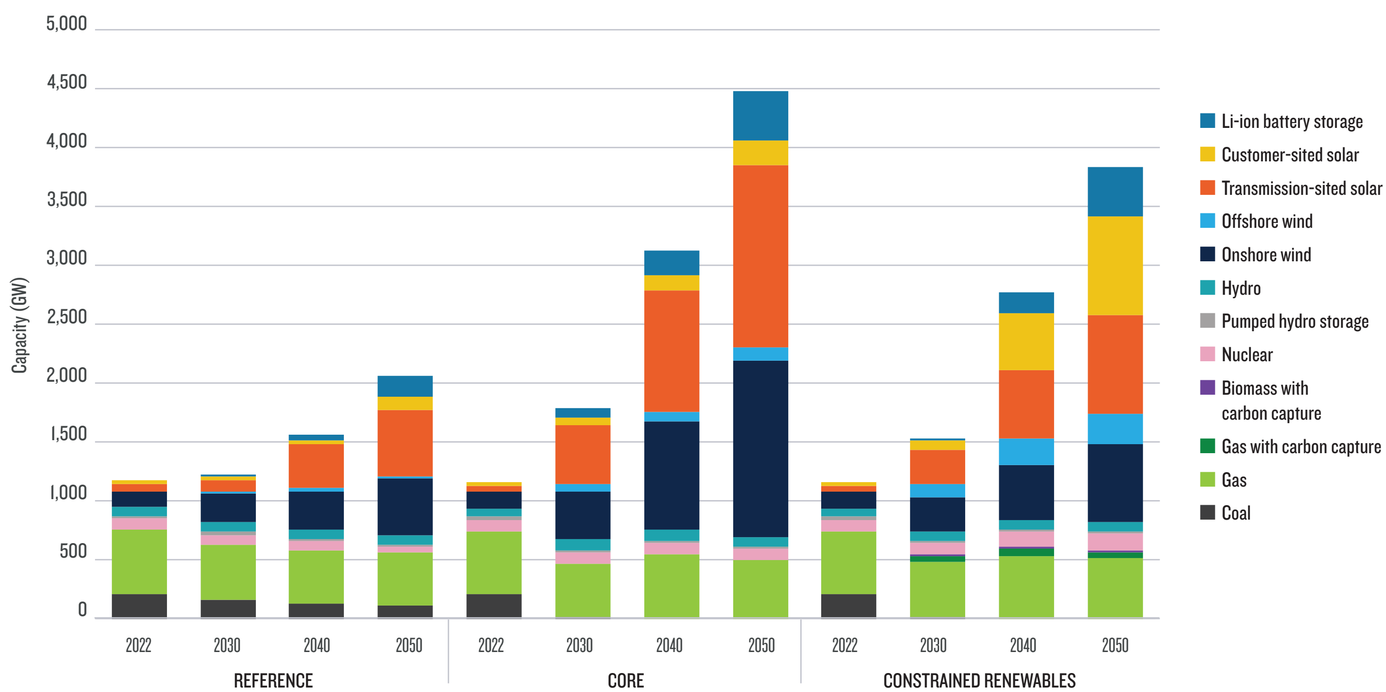
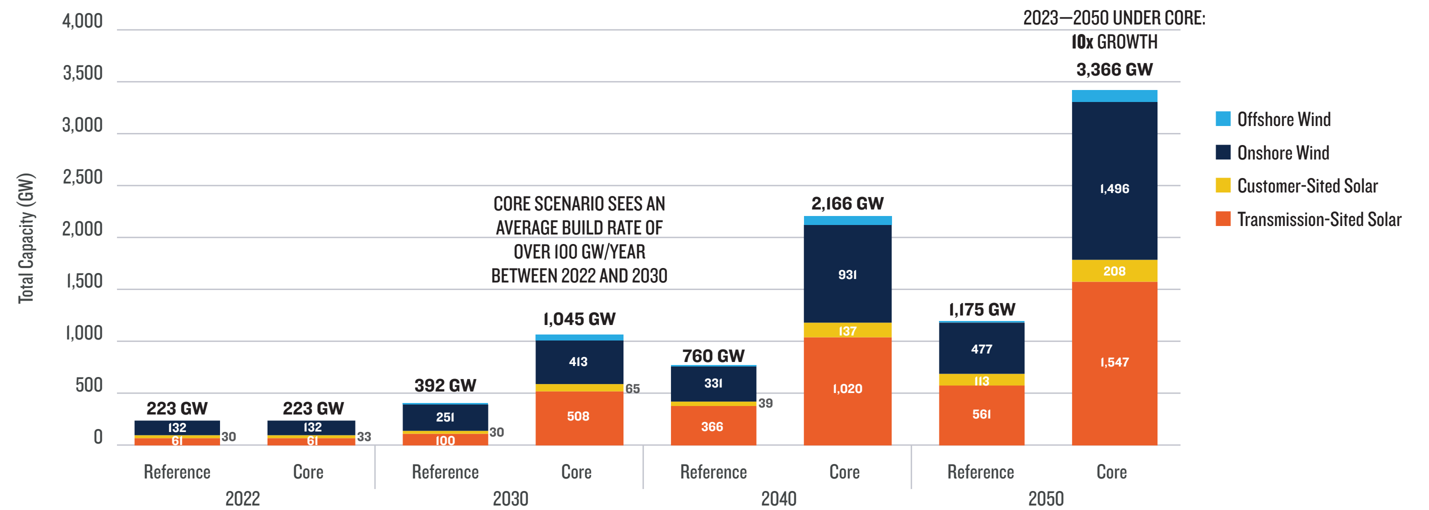


Figure 6: Wind and Solar Capacity



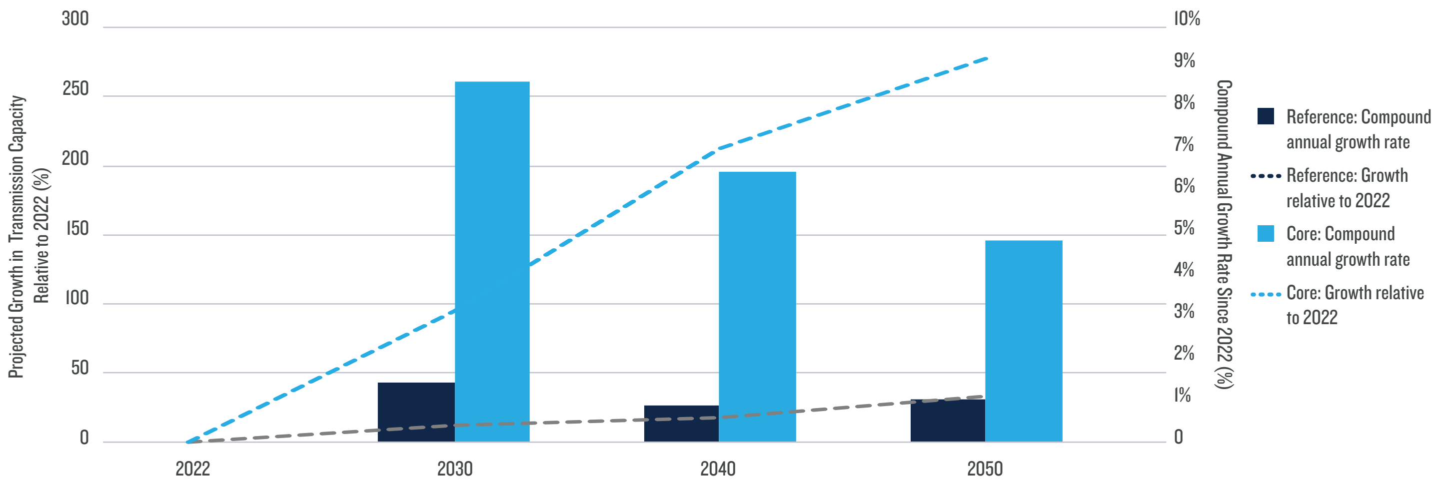
Should the pace of renewable development fail to accelerate—as in the Constrained Renewables scenario—the grid will need to deploy more expensive alternatives to meet electricity demand. When utility-scale solar and wind are restricted to only about 30 percent above their present build-out rates, the model turns to more expensive zero- and low-carbon alternatives, including rooftop solar (which is more expensive to the system on a per kilowatt-hour [kWh] basis), nuclear small modular reactors, and gas equipped with carbon capture and sequestration (CCS) to make up for the loss. Constrained renewable development has implications outside the power sector as well, as limiting the supply of cheap electricity makes both direct and indirect electrification more expensive. Without an abundance of low-cost, zero-carbon renewable electricity, the model builds less production capacity for electrolytic hydrogen and electrofuels. This leads to a much more limited and expensive supply of electrically derived fuels suitable for decarbonizing heavy industry. In the face of this limited supply, the Constrained Renewables scenario relies more on traditional fossil fuels and CCS for those applications compared to the Core case. In total, the Constrained Renewables case incurs system costs that are $25 billion more in 2050 than those of the Core scenario.

1c) Model Finding: To support transition to a carbon-free electricity grid, the interregional transmission and distribution network must expand rapidly.

Policy Takeaway: Policies and reforms should prioritize the acceleration of interregional transmission development.

The electric transmission system must expand substantially over the next three decades to keep pace with the build-out of renewable resources required for a net zero grid. In the Core scenario, interregional transmission (i.e., transmission between different balancing authorities) capacity doubles, then triples, then quadruples from today's levels in each subsequent decade leading to 2050 (Figure 7). This translates to an annual growth rate in transmission capacity of 9 percent in this decade, well beyond the historical 2 percent annual growth rate since 1978.[37] Without policy intervention, this transmission expansion will not happen: Transmission capacity is expected to grow less than 35 percent by 2050 under the Reference scenario. Sufficient transmission infrastructure is essential to achieving a decarbonized system; Evolved Energy Research's *Annual Decarbonization Perspective 2022* found that "the failure to allow sufficient new transmission to be built would likely put net zero by mid-century out of reach."[38]

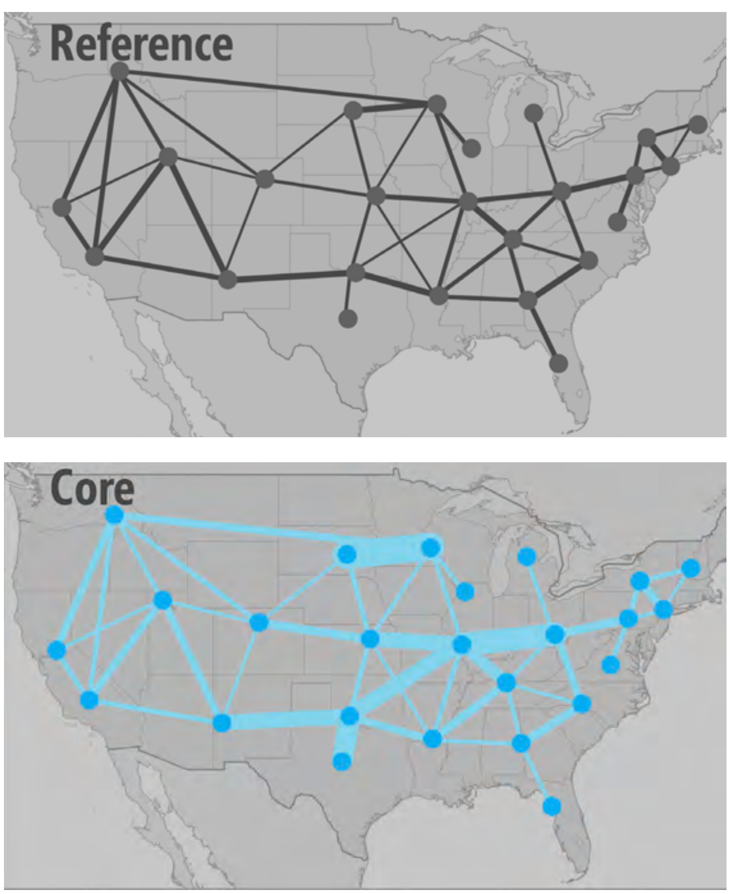
Figure 7: Growth in Interregional Transmission Capacity Relative to Today (2022)



The model builds the bulk of this new transmission capacity between areas of high renewable resource potential. In the Core scenario, the largest interconnections by 2050 occur across the Midwest and Texas (Figure 8).

Figure 8: Projected Interregional Transmission Expansion by 2050

Line thickness indicates relative capacity expansion.



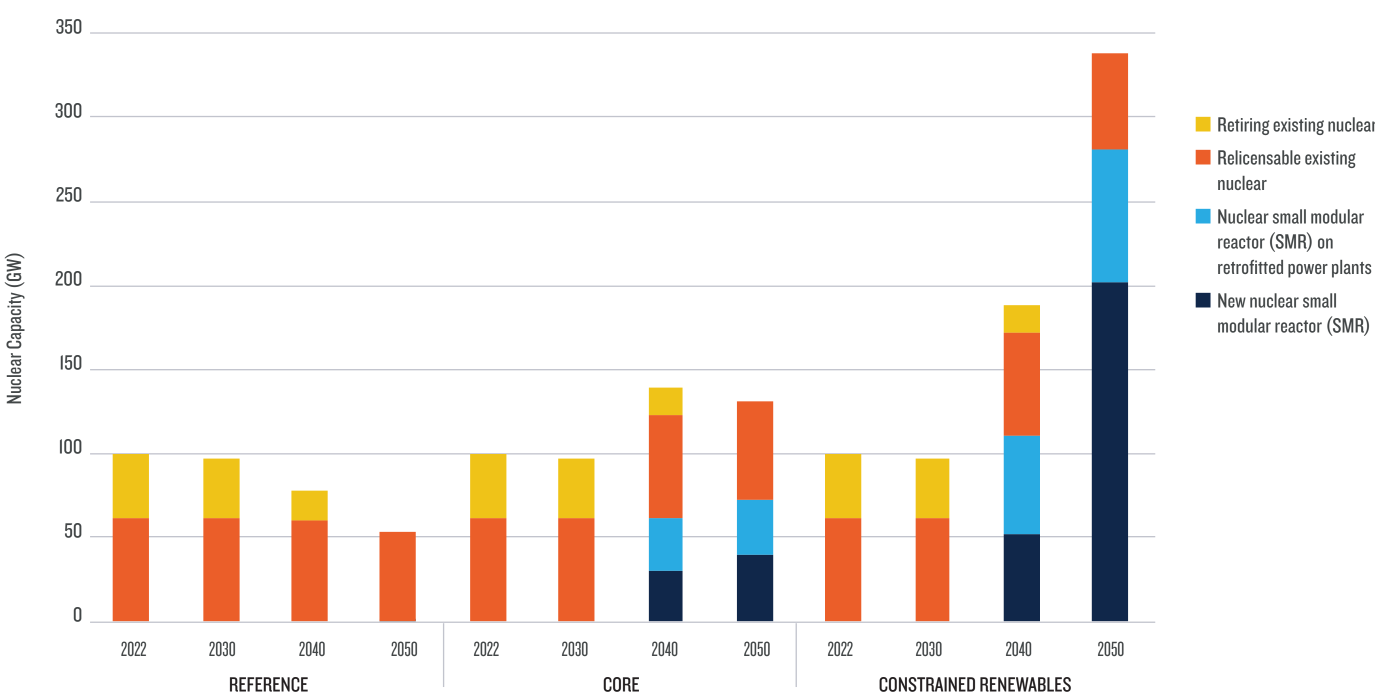
1d) Model Finding: The decarbonization pathways retain nuclear capacity where possible but build no new traditional nuclear plants; instead they build new small modular reactors, but only in later decades.

Policy Takeaway: The future role of nuclear power will depend in part on technological innovation.

Under the decarbonization pathways, the model retains a portion of the nuclear fleet, relicensing eligible plants to allow them to operate for up to 80 years.[g] It also builds new small modular reactor plants in the later decades, although nuclear capacity never exceeds 2 to 4 percent of system capacity across all decarbonization scenarios. Nuclear power is modeled as a dispatchable, firm zero-carbon resource that can provide baseload power, flexibility, and load-following services to an increasingly renewable grid (Figure 9). These characteristics allow nuclear plants to take advantage of select economic opportunities in a decarbonized system: repurposing existing energy sites, meeting new electricity demand from new applications (e.g., electrolytic hydrogen production and direct air capture), and providing temporal flexibility (e.g., allowing thermal energy storage of produced heat).[39] The Constrained Renewables scenario shows increased nuclear deployment when cheaper zero-carbon resources are restricted. However, the modeling assumes that cost reductions can be achieved as a result of projected research and development activity in the coming years. Thus, these outcomes are contingent on the success of nuclear technology innovations beyond today's prototype stages.

Specifically, the model deploys a new reactor design known as a small modular reactor, or SMR. These designs are currently under development, though none are commercially operating today. Proponents of SMRs claim that the technology can safely deliver electricity generation at competitive costs through modularization, which involves smaller plant sizes than traditional nuclear power plants.[40] However, this strategy of modularization faces challenges in licensing and regulation, societal acceptance, supply chain complexities, and factory infrastructure costs. Actual deployment of SMRs will be a function of their cost and commercial viability as the technology develops over the coming decades, as well as their competitiveness relative to other solutions (like long-duration battery storage) that may emerge to fill similar grid services. This competitiveness may continue to be influenced by concerns currently associated with nuclear power, which include reactor safety, nuclear waste, and nuclear weapons proliferation.[41]

Figure 9: Nuclear Capacity



g NRDC allows around half of the existing nuclear fleet to relicense to 80 years, based on a review of each nuclear plant's safety record, its design and safety measures, nearby populations, and other safety risk factors.

1e) Model Finding: Existing gas capacity is kept online for emergency reliability, but by 2050 turbines are rarely fired.

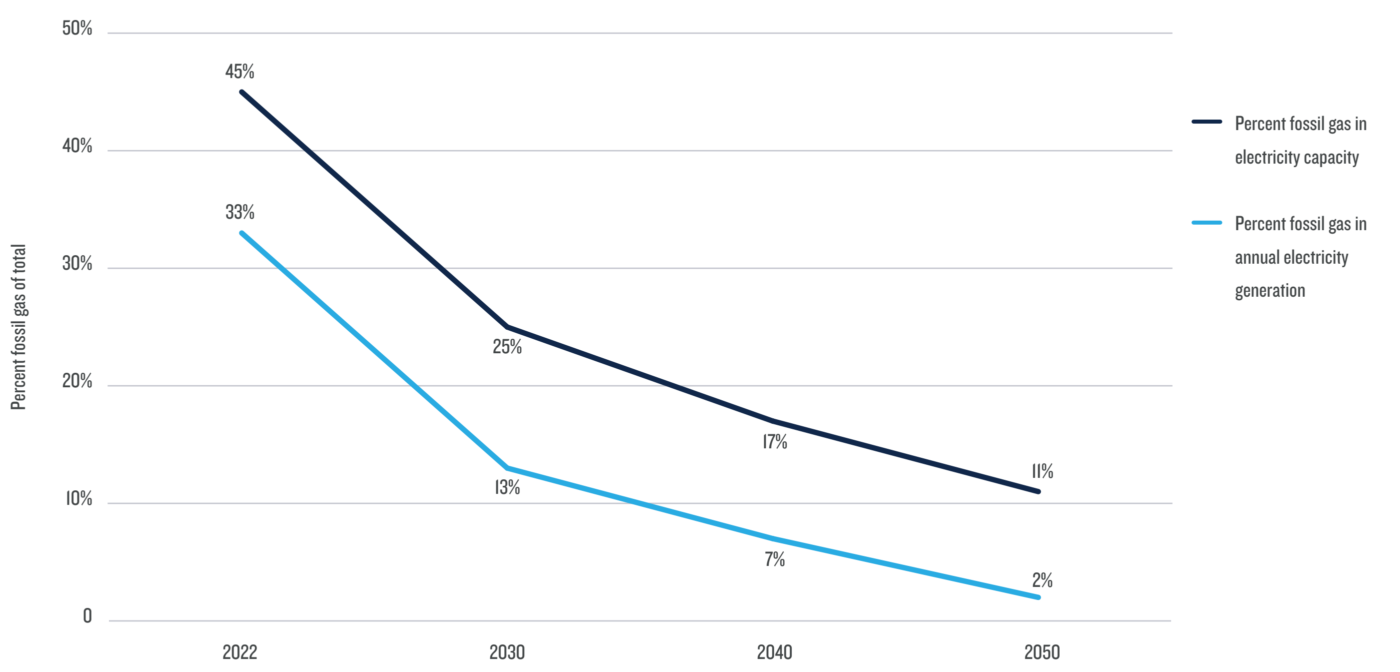
Policy Takeaway: Flexible, long-duration resources will be needed to fulfill the reliability requirements of a highly renewable grid.

As the electric grid becomes highly decarbonized, the model retains existing gas capacity to provide both capacity reserves and ancillary services (e.g., ramping and load-following). While existing gas turbines remain online for these express reliability purposes, these turbines run very infrequently, providing less than 2 percent of electricity generation in the Core scenario in 2050 (Figure 10).[42] Given the limitations of current mainstream battery technologies, which limit most grid-scale batteries to 4–10 hours of power output, the transitioning grid will continue to need a flexible, dispatchable energy resource that can be deployed over infrequent but extreme multiday reliability events with high load and low renewable output (e.g., during a winter storm). That said, there may be other long-duration, dispatchable technologies beyond fossil gas—such as long-duration storage, hydrogen turbines, or SMRs—that could rise to play this role in the future.

The model retains most existing gas capacity, though these turbines provide a very small share of electricity generation in the later decades.

Meeting the same reliability requirements without a long-duration, dispatchable resource would require a much larger swath of additional renewable build-out and incur additional system costs. This finding is consistent with recent literature: For example, a study from the National Renewable Energy Laboratory (NREL) found that the United States can approach 100 percent renewable generation cost-effectively but that transitioning the final few percent of the mix drives up a disproportionate increase in total system costs.[43]

Figure 10: Role of Fossil Gas in Providing Capacity and Generation



Strategy 2. Energy Efficiency

Energy efficiency can alleviate the costs and pressures of increasing electricity demand.

Energy efficiency allows products to deliver the same services while using less energy. Efficiency measures—such as leveraging efficient designs, technologies, and materials—can drive down the energy footprint of buildings, vehicles, and industry without compromising services, performance, or production. In this way, energy efficiency presents a cleaner, cheaper, and faster way to reduce emissions from a system than building even greater levels of new renewable and clean power generating capacity.[44]

2a) Model Finding: Final energy demand decreases across all decarbonization scenarios, even as electricity demand increases.

Policy Takeaway: Electrification should be paired with ambitious energy efficiency investments to mitigate the costs and challenges of building new electricity infrastructure.

NRDC's decarbonization scenarios assume an ambitious yet technologically feasible deployment of energy efficiency across the economy. This includes increasing sales of new high-efficiency appliances to 100 percent by 2030, transitioning to ultra-efficient building codes for new construction by 2030, retrofitting 80 percent of existing buildings by 2050, and investing in sustained efficiency measures in the industrial and aviation sectors. These measures are key mechanisms for managing load growth as buildings look to electrify.

Despite increased electricity demand due to electrification, actual energy demand per capita in the United States decreases under NRDC's decarbonization pathways, whereas energy demand per capita is predicted to increase under the Reference case. Due to energy efficiency measures and the inherent efficiency gains of electrification relative to combustion, the final energy demand in 2050 is lower across all decarbonization scenarios than in the Reference scenario. By reducing avoidable energy waste, energy efficiency can minimize the transition costs of decarbonization. It will empower the United States to "right-size" its new clean energy system, thus avoiding the unnecessary costs of overbuilding new physical energy infrastructure and ultimately reducing the costs passed on to American households.

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Strategy 3. Electrification

Electrification increases electricity load, expanding the role of the electricity system in a net zero future.

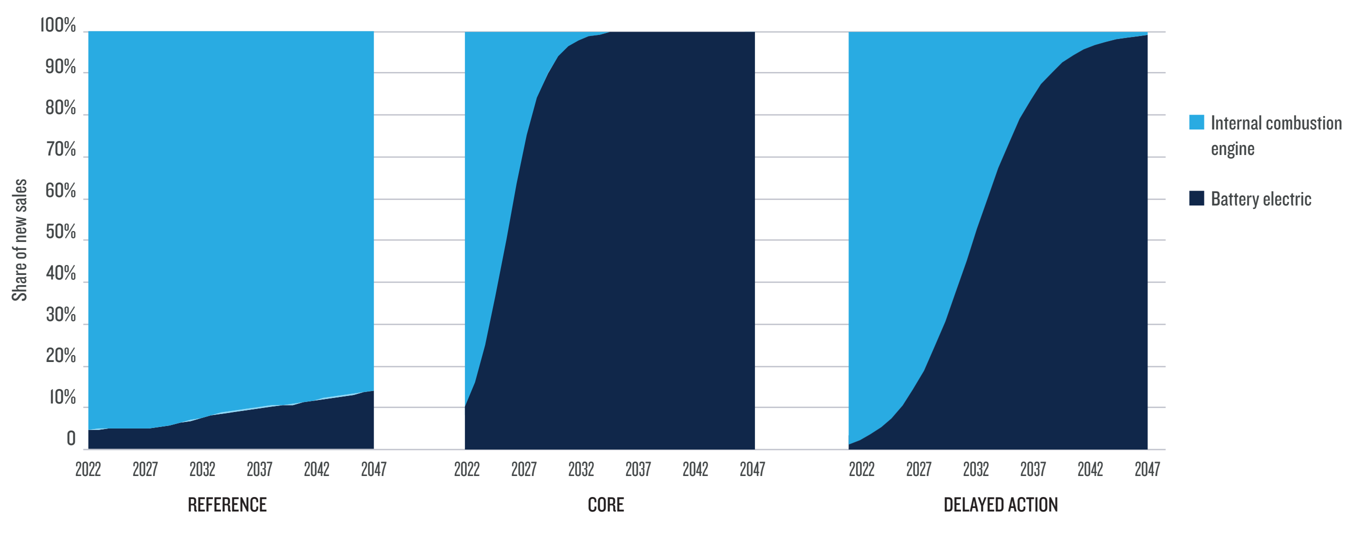
Electrification represents a paradigm shift away from the fossil fuel–dominated system of today and toward a future in which clean electricity is the dominant source for the nation's energy needs. Electrification would allow households, businesses, and industry to replace many fossil-powered end uses, such as vehicles, stoves, space heaters, and water heaters, to more efficient, electric versions. For most applications, such as light-duty passenger vehicles and residential appliances, electrification is often the best decarbonization option available.[45] Electric heat pumps, vehicles, and induction cookers are inherently more efficient than their fossil fuel–powered alternatives, and when plugged into a clean grid, they can meet energy needs with very low greenhouse gas emissions. Electrification solutions—especially when paired with energy efficiency improvements, affordability programs, and smart electric rate design—can reduce energy consumption and lower household energy burdens.[46] In addition, electrification can capitalize on low-cost, zero-emitting renewables as they are added onto the grid, offering a cost-effective option for eliminating fossil fuels—and the air pollution associated with fuel combustion—from the transportation, buildings, and industrial sectors.

3a) Model Finding: The Delayed Action scenario incurs the highest cumulative financial costs of any scenario.

Policy Takeaway: By failing to "build clean first" and locking in near-term emissions, stalled progress on economy-wide electrification policies will significantly increase the financial costs of transitioning to net zero.

NRDC's decarbonization pathways assume that the electrification of certain transportation, buildings, and industrial end uses is a core mechanism for reducing emissions. Specifically, the Core scenario relies on the wide-scale adoption of EVs (Figure 11) and highly efficient electric appliances. NRDC considered consumer preferences and technical challenges to electrification when developing these assumptions, relying on expert experience and existing literature to inform the adoption rates for electrified end uses across each sector (see Appendix A for details).

Figure 11: Light-Duty Zero-Emission Vehicle Sales



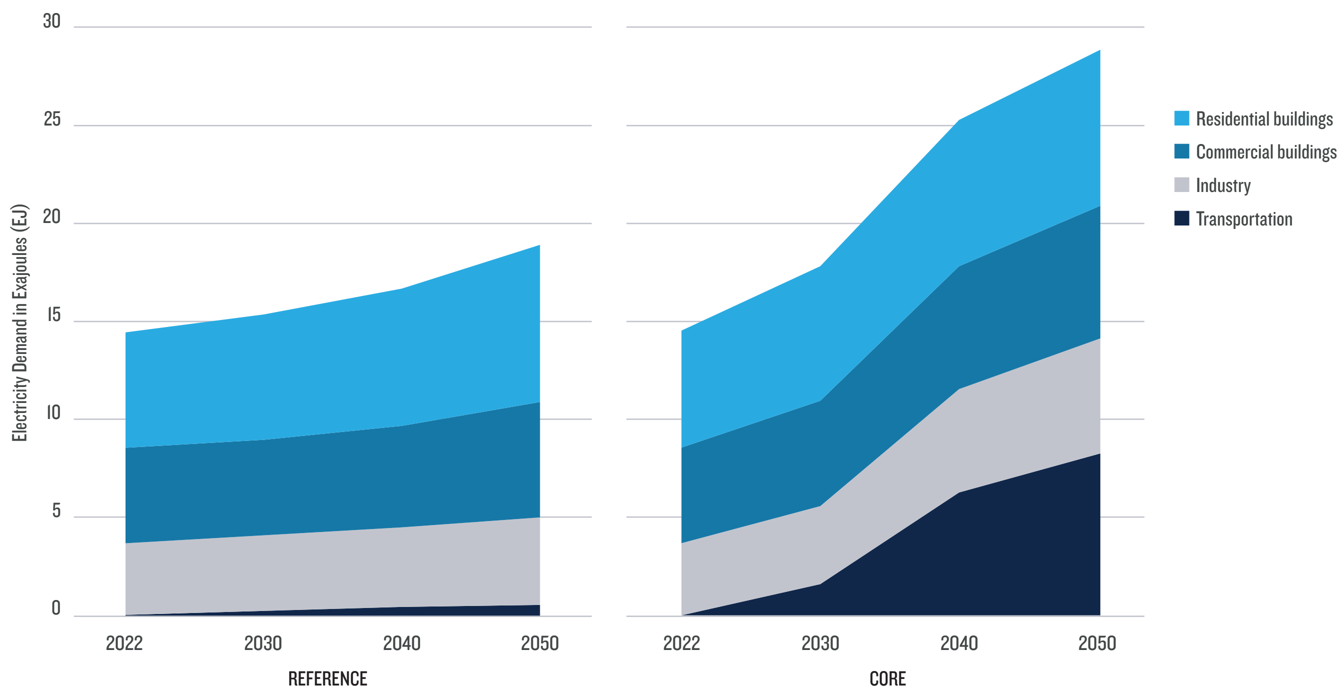
NRDC's Core scenario assumes that sales of new light-duty vehicles transition to 100 percent battery EV by 2035. The Core scenario assumes that sales for medium- and heavy-duty vehicles split between battery electric and hydrogen fuel cells, depending on the class and use of the vehicle. The Delayed Action scenario assumes these transitions happen 15 years later.

As the assumed electrification targets are met, the energy system rapidly transitions away from carbon-intensive fossil fuels and toward clean electricity as its main energy source. As a result, system-wide electricity demand increases two (Core scenario) to four times (No Fossil Fuels scenario) from today's levels by 2050 (Figure 12). These increases in load are driven primarily by light-duty (LDV) electric vehicle adoption and the production of electrolytic hydrogen (i.e., green hydrogen) to indirectly electrify certain areas of industry and freight transportation. Concurrently, energy efficiency improvements in buildings fully mitigate the load increases that would otherwise be associated with the electrification of that sector.

Electricity load under the Core scenario doubles between 2022 and 2050, driven by electrification in the transportation and industrial sectors. Electricity load under the Reference scenario is also projected to increase, but to a lesser extent.

The Delayed Action scenario assumes a 15-year delay on all electrification rates implemented in the Core scenario, including the rates of transitioning to EVs and to electric appliances. This delay causes the country to miss opportunities for reducing emissions in the near term, locking-in a wedge of emissions from fossil-powered vehicles and buildings in the 2030s. As a result, the Delayed Action scenario relies heavily on direct air capture to catch up and hastily reduce emissions in the last decade to reach net zero emissions by 2050. As a result of missing early opportunities to "build clean first" using cheaper electrification technologies, the Delayed Action scenario incurs the highest cumulative system costs of all scenarios by 2050.

Figure 12: Electricity Demand by End Use



Strategy 4. Natural Carbon Solutions

Enhancing the natural land sink mitigates reliance on riskier technological carbon dioxide removal.

Once sources of emissions are avoided or reduced to the maximum extent possible, achieving a state of net zero emissions will require netting out any remaining GHG emissions—whether from the energy system, industrial processes, or agriculture—by removing an equal amount of carbon from the atmosphere (this amount is accounted as "negative emissions"). Carbon can be removed from the atmosphere through two main mechanisms: the natural land sink and direct air capture.

1. **Natural land sink:** Soils, the ocean, and all organic materials such as trees, algae, and moss store carbon in natural carbon stocks. In a healthy ecosystem, carbon is sequestered via natural processes, such as when plants absorb carbon through photosynthesis and store it as biomass.
2. **Direct air capture (DAC):** Technology is used to remove carbon directly from the air. This carbon is then either permanently sequestered in deep geologic formations (and thus counted as negative emissions) or reused to create synthetic hydrocarbon fuels (and thus counted as carbon neutral).

Stored carbon—from either removal mechanism—can be counted as negative emissions only if the storage is long-term. Otherwise, the carbon will reenter the atmosphere as climate-warming emissions and the system will not truly be at net zero.

4a) Model Finding: A lower land sink estimate results in a higher deployment of technological carbon dioxide removal to meet negative emissions needs.

Policy Takeaway: Prioritizing land sink conservation and enhancement can reduce future reliance on riskier, more expensive technological carbon dioxide removal.

Under all decarbonization scenarios except for the Low Land Sink scenario, NRDC assumed that the U.S. land sink could grow 70 percent by 2050 relative to today.[47] This expansion will need to come from a range of measures including agricultural soils management, afforestation and reforestation, heightened protections for mature forest age classes, forest management practices that lengthen harvest rotations, ending destructive logging practices, wetland protection and restoration, and the conservation and sustainable management of marine habitats. In the model, the land sink essentially functions to net out the non-CO_2 emissions that NRDC assumed to remain from agriculture and industry in 2050—to balance the carbon budget.

Failure to expand the natural land sink via these measures results in an increased reliance on technological carbon dioxide removal (CDR) to cover remaining emissions in the system, as shown by the Low Land Sink scenario in Figure 13. This sensitivity was designed to address considerable uncertainty around quantifying the land sink—how much carbon will be naturally sequestered in the long term—and its potential to grow from today's levels.[48] The effects of climate change, the effectiveness of soil and forest conservation measures, and future logging and development patterns will all influence how the land sink will change over the next three decades. Under the Low Land Sink sensitivity, where the land sink grows little beyond today's levels, the model deploys more DAC to artificially remove carbon emissions from the atmosphere and balance the emissions budget. This increased reliance on DAC comes at a greater expense, with total system cost at roughly $40 billion above that of the Core scenario.

While recognizing that uncertainty around the land sink is worth considering from an accounting perspective, NRDC affirms that measures to protect and enhance the land sink should remain a higher near-term priority than investments in technological CDR. These measures are tested, available today, and come with a number of co-benefits in the form of ecosystem services, landscape regeneration, and climate resilience advantages. Direct air capture—while still likely to play an important role in a net zero future—is an early-stage technology, where further research and development are needed before it can achieve the necessary scale and cost reductions. Like any other infrastructure investment, it also needs the proper policy guardrails to mitigate risks of CO_2 leakage and to prevent the use of DAC for enhanced oil recovery.

4b) Model Finding: Nearly all sensitivities see a higher deployment of direct air capture relative to the Core case, as a result of needing to quickly remove emissions in the last decade before 2050.

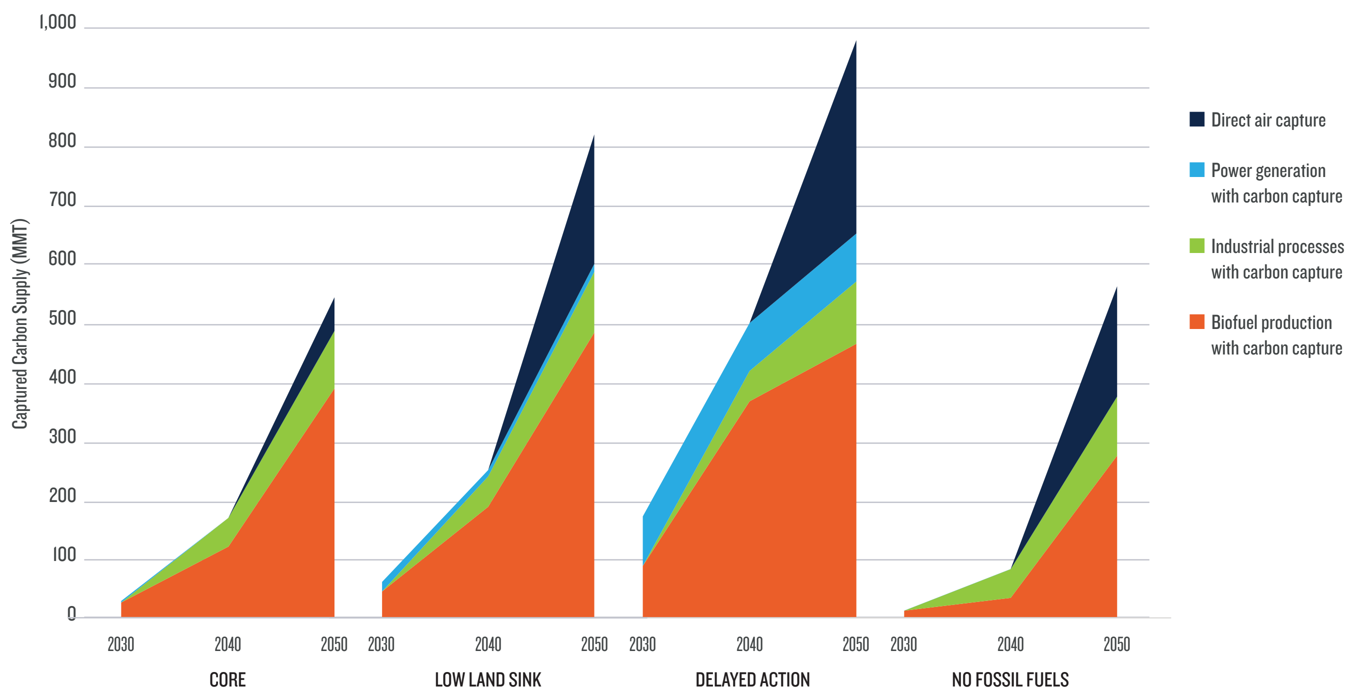
Policy Takeaway: Failure to reduce emissions in the near term will result in an increasing reliance on last-minute options for carbon removal.

NRDC's assumptions of the land sink potential and the non-CO_2 emissions trajectory gave the model an initial budget of how much carbon emissions would be allowed to remain in the system in 2050. After meeting this budget, the model could then choose to deploy DAC (at a given cost) to further capture existing carbon dioxide from the system. As shown in Figure 13, DAC becomes necessary in the modeled scenarios when:

1. **the United States does not act fast enough** and continues to emit carbon pollution at current rates over the next decade.
2. **the United States is unable to protect and grow the natural land sink** as needed. This is a possibility if, for example, deforestation rates, wetland conversion, and destructive logging practices do not decline, or climate impacts diminish the forests' ability to sequester carbon.
3. **the United States deploys synthetic fuels** (i.e., synthetic hydrocarbons, which would require the use of DAC to capture carbon for use in their production) **at a large scale** to replace remaining fossil fuel demand. This could occur when a policy over-incentivizes these drop-in fuels or requires the full phase-out of fossil fuels *without* concurrent investment in novel technologies and demand reduction from fossil-dependent applications (e.g., aviation, shipping, and chemicals and plastic production).

Relative to the Core case, direct air capture plays a larger role in the Delayed Action, No Fossil Fuels, and Low Land Sink scenarios. Most of this captured carbon is permanently stored in geologic sequestration to meet late-term needs for negative emissions leading up to 2050.

Figure 13: Sources of Captured Carbon



Strategy 5. Decarbonized Fuels

Decarbonized fuels serve the hardest-to-abate end uses of the economy.

DECARBONIZED FUELS ARE NOT A PANACEA

Decarbonized fuels—hydrogen, electrofuels, and biofuels—are critical for addressing the last few percent of carbon emissions remaining in the system by mid-century; no scenario reaches net zero without them. However, they are not a replacement for the first four strategies of decarbonization: **clean energy, energy efficiency, electrification, and natural carbon solutions**. For most end uses—like fueling passenger cars and heating buildings—electrification and energy efficiency are already technologically feasible and cost effective today. Failure to deliver on these first four strategies and relying instead on drop-in fuels is a more expensive pathway to net zero. For example, the Delayed Action scenario—which sees a 15-year delay in electrification adoption and thus a higher deployment of electrofuels than in the Core scenario—incurs the highest cumulative system costs by 2050 compared with all other pathways. Furthermore, scaling biofuel production and BECCS to meet demand for drop-in fuels will require the United States to reconcile the significant land use, water, biodiversity, and agricultural concerns of growing crops for energy use.[49] Finally, the air pollution impacts of bio- and electrofuel combustion must be addressed to ensure that they are not increasing human health burdens. Regulation of these combustion sources, such as through the Clean Air Act, will require the installation and consistent use of scrubbing technologies (scrubbers) to control and reduce emissions such as particulate matter (PM) and nitrogen oxides (NOx) from these facilities.

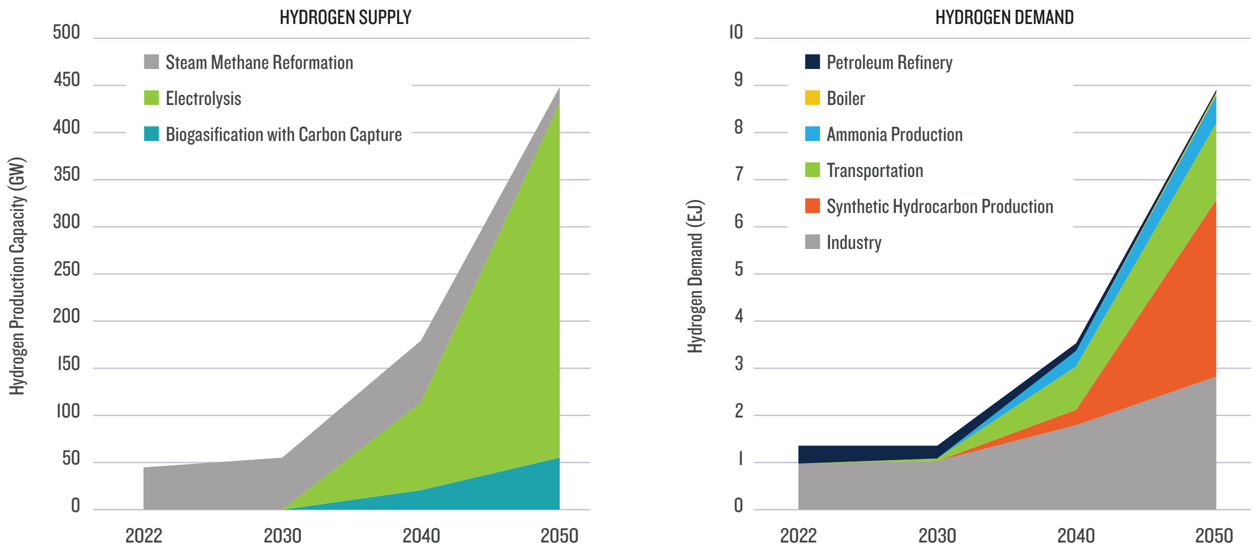
5a) Model Finding: Electrolytic hydrogen and electrofuels indirectly electrify select hard-to-abate end uses.

Policy Takeaway: Deployment of electricity-derived fuels should be targeted to their highest-value applications.

Hydrogen can act as a zero-carbon, indirect carrier of electricity when produced via electrolysis powered by zero-carbon resources. With rapid declines in electrolyzer costs expected over the next two decades, all decarbonization scenarios see increases in hydrogen production as mid-century approaches.[50] This hydrogen is deployed to decarbonize end uses where direct electrification is not technically or economically viable—namely, a portion of the heavy-duty vehicle fleet and industrial processes such as ammonia production and steelmaking. As shown in Figure 14, under the Core scenario, hydrogen production capacity in 2050 reaches 451 GW; this is nearly seven times that of the Reference scenario. The vast majority (83 percent) of this hydrogen is produced via electrolysis, with the remainder produced from biogasification with carbon capture (13 percent) and from fossil fuels (4 percent). Thirty-two percent of this hydrogen is for industrial use (e.g., producing industrial high heat), 18 percent is for transportation (e.g., fueling heavy-duty, long-haul vehicles), and 7 percent is for ammonia production (e.g., to fuel cargo ships). The remaining 43 percent is used to produce carbon-neutral electrofuels.

Electrofuels, also known as synthetic fuels, are made from captured carbon and hydrogen produced from zero-carbon electricity. They are human-made hydrocarbons designed to behave as a carbon-neutral, drop-in replacement for fossil fuels. Like hydrogen, they use electricity as their primary energy source, enabling the indirect electrification of hard-to-abate end uses. In the modeling, the decarbonization pathways deploy electrofuels to decarbonize applications with very limited low-carbon alternatives, such as asphalt production. Though not modeled here, NRDC advocates for reducing and eliminating demand for plastics and hazardous chemicals that rely on petrochemical feedstocks; this type of demand reduction would additionally mitigate reliance on these drop-in fuels.

Figure 14: Hydrogen Supply and Demand Under Core Scenario



5b) Model Finding: Biofuels meet remaining demand for liquid fuels.

Policy Takeaway: Sustainably sourced biofuels can act as a carbon-neutral or carbon-negative replacement for fossil fuels, though policies must ensure that they are supplied through sustainable feedstocks.

Similar to electrofuels and electrolytic hydrogen, biofuels—which are derived from biomass feedstocks such as perennial grasses and certain agricultural residues—can act as a carbon-neutral solution for hard-to-electrify applications. In the model, they play an especially important role in replacing jet fuel in aviation, for which there are few other low-carbon alternatives. The decarbonization scenarios see a modest deployment of biofuels, ranging from 1.1 EJ (Core) to 4.7 EJ (No Fossil Fuels) in 2050.

From a policy perspective, not all biomass feedstocks should be supported equally. NRDC estimates that there is a limited supply of truly sustainable biomass feedstocks: These are constrained to perennial grasses, sorghum, secondary agricultural residues, non–corn stover primary agricultural residues, urban and mill wastes, and manure.[h] NRDC does not support the use of forest biomass or woody energy crops for bioenergy purposes, due in part to significant negative environmental externalities and inefficiencies relative to other climate solutions. Thus, while biofuels can provide a carbon-neutral supply of liquid fuels, this supply is finite, with significant constraints on what can be sustainably harvested over the long term.

Adding carbon capture to bioenergy processes, such as using biomass to create hydrogen via biogasification and permanently sequestering the captured carbon, offers a form of negative emissions to the model. Evolved Energy Research notes that bioenergy with carbon capture and sequestration (BECCS) and direct air capture are likely to compete to meet negative emissions needs, as both represent net-negative technology options to help net out GHG emissions. Their competitiveness and eventual roles will ultimately depend on cost declines and feedstock availability.[51]

5c) Model Finding: Carbon capture appears across all decarbonization scenarios.

Policy Takeaway: Where economically viable, on-site carbon capture can play an important role in reducing emissions and supplying carbon for electrofuels.

All decarbonization scenarios see some degree of carbon capture technology, processes that capture emissions before they leave the smokestack. Between 540 MMT CO_2 (Core) and 930 MMT CO_2 (Delayed Action) are captured in the decarbonization scenarios, from biofuel production facilities, power plants, and industrial processes. In most cases,

h NRDC modeled a biomass supply curve of 435 million dry tons available annually. This includes 280 million dry tons from perennial grasses and sorghum, 77 million dry tons from agricultural residues (excluding corn stover residues), and 72 million dry tons from waste materials (urban and mill wastes and manure). There is no biomass supply from woody or forest biomass available.

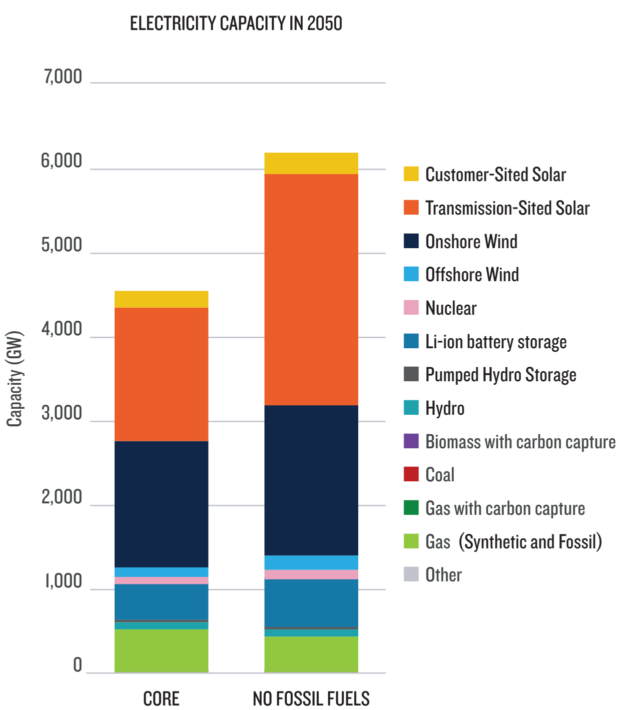
the majority of this carbon is permanently sequestered in geological formations, with less than one-quarter of captured carbon going toward electrofuel production in 2050. The one exception is the No Fossil Fuels scenario, where 100 percent of captured carbon is used for electrofuel production to completely replace fossil fuel use economy wide. It is important to note that while the installation of carbon capture will address carbon emissions from power generation and industrial processes, there may still be other forms of air and water pollution created from these power and industrial facilities. Any installation of carbon capture should be paired with strong safeguards and complementary measures (e.g., additional polishing scrubbers to reduce sulfur dioxide emissions) to protect the health of local communities. Use of carbon capture must not be seen as a license to continue polluting the air and lungs of local communities, who are often low-income communities and communities of color.

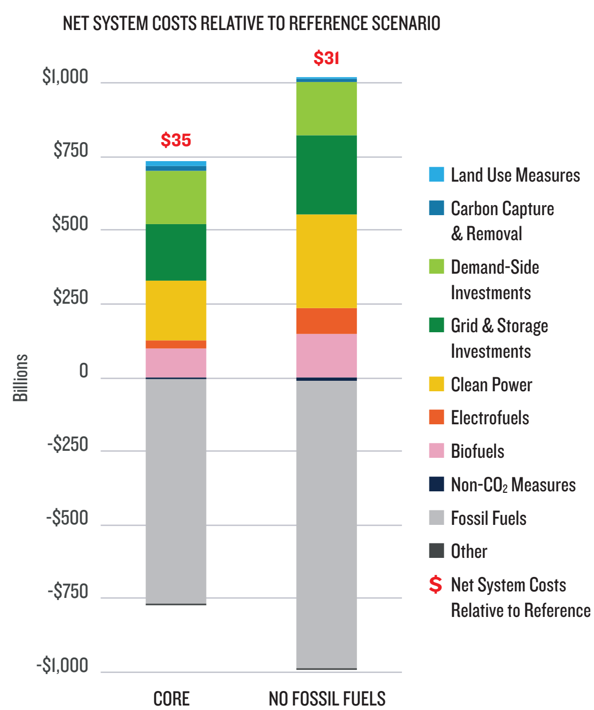
5d) Model Finding: Eliminating All Fossil Fuel Use by 2050 Poses Challenges.

Policy Takeaway: Replacing the last tranche of fossil fuel use without concurrent demand reduction measures becomes disproportionately expensive.

The No Fossil Fuels scenario was designed to test for the impacts of a fossil-free world—that is, one where fossil fuel production and use are completely barred by 2050. Eliminating the last few percent of fossil fuels—across both the power and industrial sectors—is feasible but comes at higher costs.[52] This scenario requires a far greater build-out of renewable energy facilities and storage than do other scenarios (Figure 15). This renewable expansion is driven primarily by increased demand for decarbonized fuels to address the hardest-to-abate end uses of the economy. To replace the fossil-derived energy that otherwise remains in the Core scenario, the No Fossil Fuels scenario sees a higher deployment of biofuels, electrolytic hydrogen, synthetic hydrocarbons, and industrial thermal energy. By 2050, electricity demand is 40 percent higher than in the Core scenario, driven by this larger appetite for electricity-derived fuels. To meet this demand, the model builds more than four times as much renewable capacity and 18 percent more nuclear SMR capacity than the Core scenario does. Overall, costs are 200 percent higher in 2050 relative to the Core case. Pursuing additional demand reduction measures, such as reducing plastics production and consumption, can help lower demand and costs for these decarbonized fuels in a No Fossil Fuels scenario.

Figure 15: Electricity Capacity and System Costs Under Core and No Fossil Fuels Scenarios





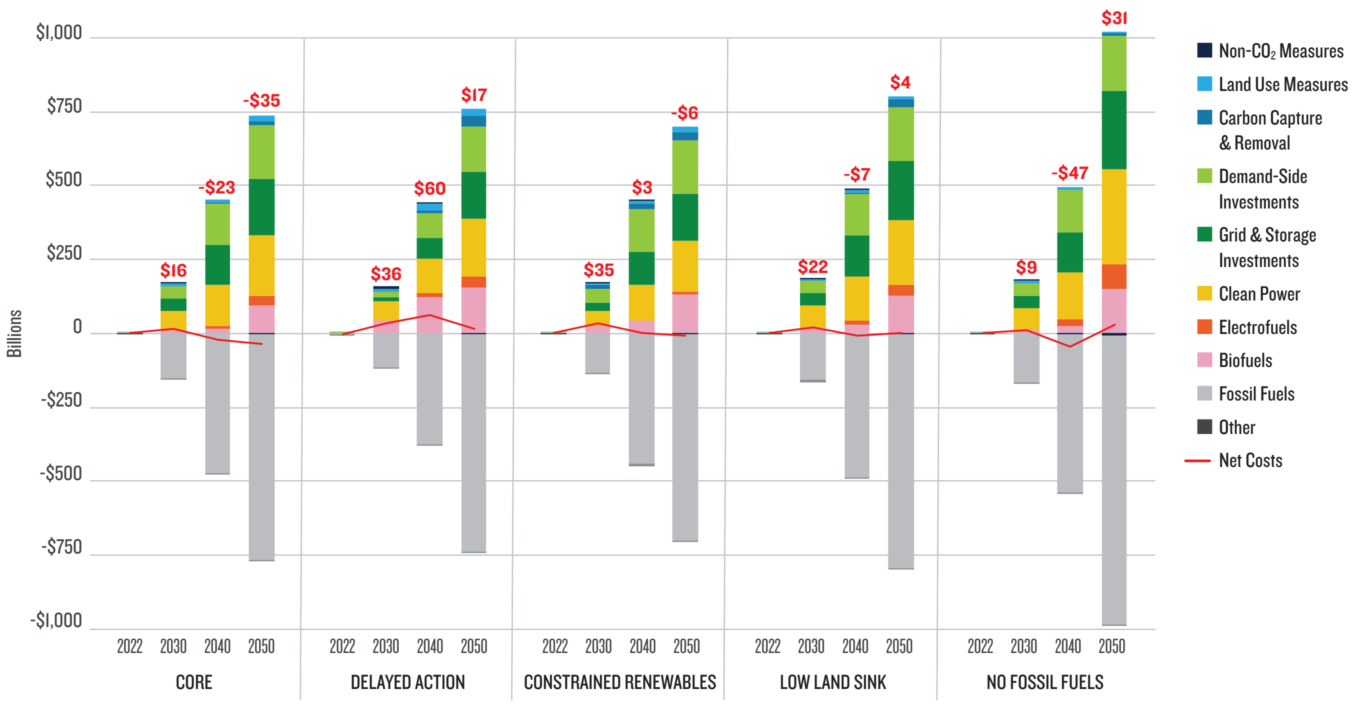
5e) Model Finding: All sensitivities rely more heavily on decarbonized fuels than the Core scenario does, leading to increased system costs.

Policy Takeaway: Overreliance on decarbonized or drop-in fuels due to missed early emissions-reduction opportunities will increase the costs of transitioning to net zero.

The transition to a net zero energy system can come at a modest cost—or even a *lower* cost—relative to the Reference scenario. The model tracks gross system costs—that is, the annualized capital and operating costs of both energy supply and end-use technologies. These costs are expected to grow even under the Reference case as the U.S. energy system expands to meet the demands of a growing population. Energy system costs under the Core scenario are actually $35 billion *cheaper* than the Reference scenario by 2050 due to savings from energy efficiency measures, which reduce overall energy demand (Figure 16). The Constrained Renewables and Low Land Sink scenarios are $30 billion to $40 billion more expensive in 2050 than Core, respectively. While the No Fossil Fuels scenario is the most expensive *in* 2050, the Delayed Action case incurs the most cumulative costs over the entire three decades to 2050.

The net costs above do not account for the economic damage that would be incurred under the Reference scenario, where the failure to meaningfully reduce emissions would incur profoundly higher levels of warming and climate impacts. Even at billions of dollars, the transition costs to net zero are an order of magnitude smaller than the trillions of dollars in losses expected under a warmer future in the United States alone. Over just the past five years, natural disasters in this country (e.g., hurricanes, wildfires, droughts, floods) exceeded $765 billion in economic losses.[53] Climate change, especially beyond 1.5 °C, is expected to make extreme weather events more frequent and severe. The direct costs of these events compound the many other economic losses associated with, for instance, sea-level rise, agricultural disruptions, human migration, and health impacts. By pursuing decarbonization, the United States will not only help protect Americans against these growing risks but also bolster a revitalized and resilient energy economy.

Figure 16: Net System Costs (in Billions) Relative to Reference Scenario



IV. POLICY IMPLICATIONS

Successfully achieving the net zero goal will depend on how quickly the United States acts to reduce emissions and how it invests in the transition to a net zero economy. The choices that U.S. leaders—across government, business, and technology alike—make today will determine which pathway the country pursues and what financial, social, and environmental impacts that pathway will entail. The gap between the current U.S. trajectory and any net zero pathway, as well as the commonalities across all decarbonization scenarios, should inform U.S. policy going forward. This analysis identifies key milestones and strategic recommendations for policy, research, and investment priorities to achieve net zero while minimizing the economic costs and climate risks of the transition.

THE UNITED STATES MUST BUILD ON THE MOMENTUM OF THE INFLATION REDUCTION ACT OF 2022

In 2022 Congress passed the biggest climate bill in U.S. history. The Inflation Reduction Act (IRA) includes more than $369 billion for clean energy investments, including major incentives that will support the deployment of key clean energy technologies and funding for other pollution-reduction programs, in addition to imposing emissions fees on the oil and gas industry.[54]

The IRA is a significant step forward for U.S. climate action, but it is not enough in and of itself to meet national climate targets. If properly implemented, the IRA can cut U.S. greenhouse gas pollution by 40 percent below 2005 levels by 2030. While this is a much better outcome than business as usual" without the IRA, it still falls short of the U.S. climate commitment of a 50–52 percent reduction in GHG emissions by 2030.

The investments that Congress has made in the IRA will buy down the cost of many clean energy technologies, including wind and solar, as well as electric cars, heat pumps, and other energy-efficient products. Lowering the cost of these technologies will speed their adoption by individuals, businesses, utilities, and governments while also reducing the costs of climate action. These investments and incentives in clean energy, domestic clean energy supply chains and manufacturing, and other supporting infrastructure will be critical to achieve the rapid uptake of clean energy and efficient electric end uses required to achieve a net zero trajectory. Since this analysis began before the IRA's passage—and therefore did not factor in its policy support for these investments—the modeling in this report may underestimate the near-term deployment of clean energy solutions in this decade while overestimating the costs of the transition to the system and consumers.

The United States can build on the clean energy funding in the IRA, pursuing new federal regulations and state clean energy policies to close the gap to the 50-percent-by-2030 GHG emissions-reduction goal, and get the country on track to achieve the net zero economy envisioned in this report. Some near-term policy actions to close this gap include: implementing U.S. Department of Agriculture and Department of the Interior regulations that protect mature and old-growth forests on federal lands from logging; approving EPA regulatory rules to address power plant pollution, methane emissions from oil and gas production, and tailpipe emissions from cars and heavy-duty vehicles; and implementing federal standards for phasing down HFCs and increasing appliance efficiencies. On state and local levels, utilities and state policymakers can pass (or enhance existing) clean energy standards, energy efficiency standards, building codes, and state zero-emission vehicle standards. When paired with actions like utility regulatory reforms, improved planning processes, and sustainable agriculture programs, these actions can help bend the climate curve in this decade. There is much work to be done, but national climate goals are achievable if the United States rapidly builds on the momentum of the IRA.

a. Key Milestones

Transforming the U.S. energy system by 2050 will require incremental progress in each of the next three decades. The key milestones below outline the emissions reductions that the United States will need to achieve by 2030, 2040, and 2050 to stay on track with a net zero trajectory; beneath each are the clean energy policy objectives that will enable the country to achieve them. Missing these milestones, as shown by the sensitivity scenarios, will not preclude a net zero future but risks increasing the economic and environmental costs of the energy system transition.

By 2030: Reduce net U.S. GHG emissions to at least 50–52 percent below 2005 levels. Reduce energy-related CO_2 emissions by at least 50 percent below 2005 levels. Policies, investments, and research should prioritize implementation of strategies 1–4.

- **Clean Power:** At least 80 percent of the electricity grid should be powered by zero-carbon resources. This can be achieved by retiring coal- and oil-fired power plants and preventing the build-out of new natural gas–fired plants. Investments should accelerate the build-out of new wind turbines, solar panels, battery storage, and interregional transmission. Rules should mitigate methane emissions from any gas use in the power sector.
- **Energy Efficiency:** By 2030 all new buildings should be ultra-efficient (e.g., have net zero building codes), and all new appliances should adhere to high-efficiency standards. At least one-third of existing buildings should have undergone energy efficiency retrofits. Investments should go toward efficiency improvements in new and existing buildings and at industrial facilities. Utilities and governmental agencies should have already ramped up energy efficiency programs across all customer segments. Strategic energy management should be a common practice for all industrial facilities.
- **Electrification:** Around 67 percent of all new light-duty vehicle sales should be electric by 2030, as well as all new appliances in buildings. Policies should incentivize consumers to mainly purchase electric options for new appliances and vehicles.
- **Natural Carbon Solutions:** Mitigate declines in the existing natural land sink by halting destructive logging practices, preventing degradation of old- and mature-growth forests, and preventing development of carbon-rich wetlands. Sustainable agriculture practices, such as organic farming and the use of cover crops, should be widely adopted to improve the health and carbon storage potential of working lands.
- **Decarbonized Fuels:** Emissions from existing fossil fuel use should be reduced as much as possible through electrification and efficiency measures. Efforts should focus on:
  - Addressing methane emissions from the oil and gas sector to reduce the carbon intensity of fossil fuel use in the near term.
  - Aggressively reducing the use of "super-pollutants" like HFCs by transitioning to alternatives with low or zero global warming potential.

After prioritizing near-term emissions reductions, investments should begin to fund the research, development, and demonstration (RD&D) of emerging technologies for use in the hardest-to-abate applications of the economy (shipping, aviation, and heavy industry). These technologies include long-duration storage; carbon dioxide removal; and the manufacture of green hydrogen, electrofuels, and other alternative materials to reduce demand for fossil-derived chemicals and plastics. Electrolyzer capacity for hydrogen production should be built with robust measures around additionality, deliverability, and hourly matching with renewable power.

Robust accounting practices and regulatory oversight should be established by 2030 to ensure the safe and responsible production, use, and transport of captured carbon and synthetic fuels in future decades.

By 2040: Reduce net U.S. GHG emissions to at least 77 percent below 2005 levels. Reduce energy-related CO_2 emissions by at least 75 percent below 2005 levels. Policies, investments, and research should maximize the deployment of strategies 1-4 while bringing solutions from strategy 5 to commercial scale for the hardest-to-abate applications.

- **Clean Power:** Nearly 100 percent of the grid should be powered by zero-carbon resources by 2040, with the use of gas plants restricted to infrequent, high-demand, and low-output emergency events. Investments should continue to support renewable and other zero-carbon resource development, storage, and transmission as well as grid enhancements to operate and improve the resilience of a highly renewable grid.
- **Energy Efficiency:** At least half of the existing building stock in 2040 should have undergone an energy efficiency retrofit to improve their shell efficiency.
- **Electrification:** All new vehicles—light, medium, and heavy duty—should be zero-emission vehicles (e.g., powered by batteries or hydrogen fuel cells). With new appliances already electric, investments should focus on retrofitting existing buildings to replace existing gas-fired appliances.
- **Natural Carbon Solutions:** Investments in reforestation, afforestation, and native ecosystem restoration should continue to expand the natural land sink.
- **Decarbonized Fuels:** Decarbonization technologies should be deployed in the industrial sector at commercial scale. These should include the use of carbon capture to address process emissions from hard-to-abate end uses (e.g., cement manufacture) and the use of hydrogen to make steel and carbon-free ammonia for shipping fuel. All hydrogen supply should be produced using excess renewable electricity. The production of biofuels should include carbon capture. Robust accounting practices should ensure that any alternative fuels replacing remaining fossil fuel use have carbon-neutral or carbon-negative production cycles.
- **Non-CO_2 emissions:** Efforts should continue to mitigate non-CO_2 emissions from the industrial and agricultural systems.

By 2050: Achieve net zero: Reduce net U.S. GHG emissions to at least 100 percent below 2005 levels. Achieve the U.S. carbon budget: Reduce energy-related CO_2 emissions by at least 95 percent below 2005 levels. At this point and in each year following, any remaining GHG emissions should be equal to or less than the amount of carbon being sequestered in natural carbon sinks or in geological formations.

- **Clean Power:** A nearly carbon-free electricity grid should act as the backbone of the U.S. energy system.
- **Energy Efficiency:** At least 80 percent of the existing building stock should have undergone an energy efficiency retrofit to improve their shell efficiency.
- **Electrification:** All new and existing end uses across the entire buildings sector, much of the transportation sector, and some of the industrial sector should be fully electrified where technologically and economically feasible.
- **Natural Carbon Solutions:** Investments in reforestation, afforestation, and native ecosystem restoration should continue to expand the natural land sink.
- **Decarbonized Fuels:** Any use of fossil fuels should be minimal or eliminated. While some fossil fuels may be used as fuels or feedstock for certain industrial, power, or transportation applications, the majority of energy demand should be met with electricity or electricity-derived fuels. Non-CO_2 emissions should be minimized as much as possible.

  The targeted use of non-fossil alternatives like hydrogen, electrofuels, and sustainable biofuels with CCS should be commonplace in those hardest-to-abate applications where there are barriers to electrification. There should be clear, robust, and transparent reporting on the supply chain for these fuels and accurate emissions accounting. Where necessary, direct air capture and other carbon dioxide removal technologies should be deployed to net out any remaining emissions.

b. Strategic Recommendations for Policymakers

Using the recommendations below as a guiding light, U.S. policymakers, business leaders, and utilities can drive the economy to net zero GHG emissions while maximizing the co-benefits of the clean energy transition and minimizing the economic and climate risks. **Most importantly, U.S. leaders must capitalize on the momentum of the IRA, pursue the highest-priority emissions-reduction opportunities, and get the country on track to a net zero future.**

CLEAN POWER:

- **Address fossil power plant pollution.** EPA standards—for carbon emissions and other air and water discharges—are essential to ensure reductions of pollution harmful to public health and climate. These standards also give the industry the regulatory certainty it needs to guide future investment. The EPA should use its existing regulatory authority to set stringent carbon pollution standards for existing and new fossil-fueled plants. These standards directly address the carbon pollution emitted by existing power plants based on what can be achieved through pollution control measures at the plant itself, though states and utilities have flexibility to reduce emissions from fossil generation through direct measures at fossil plants or other clean investment.
- **Transition to a clean electricity grid as quickly as possible.** Implement, strengthen, and enhance clean energy standards (CES) and renewable portfolio standards (RPS) to accelerate the transition to zero-carbon electricity resources. Support supply chain improvements and labor markets to meet increased demands from the clean energy industry. Prevent the build-out of new fossil fuel infrastructure (e.g., new gas-fired power plants), which risk locking emissions into the system for many decades to come. Support innovation to improve methods for managing and forecasting energy supply and demand.
- **Update and reform processes to streamline and accelerate clean energy development.** This includes updates to utility business and regulatory models; long-term planning processes; and interconnection, permitting, and siting rules.
- Update existing wholesale energy markets to better suit the dynamics of a highly renewable grid; include updates to existing capacity markets to account for and value seasonal variability, demand flexibility, energy storage, and grid services.

ENERGY EFFICIENCY

- **Invest in energy efficiency to the maximum extent possible.** Implement and strengthen energy efficiency resource standards (EERS) and utility energy efficiency programs. Support innovation that continues to push the bounds of energy efficiency improvements available to appliances and EVs.
- **Incentivize demand reductions and flexibility.** Energy efficiency can also take the form of demand reduction: Implement smart utility rate designs that can reduce energy demand during peak hours. Reduce EV-miles traveled by expanding bike, pedestrian, and transit infrastructure. Disincentivize the overproduction of fossil fuel–derived goods, such as plastics and hazardous chemicals, to avoid demand for new fossil fuel infrastructure.

ELECTRIFICATION

- **Build clean the first time:** To avoid a more costly transition, policies should promote the purchase of efficient electric options when households, businesses, and industry are investing in new infrastructure such as boilers, heaters, and vehicles. Encouraging consumers to make climate-smart decisions today, given the long life of many of these end uses, means that the appliance will not need to be replaced prematurely. Updated building codes and standards can reduce building emissions today by requiring net zero and all-electric building construction and by incentivizing “EV-ready” homes. Utilities can implement efficiency programs and rebates to lower the initial costs of transitioning to efficient electric alternatives. States should implement and strengthen zero-emission vehicle standards and purchasing incentives for all classes of on-road transport.
- **Avoid new fossil infrastructure:** New fossil fuel projects risk locking in emissions due to the long-lived nature of fossil fuel infrastructure. New pipelines and power plants, for example, are designed to operate and be financially supported for 40–60 years, well beyond the time frame in which the United States must minimize its climate footprint and achieve a net zero economy. Policymakers should be especially skeptical of proposals that suggest fossil fuel infrastructure—such as pipelines and turbines—can eventually be converted for non-fossil use (e.g., hydrogen in building pipes), given uncertainty about conversion costs and long-term climate risks relative to building clean from the start.

NATURAL CARBON SOLUTIONS

- **Incentivize the transition to sustainable agriculture practices**, which can reduce emissions from the agricultural system while also increasing the carbon storage potential of working lands. These practices include cover cropping, agroforestry, composting, reducing the use of synthetic fertilizers and pesticides. Reducing consumption of industrial meat and dairy products can support the transition to more sustainable livestock practices.
- **Permanently protect and restore forests (especially old-growth and mature forests), wetlands, and coastal ecosystems.** These efforts will expand the natural land sink while providing co-benefits such as protecting biodiversity and providing natural buffers against extreme weather. Without these measures, the natural land sink is expected to decrease due to deforestation, development, and climate impacts.

DECARBONIZED FUELS

- Support RD&D, alongside robust and transparent accounting oversight, for emerging solutions. The United States can get very far using “no-regrets” solutions. However, more nascent technologies will be needed to

address the hardest-to-abate applications of the economy, including aviation, shipping, peaking power generation, and industrial processes such as steel and cement making. Addressing these needs will require innovation and cost reductions in decarbonized fuels, carbon dioxide removal technologies, alternative materials to replace fossil-derived chemicals and plastics, and nuclear and storage technologies. Investing in RD&D today can help ensure that the nation has a toolbox of scalable, cost-effective solutions to address all energy needs in a net zero world.

TACKLING NON-CO_2 EMISSIONS

- While non-CO_2 emissions may be a small portion of the U.S. climate footprint, many of these pollutants are much more potent greenhouse gases than CO_2. Since warming is a function of cumulative emissions, near-term cuts in these super-pollutants can have outsize climate benefits in the long term. The United States has committed to cutting methane emissions by 30 percent by 2030, and the EPA has published proposed rules that could cut methane emissions from the oil and gas sector by up to 87 percent.[55] The IRA also includes additional funding for methane capture and a methane fee imposed on emitters. Policymakers should ensure that these strong standards are finalized and that the oil and gas industry makes the necessary investments to monitor, measure, and stop methane leaks from their operations. Congress also passed the American Innovation and Manufacturing (AIM) Act in 2020, requiring the EPA to phase down the use of HFCs and facilitate the transition to next-generation refrigerants.[56] Policymakers should support efforts to accelerate the transition away from HFCs.

PRIORITIZING EQUITY AND PUBLIC HEALTH

In any pathway to net zero, policymakers must ensure that decarbonization policies are developed and implemented with equity and health in mind. Earlier work by NRDC and Evolved Energy Research (in partnership with GridLab, the Sierra Club, and PSE Health Energy) exploring net zero scenarios for the western states laid out important policy recommendations for ensuring that decarbonization policies support the transition to a net zero system while unlocking the significant potential public health, equity, and economic benefits of this transition. Those policy implications are as follows:[57]

- Equity must be integrated from the beginning to ensure that public health and economic benefits of the transition accrue evenly.
- To be successful, policies must intentionally and specifically address equity and fairness.[58]
- Decarbonization plans that address equity can result in greater public health and economic benefits than approaches that exclusively focus on lowering greenhouse gas emissions.
- Certain communities, such as those with high pollution, a large fraction of low-income households, or high energy cost burdens, may see some of the greatest benefits from clean energy adoption.
- Engagement with affected communities must be prioritized throughout the process to help identify both socioeconomic and pollution burdens of concern and strategies to mitigate them.
- Disparities in fossil fuel pollution and economic impacts may be exacerbated with a decarbonization strategy focused exclusively on carbon emissions.
- Policies supporting clean energy adoption should be prioritized in populations with the lowest income and highest pollution and cost burdens.

V. CONCLUSION

The United States can and must achieve net zero GHG emissions by mid-century. To do so, it must commit to deploying decarbonization strategies with speed and at scale. The clean energy transition is already well underway, with many of the solutions discussed in this report already entering the mainstream. One need not look far to see an EV on the street or solar panels on a rooftop. However, achieving net zero emissions within three decades will require a rise in political ambition and an accelerated deployment of these solutions.

To meet this target, the United States must focus its policy efforts and investment capital on the most effective decarbonization strategies. It must rapidly clean up the electricity grid through the widespread deployment of wind and solar resources. It must expand the interregional transmission network to support the integration of these renewable resources. It can cut emissions from end-use sectors through electrification but should maximize energy efficiency gains to mitigate the need for new electricity infrastructure. It must conserve and expand the natural land sink through policies that protect America's soils, forests, wetlands, and oceans. And finally, it must develop sustainable supplies of decarbonized fuels to address the hardest-to-abate end uses of the economy.

Should the United States fail to reduce emissions in the near term, it will need to rely on riskier and more expensive technologies in later decades to rush to the net zero target. If the country does not accelerate the pace of renewable and transmission build-out, it may need to look toward more expensive electricity resources (e.g., nuclear small modular reactors or gas with carbon capture), compromising the country's supply of abundant, cheap, zero-carbon electricity. If the United States does not preserve the land sink or fails to electrify the economy quickly enough, it will need to find ways to deploy technological carbon dioxide removal technologies that have yet to be proved at commercial scale.

The economic stakes of inaction are profound. By missing early opportunities to decarbonize, the United States could land on a pathway with much higher system costs—billions of dollars that will be footed by American ratepayers and taxpayers. If the United States and other countries miss their net zero targets entirely, the damages wrought by climate change are expected to cost trillions of dollars.

Looking beyond decarbonization, the clean energy transition is an opportunity to reinvent America's physical infrastructure system into one that is more sustainable, more equitable, and more just. The co-benefits of decarbonization are not guaranteed without complementary policy guardrails that limit harms to the environment and communities. Policies should work in tandem to reduce GHG emissions while also improving public health outcomes, conserving biodiversity, and promoting racial and socioeconomic equity both domestically and abroad. These points highlight the need for thoughtful policy design and community engagement at the local, state, and federal levels as the United States continues through this transition.

VI. TECHNICAL APPENDICES

Appendix A: Scenario Assumptions

This appendix provides details on the assumptions made for specific sectors and energy technologies (rows) for each of the six scenarios modeled in the study (columns).

SCENARIO ASSUMPTIONS	REFERENCE	CORE	NO FOSSIL FUELS	CONSTRAINED RENEWABLES	DELAYED ACTION	LOW LAND SINK
Clean Electricity Policy	None.	None; clean electricity outcomes driven by GHG emissions policy.				
Economy-Wide GHG Policy	No emissions constraint.	Economy-wide GHG emissions constrained to 53% below 2005 levels by 2030 and net zero by 2050.				
Clean Resource Qualification	Constrained only by transmission limits.					
Buildings: Electrification	Reflects EIA's Annual Energy Outlook (AEO) 2022 Reference case.[59]	New appliance sales are 100% electric or hybrid by 2030.			New electric or hybrid appliance sales are delayed to 100% by 2045 (15-year delay).	Same as Core.
Buildings: Tech Energy Efficiency	Reflects AEO 2022 Reference case.	New appliance sales reach 100% high-efficiency models by 2030. New building shells achieve 60% efficiency gains by 2030. Existing building shell retrofits achieve 30% efficiency gains by 2030. These retrofits impact 30% of existing stock by 2030, 50% by 2040, and 80% by 2050.			New high-efficiency appliance sales are delayed to 100% by 2045 (15-year delay). Building shell retrofits are delayed to 30% by 2040 and 50% by 2050 (10-year delay).	Same as Core.
Buildings: Service Demand	Reflects AEO 2022 Reference case.	Commercial heat and appliances achieve a 15% reduction in demand by 2050. Commercial light achieves a 28% reduction in demand by 2050. Residential buildings achieve a 10% reduction in electricity demand by 2050.			All Core service demand targets are delayed by 10 years.	Same as Core.
Transportation: Light-Duty Vehicles (LDV)	Reflects AEO 2022 Reference case.	New LDV vehicle sales are 100% battery electric by 2035.			New LDV vehicle sales are delayed to 100% electric by 2050 (15-year delay).	Same as Core.
Transportation: Medium-Duty Vehicles (MDV) and Heavy-Duty Vehicles (HDV)	Reflects AEO 2022 Reference case.	New HDV long-haul sales are 25% battery electric, 5% hydrogen fuel cell by 2030; 50% battery electric, 50% hydrogen fuel cell sales by 2040. New HDV short-haul sales are 25% battery electric by 2030; 80% battery electric, 20% hydrogen fuel cell sales by 2040. New MDV sales are 35% battery electric, 5% hydrogen fuel cell by 2030; 80% battery electric, 20% hydrogen fuel cell by 2035.			All Core M- and HDV transition targets are delayed by 10 years.	Same as Core.
Transportation: Aviation	Reflects AEO 2022 Reference case.	Aviation achieves efficiency gains of 1.5% a year relative to Reference scenario.				
Industry	Reflects AEO 2022 Reference case.	Industry achieves overall efficiency improvements of 1% per year relative to Reference Scenario. Fuel switching measures (i.e., industrial electrification) implemented for applications where feasible.			Industrial fuel switching measures delayed by 15-years.	Same as Core.

SCENARIO ASSUMPTIONS	REFERENCE	CORE	NO FOSSIL FUELS	CONSTRAINED RENEWABLES	DELAYED ACTION	LOW LAND SINK
Resource Availability	Technical potential estimates from NREL's Annual Technology Baseline (ATB).[60] Transmission potential assumed to be unconstrained. Transmission costs from ReEDS.[61] Nuclear extension eligibilities from NRDC. No large nuclear allowed; SMRs allowed starting in 2035.			Annual renewable capacity additions are constrained to 18.5 GW a year of wind and 28 GW a year of solar.[62]	Same as Core.	
Fuels	Fuel prices reflect AEO 2022 Reference case.		No fossil fuels permitted in the economy by 2050.	Same as Core.		
DER Schedule	Evolved Energy Research's default assumptions.					
Land Sink	Existing land sink as of 2020 from EPA.[63] Land sink decreases to 800 MMT CO_2 in 2020, 750 MMT CO_2 in 2030, 550 MMT CO_2 in 2040, 490 MMT CO_2 in 2050.	Land sink expands from 740 MMT CO_2 today (EPA) to 1,240 MMT CO_2 in 2050, fully implementing the estimated 500 MMT CO_2 affordable growth potential from NASEM.[64]				Land sink expands from 740 MMT CO_2 today to only 850 MMT CO_2 in 2050, using the lower growth potential estimate from Jenkins et al.[65]
Non-energy Emissions	Reflects non-CO_2 projections from EPA.[66]					

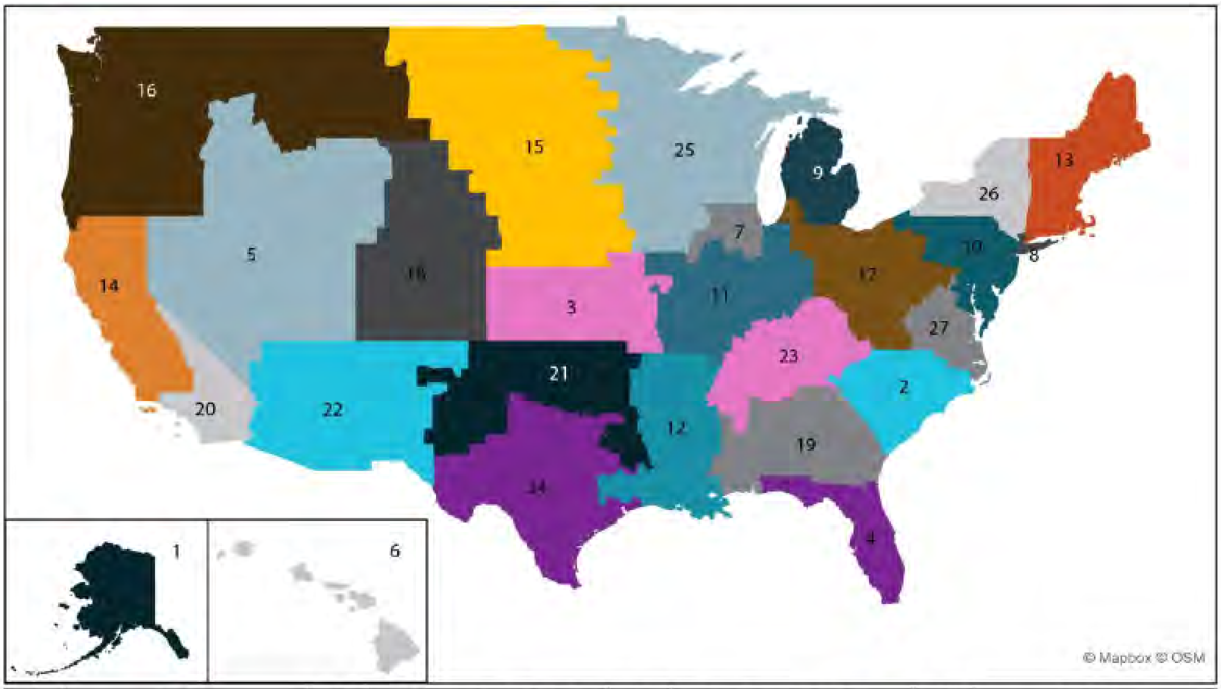
Appendix B: About the Models—EnergyPATHWAYS and the Regional Investment and Operations Platform

EnergyPATHWAYS is a scenario analysis tool focusing on detailed and explicit accounting of energy system decisions.[67] It can be used to account for the costs and emissions associated with producing, transforming, delivering, and consuming energy in an economy—assessing how these energy system decisions impact future infrastructure needs, emissions, and costs to both energy consumers and the general economy.

The EnergyPATHWAYS model is designed to examine large-scale energy system transformations. To do this, it projects energy demand and costs across 65 subsectors on the basis of explicit (exogenous) inputs about technology adoption (e.g., EV sales, heat pump adoption) and activity levels (e.g., assumptions about vehicle-miles traveled and building efficiency). These subsectors, like residential space heating, represent energy use associated with the performance of an energy service. The model then solves for the supply side, calculating upstream energy flows, primary energy usage, infrastructure requirements, emissions, and the costs of supplying energy based on the user-defined demand-side energy needs. This then provides outputs on total energy flows, emissions, and costs of the modeled energy system.

Each scenario is modeled in every year starting from the present, for all the infrastructure stocks and activities within all major economic sectors and subsectors. The model is geographically divided into 27 separate regions (Figure A1) that follow North American Electric Reliability Corporation (NERC), independent system operator (ISO), and regional transmission organization (RTO) regional boundaries and use the geographic names from EIA's National Energy Modeling System (NEMS), which are approximations of jurisdictional borders.

Figure A1: Region Representations in EnergyPATHWAYS + RIO



1	Alaska	8	Metropolitan New York	15	Northern Great Plains	22	Southwest
2	Carolinas	9	Michigan	16	Northwest	23	Tennessee Valley
3	Central Great Plains	10	Mid-Atlantic	17	Ohio Valley	24	Texas
4	Florida	11	Middle Mississippi Valley	18	Rockies	25	Upper Mississippi Valey
5	Great Basin	12	Mississippi Delta	19	Southeast	26	Upstate New York
6	Hawaii	13	New England	20	Southern California	27	Virginia
7	Metropolitan Chicago	14	Northern California	21	Southern Great Plains		

Figure provided by Evolved Energy.[68]

EnergyPATHWAYS also leverages many of the same input files used in NEMS for the EIA's Annual Energy Outlook (AEO). The 2022 version of EnergyPATHWAYS used for this analysis draws from both the AEO 2022 and NREL's 2021 Annual Technology Baseline for key underlying technology and demand assumptions.[69]

EnergyPATHWAYS runs with the Regional Investment and Operations (RIO) platform to cost-optimize certain supply-side energy decisions. This allows the co-optimization of fuel and supply-side infrastructure decisions under different energy demand and emission scenarios.

RIO has three main functionalities. First, it can be used to optimize capacity and generation decisions in the power system, determining the least-cost portfolio of electricity resources and electricity storage to meet both energy needs and any emissions constraint applied in the scenario. Second, RIO can represent hourly dispatch for all zones and resources, including both supply-side technologies and any flexible demand loads. This allows users to employ RIO to assess the reliability of the electricity system from an 8,760 perspective (i.e., every hour of the year) for any scenario. Third, RIO can optimize the liquid fuels segment—optimizing investment decisions around fuel conversion processes and the least-cost blend ratios for fuels (Figure A2). This means that the model can determine how to meet any remaining non-electricity energy demand with bio-based, fossil-based, and electricity-produced fuels (e.g., hydrogen, synthetic fuels, electrofuels) within the bounds of any emissions constraints. Low- and no-carbon fuel conversion pathways represented in EnergyPATHWAYS + RIO are shown in the figure below.

Figure A2: Diagram of Potential Low- and No-Carbon Fuels available in RIO

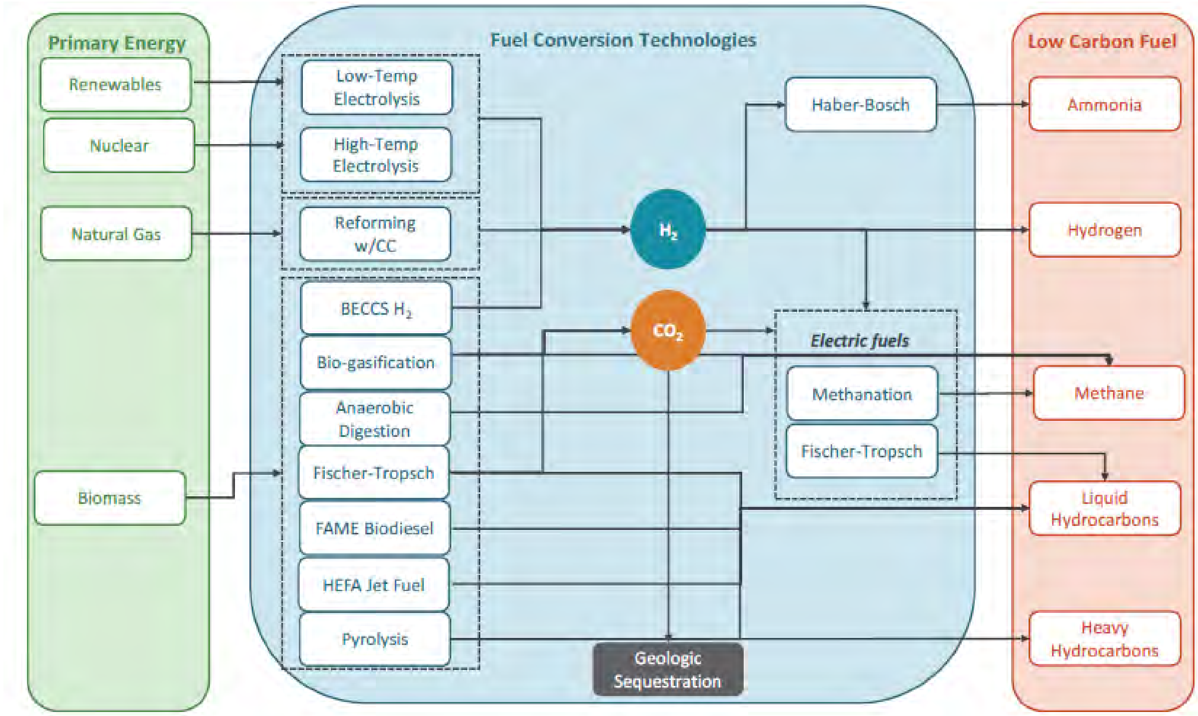


Figure provided by Evolved Energy.[70]

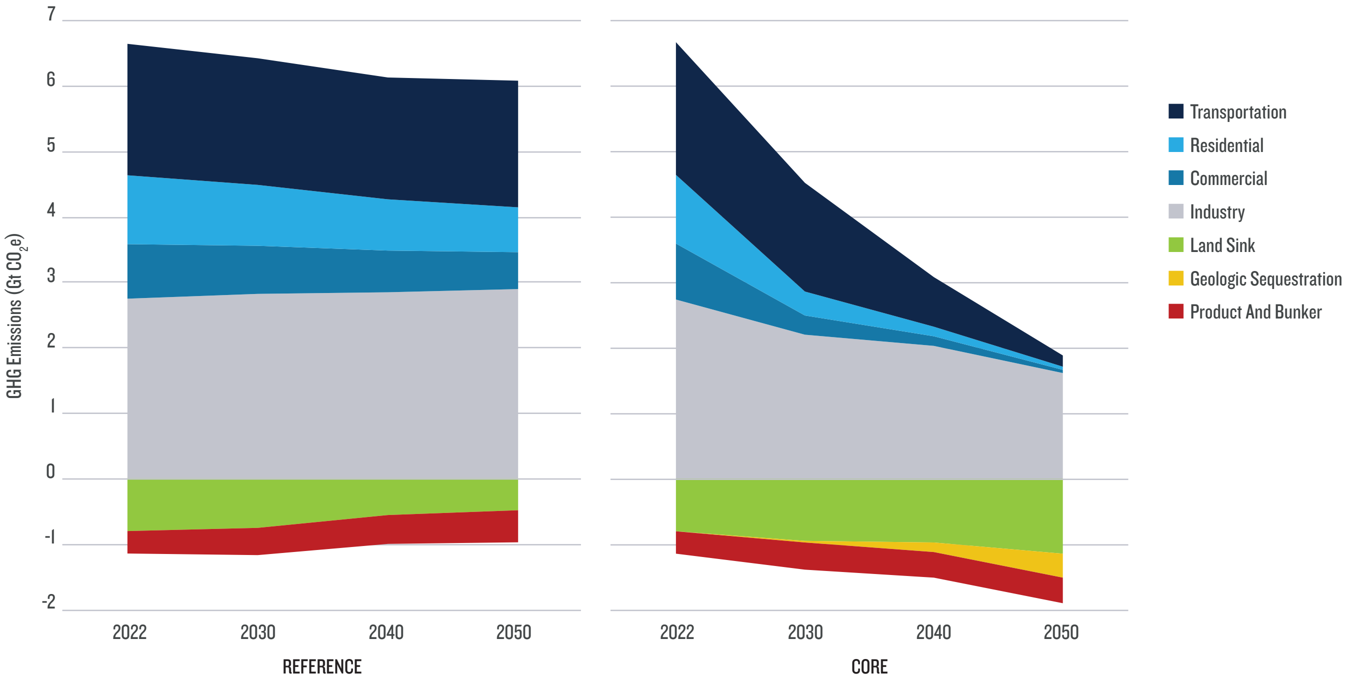
The 2022 version of the EnergyPATHWAYS + RIO model used for this analysis also includes explicit representations of new pipeline capacity for transporting hydrogen, ammonia, and CO_2. The model can also build new electricity transmission as well as model reconductoring of existing electricity transmission corridors (i.e., renewing or replacing conductors in transmission lines to maintain transmission efficiency and/or increase the capacity of existing lines; available for up to 50 percent of existing transmission capacity in the model).

To summarize, EnergyPATHWAYS is used to define energy demand scenarios. These demand parameters are then input into RIO, which is used to optimize supply-side investments in the power sector and fuel conversion processes and to determine optimal blends of fuel components. These optimized energy decisions are use as inputs for validating the EnergyPATHWAYS model, and the outputs represent an optimal scenario with the full, comprehensive accounting detail included in EnergyPATHWAYS.

Appendix C: Results Summarized by Sector

Below, the model's relevant outputs and sector-specific details are summarized by economic sector (buildings, transportation, or industry).

Figure C1: Emissions by Sector



TRANSPORTATION SECTOR RESULTS

Figure C2: Transportation Emissions

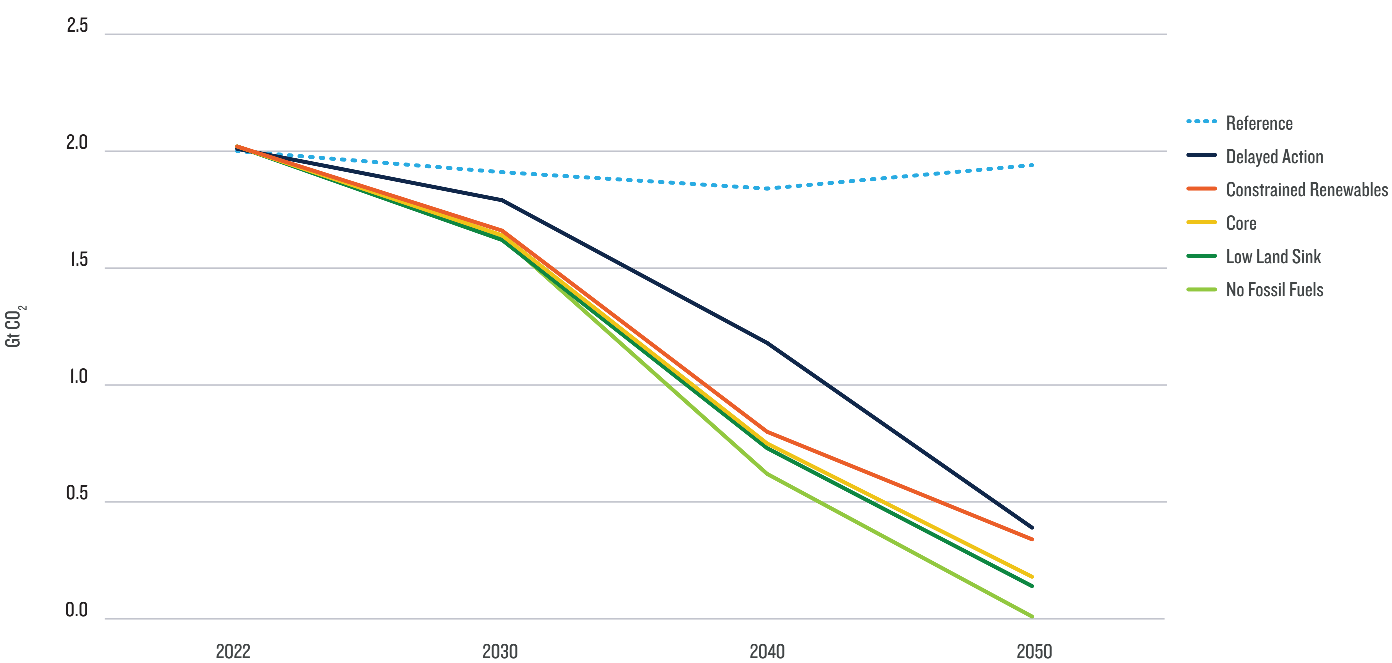
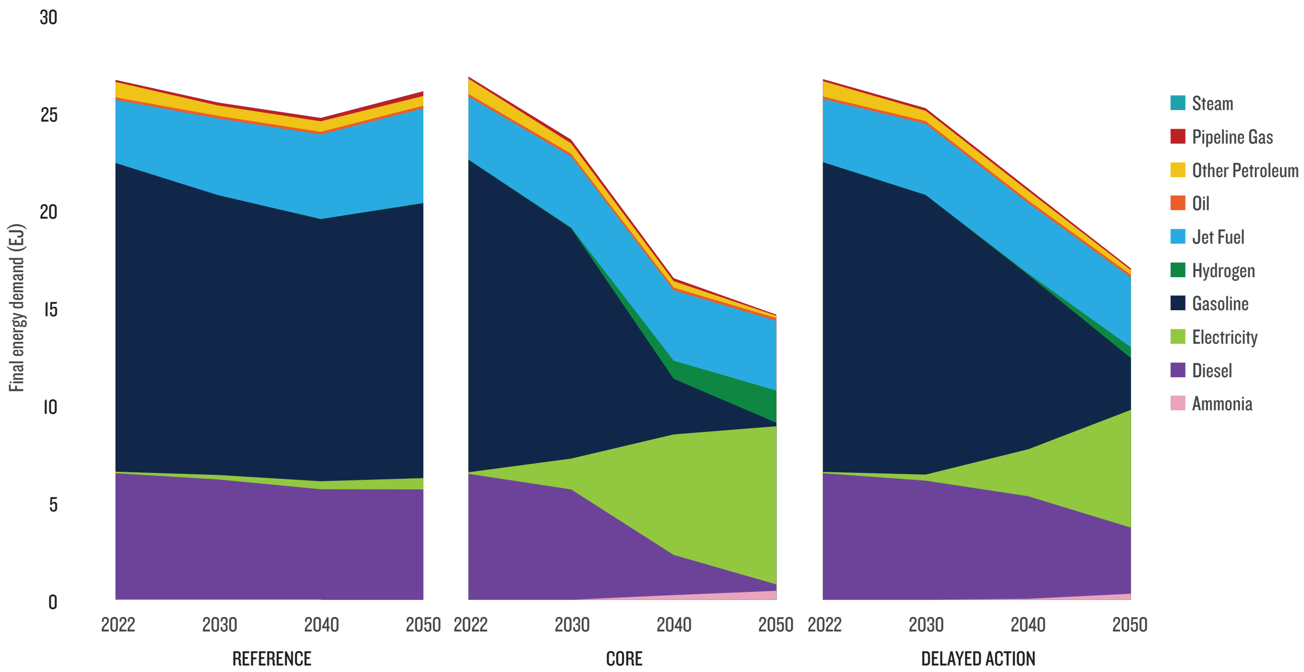


Figure C3: Transportation Final Energy Demand by Fuel



BUILDINGS SECTOR

Figure C4: Buildings Emissions

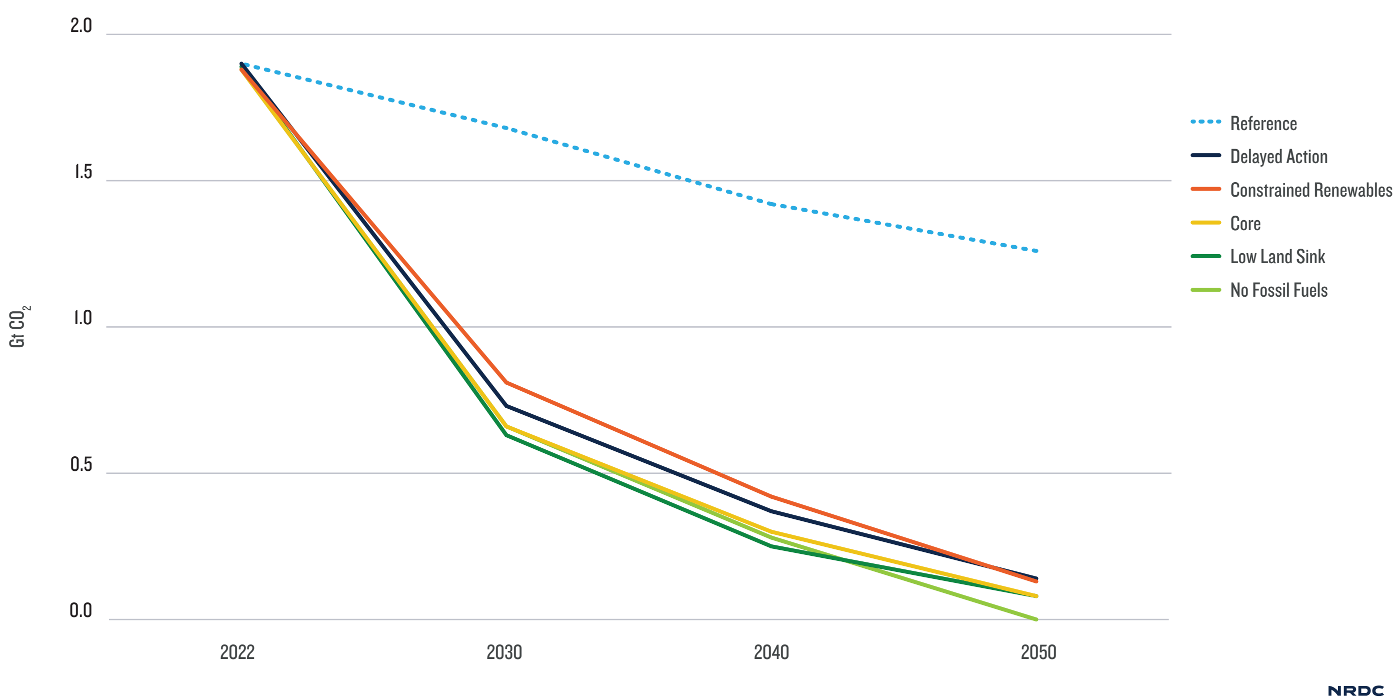
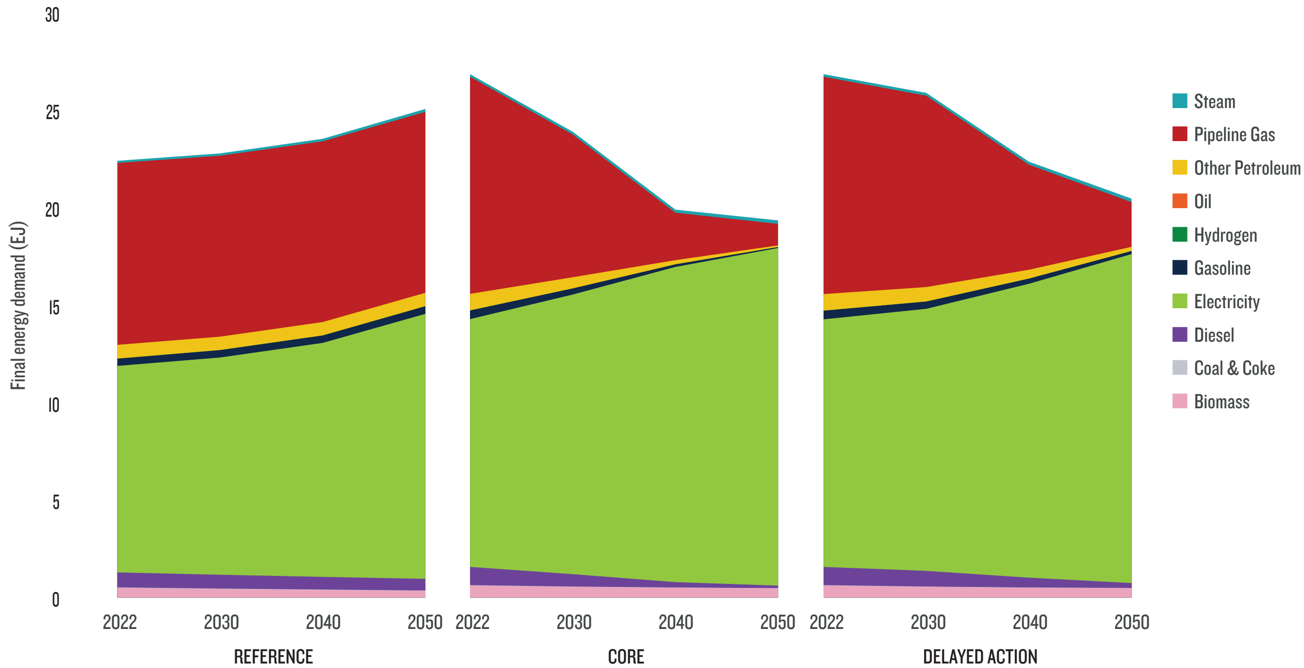
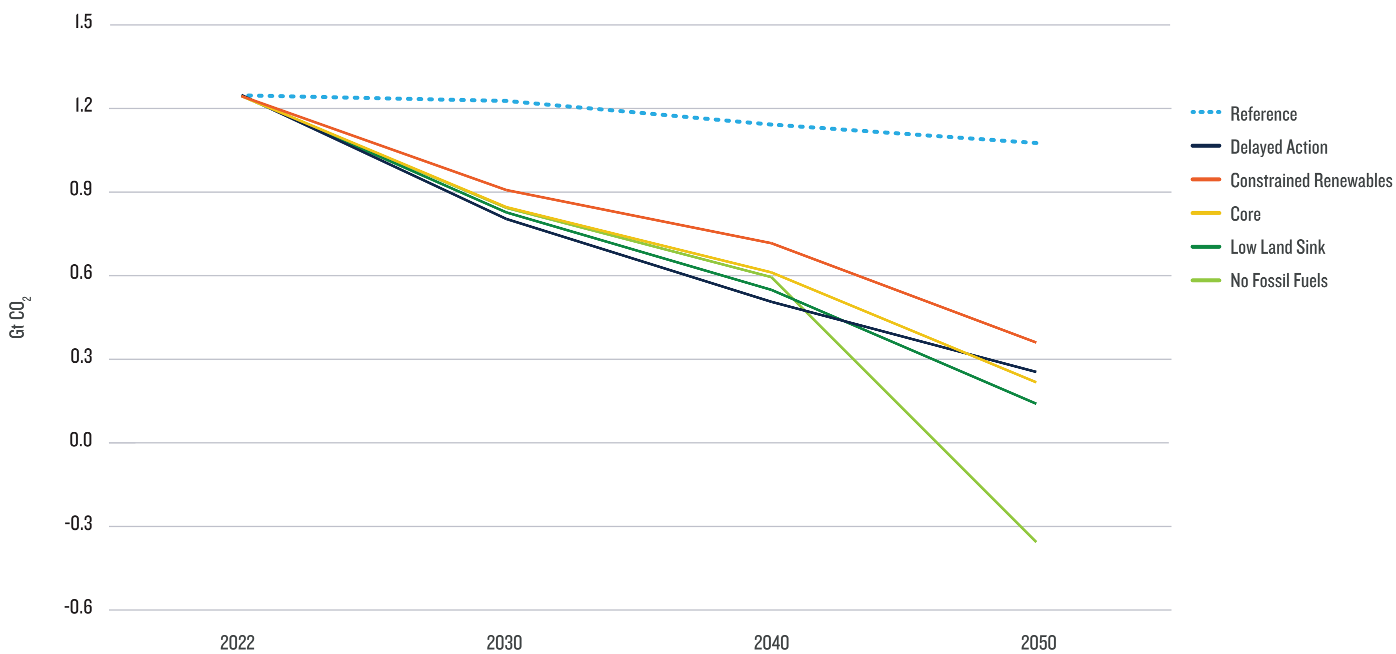


Figure C5: Buildings Final Energy Demand by Fuel



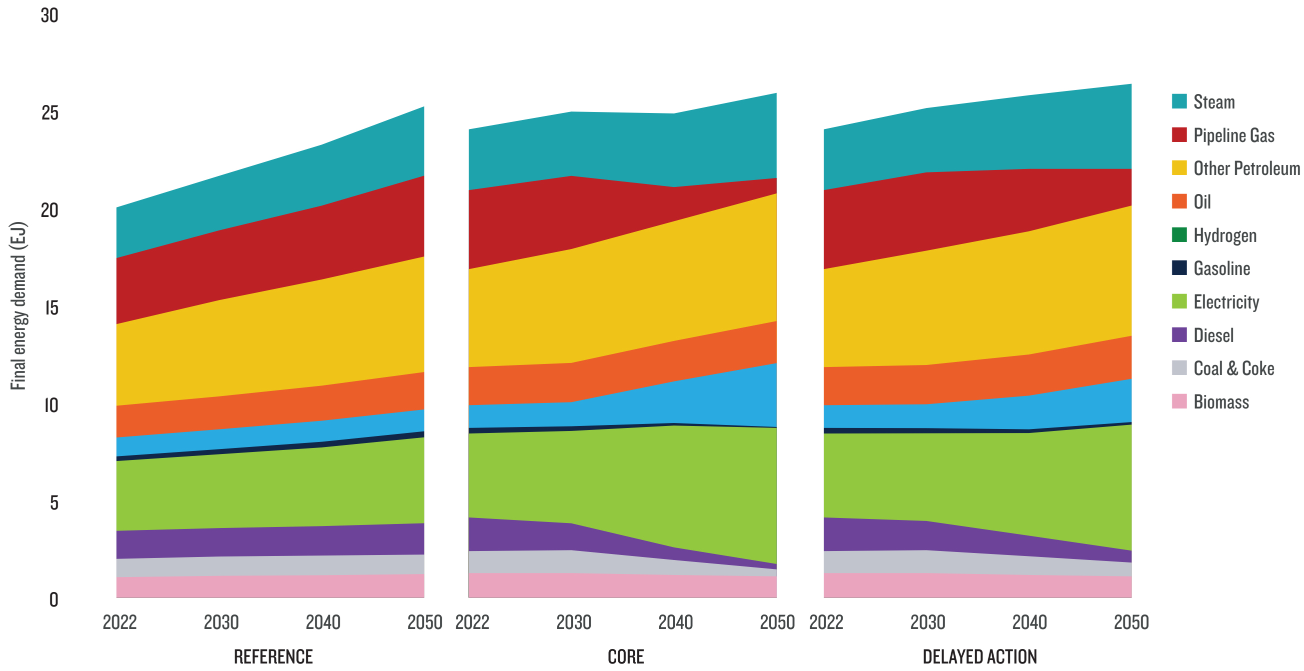
Industrial Sector

Figure C6: Industrial Emissions



Note: Industrial emissions in this graph are inclusive of sequestered emissions related to product and bunkering and industrial carbon capture and sequestration.

Figure C7: Industrial Final Energy Demand by Fuel



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