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Designs for Net-Zero Energy Systems: Meta-Analysis of U.S. Economy-Wide Decarbonization Studies

DESIGNS FOR NET-ZERO ENERGY SYSTEMS: META-ANALYSIS OF U.S. ECONOMY-WIDE DECARBONIZATION STUDIES (Meta NZ)

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Executive Summary

This report provides a detailed meta-analysis of U.S. economy-wide net-zero studies, enabling like-for-like comparisons among different studies and scenarios. This study was performed through a process of collaboration among the authors of each of the five studies evaluated. This meta-analysis brings together a diversity of perspectives, analytical frameworks, and datasets to offer a comprehensive look at designs for net-zero energy systems.

Informing the Designs of Net-Zero Systems

Transitioning to net-zero requires an informed view of net-zero energy system designs. What pathways and technologies might be deployed? How might these systems be integrated? What infrastructure is critical to achieve that integration? What investments might be needed? Economy-wide net-zero modeling efforts are helping to answer these questions.

Energy system models offer an analytically informed means for evaluating the potential evolution of energy systems. These models leverage economic optimization to balance energy supply and demand under different scenarios, assumptions, and inputs. Historically, the scope of these models was limited to a particular sector (e.g., the power sector) and/or focused on less stringent emissions targets (e.g., 50% reduction). It has only been within recent years that modeling teams have taken on the complex task of evaluating the full U.S. economy under net-zero conditions. By looking across sectors, value chains, and energy carriers, these modeling efforts provide some of the most in-depth assessments available for informing the design of net-zero energy systems.

This report presents a comparison of five publicly accessible comprehensive U.S. economy-wide net-zero studies.[1,2] This meta-analysis is built upon a collaborative effort among the team members from each of these studies aimed at ensuring accurate interpretation of model information and results. The harmonized set of results presented in this report offers fresh insight into the design of net-zero systems—the common approaches, the range of possibilities, and the areas of differentiation.

Table ES-1: Studies Evaluated in this Meta-Analysis

Study	Team	Date Published	Scenarios Evaluated
Net-Zero 2050: U.S. Economy-Wide Deep Decarbonization Scenario Analysis (report)	Low-Carbon Resources Initiative (LCRI)	September 2022	3 net-zero 1 business as usual 0 other
An Open Energy Outlook: Decarbonization Pathways for the USA (report)	Open Energy Outlook (OEO)	September 2022	1 net-zero 1 business as usual 2 other
Annual Decarbonization Perspective: Carbon-Neutral Pathways for the United States 2022 (report)	Evolved Energy Research (EER)	August 2022	7 net-zero 1 business as usual 0 other
Net-Zero America: Potential Pathways, Infrastructure, and Impacts (report)	Princeton University	October 2021	5 net-zero 1 business as usual 0 other
Pathways to Net-Zero Emissions (report)	Decarb America	February 2021	7 net-zero 1 business as usual 1 other

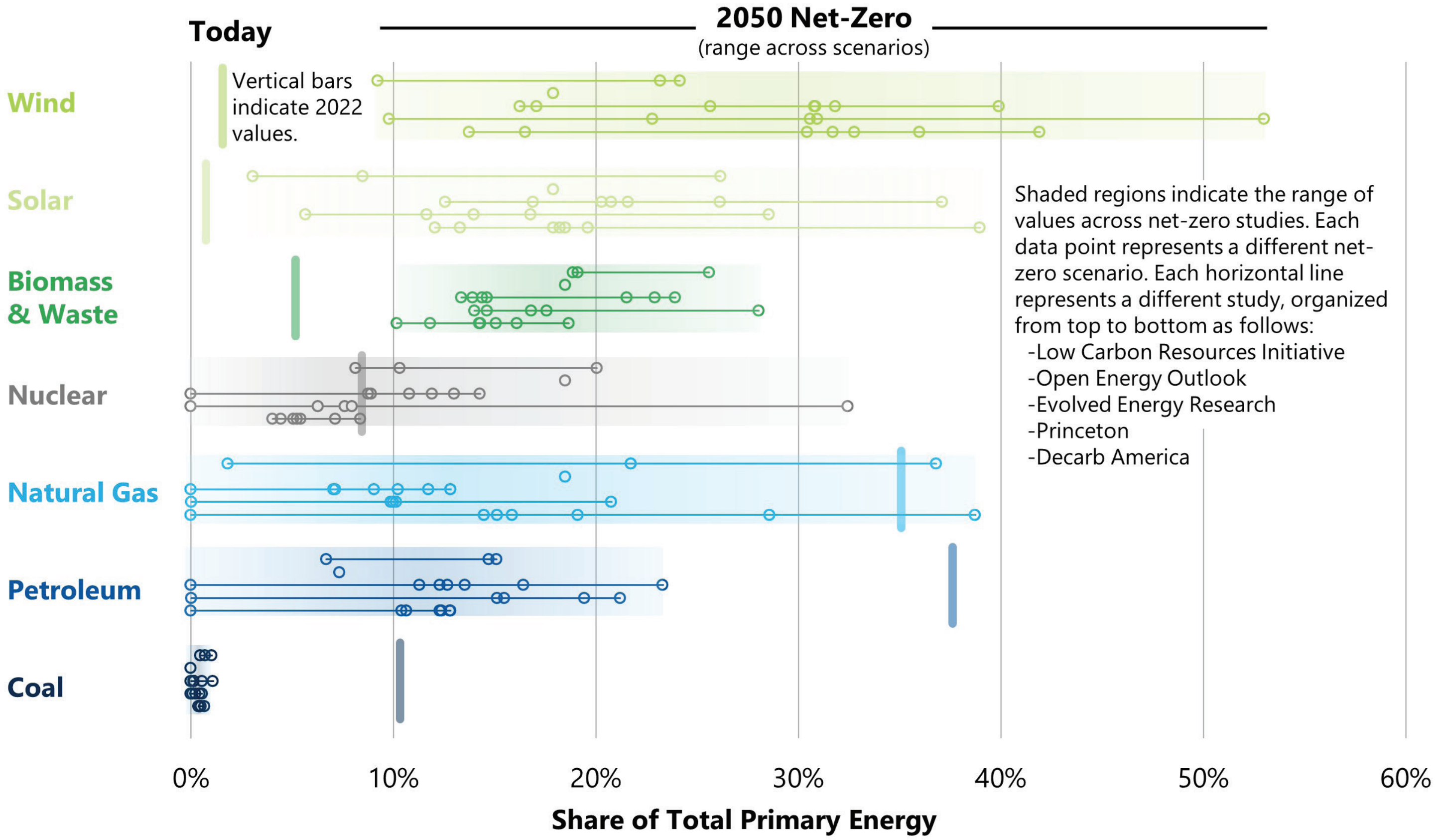
Commonalities Across U.S. Economy-Wide, Net-Zero Studies

Renewables grow the supply of low-carbon energy. Wind and solar deployments increase considerably from today's levels (Figure ES-1), contributing a large share of electricity generation. Bioenergy resources, such as cellulosic biomass, grow substantially to serve a range of markets, including low-carbon fuels production. Altogether, these studies project that renewables could supply the majority of energy in a net-zero U.S. economy.

Electricity expands across sectors. Today, 18% of energy supplied to end-use customers is in the form of electricity—the remainder is in the form of a gaseous, liquid, or solid fuel. This share grows to between 36 and 59% of all final energy under these net-zero scenarios (Figure ES-2). Electricity generation is dominated by wind and solar across most scenarios, with other forms of generation deployed to balance the inherent variability of these resources. Energy storage technologies, predominantly batteries, are deployed to balance short-duration variability (hourly, intraday). Fuel-based generation, chiefly from pipeline gas, is leveraged to balance long-duration (multiday, seasonal) renewables and demand variations, with total installed capacity comparable to today in most net-zero scenarios.

Fuels diversify and serve multiple markets. Fuels continue to have a sizeable role in these net-zero systems, accounting for between 41 and 64% of final energy (Figure ES-2). In all net-zero scenarios, fuels are used across all end-use sectors—transportation, industry, and buildings. Liquid fuels and pipeline gas are increasingly produced via low-carbon approaches, such as bioenergy and synthetic fuel production, where hydrogen and carbon dioxide are used as feedstocks to produce fuels.[3,4] Hydrogen grows considerably from today's levels, though is below 10% of final energy in 2050 across most scenarios, with production through a variety of low-carbon pathways including electrolysis, natural gas with carbon capture and sequestration, and bioenergy with carbon capture and sequestration.

Figure ES-1: Share of Total Primary Energy by Source

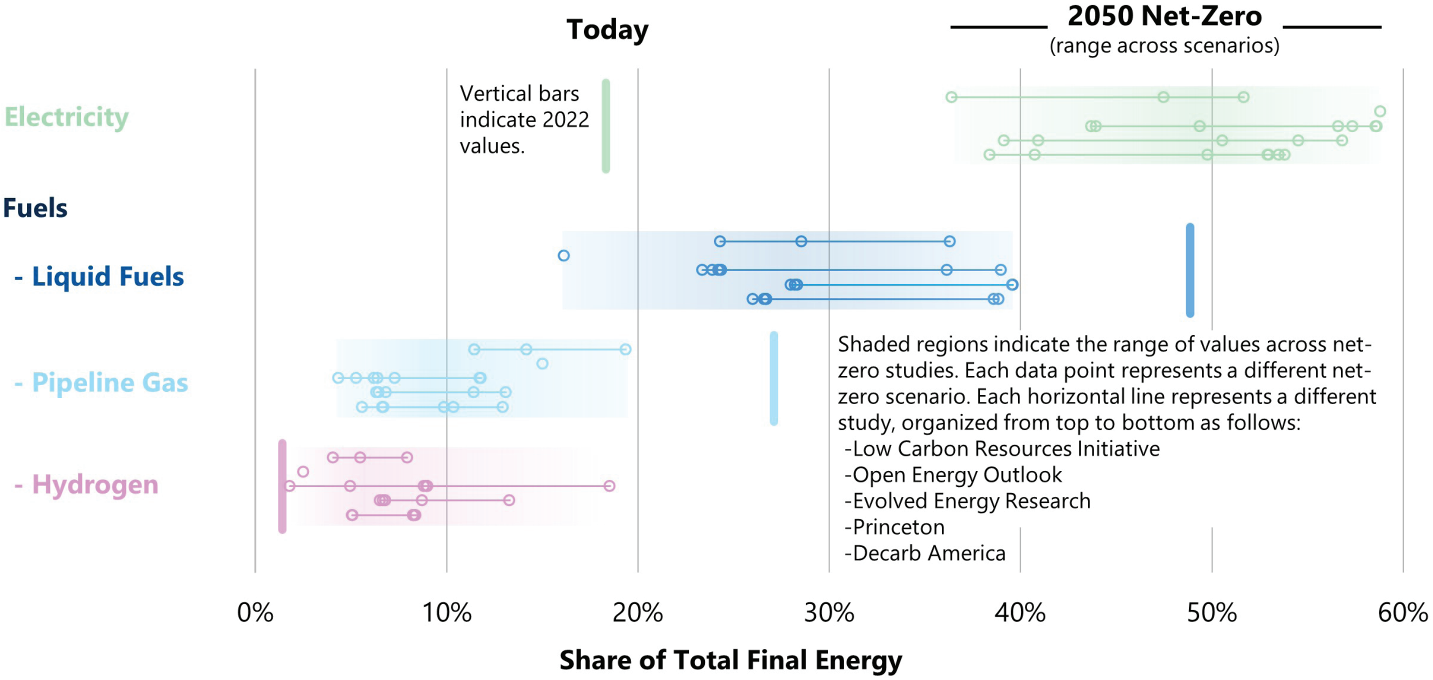


Vertical bars indicate 2022 values.

Shaded regions indicate the range of values across net-zero studies. Each data point represents a different net-zero scenario. Each horizontal line represents a different study, organized from top to bottom as follows:
- Low Carbon Resources Initiative
- Open Energy Outlook
- Evolved Energy Research
- Princeton
- Decarb America

Renewables grow the supply of low-carbon energy, with nuclear and fossil fuels contributing to the energy mix in most net-zero scenarios. Geothermal and hydro energy, not shown in this figure, account for 2% or less of primary energy consumption across net-zero scenarios.

Figure ES-2: Share of Total Final Energy by Carrier



Vertical bars indicate 2022 values.

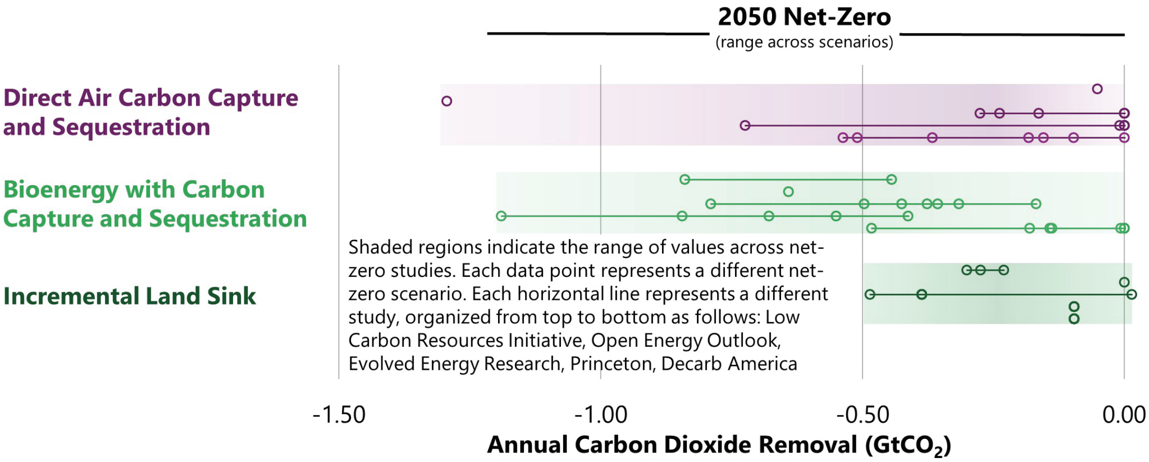
Shaded regions indicate the range of values across net-zero studies. Each data point represents a different net-zero scenario. Each horizontal line represents a different study, organized from top to bottom as follows:
- Low Carbon Resources Initiative
- Open Energy Outlook
- Evolved Energy Research
- Princeton
- Decarb America

Final energy, the form of energy used by end-use customers in the buildings, transportation, and industrial sectors, transforms in net-zero scenarios relative to today. The share of final energy supplied by electricity grows in all scenarios. Gaseous and liquid fuels continue to serve across sectors, with growing shares of hydrogen. Coal and biomass, not shown in this figure, provide less than 2% and 4% of final energy across net-zero scenarios, respectively. These final energy results include both energy and non-energy use of fuels.[5]

Efficiency reduces energy consumption while enabling economic growth. All of these studies target net-zero emissions in 2050. These net-zero studies assume continued economic growth over the next three decades, leveraging projections from the U.S. Energy Information Agency for future energy service demands (e.g., vehicle miles driven, square footage of buildings heated and cooled, etc.). Even with growing service demand, final energy consumption is reduced from 81 EJ today to between 40 and 62 EJ in 2050 across net-zero scenarios. Similarly, primary energy consumption is reduced from 100 EJ today to between 52 and 88 EJ in 2050. These reductions are achieved through efficiency improvements across sectors, including increased adoption of electric vehicles and heat pumps which have substantial efficiency gains relative to conventional combustion vehicles and gas-fired furnaces respectively.[6]

Carbon dioxide removal balances remaining emissions. The net-zero scenarios evaluated in these studies achieve deep emissions reductions relative to today; yet all scenarios indicate some level of positive emissions remaining from costly-to-abate activities. These positive emissions are balanced by negative emissions approaches where carbon dioxide is removed from the atmosphere and durably stored. This can include technologies such as direct air carbon capture and sequestration, or bioenergy with carbon capture and sequestration. Carbon dioxide removal can also be achieved by incrementally increasing the carbon land sink through changing land use practices and other means. In these net-zero systems, carbon dioxide removal pathways account for total negative emissions flows of between −0.3 and −1.9 $GtCO_2$/year (Figure ES-3) versus total positive greenhouse gas emissions of 6.3 $GtCO_{2e}$/year today.

Figure ES-3: Annual Carbon Dioxide Removal by Approach



Shaded regions indicate the range of values across net-zero studies. Each data point represents a different net-zero scenario. Each horizontal line represents a different study, organized from top to bottom as follows: Low Carbon Resources Initiative, Open Energy Outlook, Evolved Energy Research, Princeton, Decarb America

Carbon dioxide removal is deployed across net-zero scenarios to offset positive emissions from difficult-to-abate activities. Incremental land sink characterizes the change in the carbon land sink from today's levels (Updated February 2024).[7]

Implications for Transitioning to Net-Zero

There is no single design for net-zero energy systems. Each of these studies points to a wide array of energy carriers, technologies, and regionally specific solutions to meet the energy demands of an expanding U.S. economy. The range of results across these studies highlights a range of perspectives and possibilities for the design of net-zero systems. This range stems partly from intentioned efforts within these studies to evaluate corner point scenarios as a means for highlighting the dynamics and tradeoffs of different net-zero designs. Despite their differences, these studies are consistent in finding that constrained scenarios—where certain technologies or pathways are explicitly excluded or limited—have higher costs than unconstrained scenarios. There is value in considering a range of options to reach net-zero, particularly in these early stages of energy transitions when there is a lot of learning yet to come. At the same time, the insights shared across these studies can inform the decisions made today.

Net-zero systems entail net-zero infrastructure. Large-scale investment in energy infrastructure is needed to achieve the unprecedented level of transformation projected across these studies. These models point to expansion of the electric grid to accommodate increasing wind and solar deployments and growing electricity demands. Infrastructure to move and store gaseous molecules at scale is required to employ hydrogen as a versatile low-carbon energy carrier and to enable carbon dioxide removal and sequestration. The existing liquid hydrocarbons and pipeline gas infrastructure will need to be leveraged where it supports the net-zero system designs envisioned in these studies.

Innovation is a foundation for transformation. The net-zero designs envisioned in these studies all rely on large-scale deployment of new technologies. This includes investing in innovations already proven out at scale, such as wind, solar, and battery technologies. It also includes investing in a broad portfolio of nascent solutions, such as hydrogen, bioenergy, carbon capture, and sequestration. The net-zero systems projected in these studies are based on the information available today. The understanding of these systems is certain to evolve as progress is made towards net-zero. Innovation in a variety of forms—technologies, operating models, market frameworks, and beyond—will be central to enabling the transition to net-zero economies.

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U.S. Economy-Wide, Net-Zero Analyses

More than 90 countries have committed to reaching net-zero by the end of this century,[8] with the United States targeting economy-wide net-zero emissions by 2050. The list of countries with net-zero pledges expands every year. **Delivering on these net-zero commitments requires an informed view of the design of net-zero systems**—the technologies, the infrastructure, and the associated investments to deploy, integrate, and operate these systems.

A growing number of researchers, modelers, and analysts are working to inform the design of energy systems capable of achieving economy-wide, net-zero emissions by mid-century. These emerging efforts consider a range of sectors, value chains, and energy carriers, offering detailed assessments and insights on least-cost pathways to reach net-zero. An increasing number of U.S. economy-wide, net-zero studies have been performed in recent years. To draw upon the collective wisdom of these analyses, a framework for comparing and contextualizing studies relative to one another is needed.

This study provides a comprehensive assessment of U.S. economy-wide analyses performed to date, enabling like-for-like comparisons of results, scenarios, and approaches. This meta-analysis—study of studies—has been performed through a collaborative effort among team members from each of the studies evaluated to ensure accurate interpretation of model information and results. The harmonized set of results presented in this report offers fresh insight into the design of net-zero systems—the common approaches, the range of possibilities, and the areas of differentiation.

Economy-Wide Models

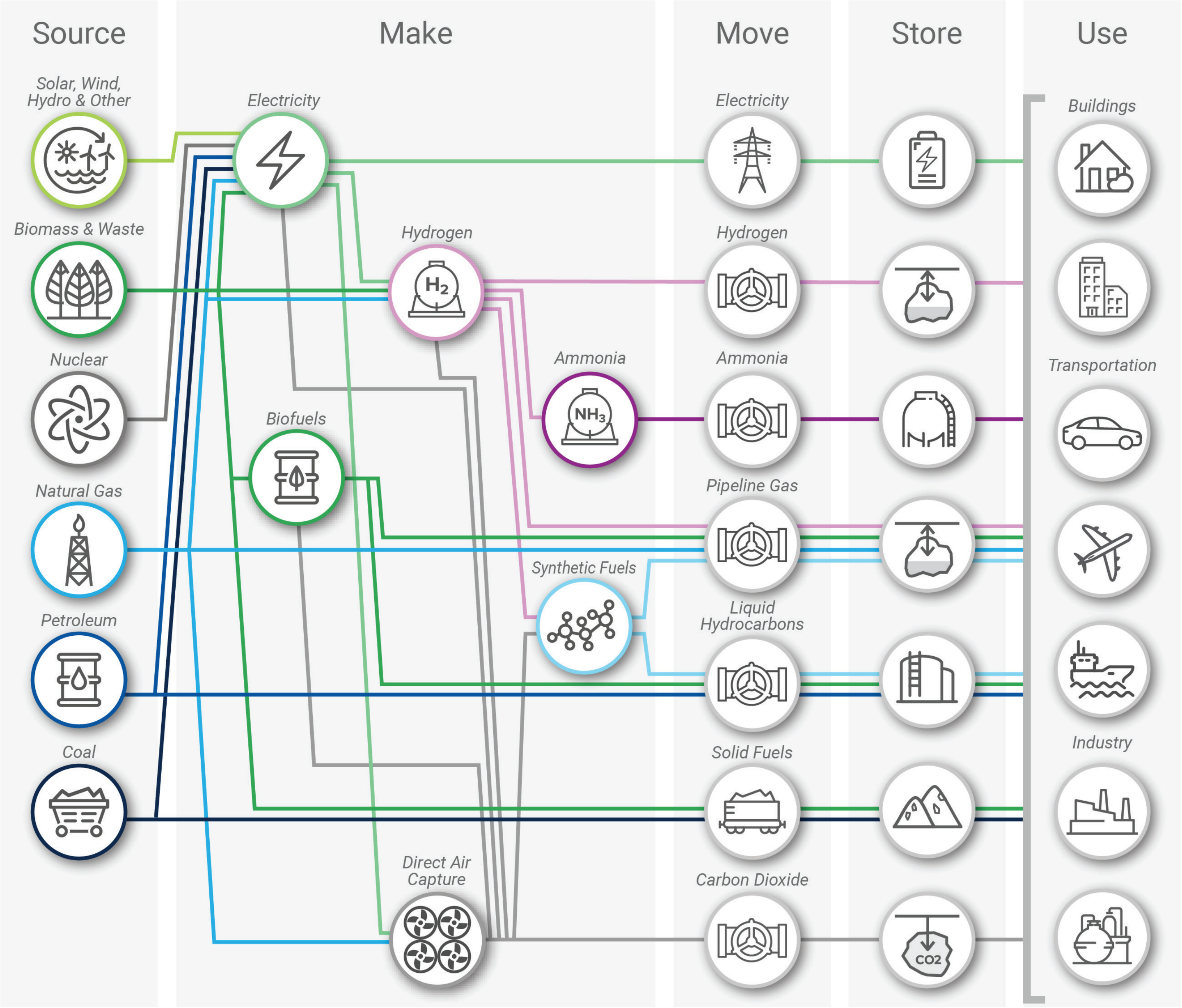
The economy-wide energy systems models evaluated here encompass a comprehensive set of sectors, technologies, and energy carriers, applying economic optimization to solve for pathways to **source, make, move, store,** and **use** energy. When exploring net-zero scenarios, these models solve for systems that achieve economy-wide carbon neutrality under assumptions about technologies, markets, and policies. While the results from these models point to deep reductions in greenhouse gas (GHG) emissions, the economy-wide framing of these analyses is such that negative emissions activities can be deployed in one part of the economy to balance remaining positive emissions elsewhere in the economy.

These models apply economic optimization to balance energy supply and demand under different scenarios and assumptions. Demand projections are typically defined in terms of energy services: for example, the vehicle miles driven for a given vehicle class, or the square footage of buildings heated and cooled in a given climate zone. These service demands can be met in a variety of ways. For example, internal combustion vehicles, battery electric vehicles, or hydrogen fuel cell vehicles could all be used to satisfy vehicle service demands. Determining which demand-side options will help realize the net-zero target requires additional supply-side information. Namely, the associated cost and emissions of supplying liquid fuels, electricity, and hydrogen to these vehicles. There are multiple ways to produce and deliver these energy carriers, each with their own cost, performance, and emissions profiles. The economy-wide models evaluated in this study incorporate this information to solve for least-cost pathways to supply energy across the economy.

The scope of technologies included in these models is extensive (Figure 1). A comprehensive set of primary energy resources is considered—renewable, fossil, nuclear—all of which can be leveraged to generate electricity. Hydrogen can be produced from electricity via electrolysis or through conversion processes that leverage fossil or bioenergy resources. Liquid and gaseous hydrocarbon fuels can be produced through conventional fossil-based routes, or bioenergy and synthetic pathways. These synthetic fuels pathways leverage hydrogen and captured carbon dioxide (CO_2) as feedstocks. Carbon dioxide can be captured from power generation, hydrogen production, biofuels processing, or other industrial facilities, as well as directly from the air via direct air capture (DAC) technologies. While CO_2 can be used as a feedstock, it can also be sequestered to abate emissions from fossil sources or to achieve negative emissions flows when captured from bioenergy sources or the air.[9] Negative emissions flows can also be achieved through activities aimed at expanding the land sink to enhance the terrestrial uptake of CO_2. These negative emissions activities can offset positive emissions from activities elsewhere in the economy.

In addition to how energy is **sourced** and **made**, these models characterize the ways in which energy carriers are **moved**, **stored**, and **used**. The existing electric grid and fuels infrastructure are represented. These models also characterize the build-out of new infrastructure to support growing demand, including electricity transmission and distribution infrastructure, and transport and storage

Figure 1: Illustrative Technology Pathways Considered in Economy-Wide, Net-Zero Analyses



A broad set of sectors, technologies, and energy carriers are considered in economy-wide, net-zero analyses. The potential designs of net-zero systems involve a diverse array of energy value chains with a high degree of integration for how to source, make, move, store, and use energy.

networks for hydrogen, ammonia, and captured carbon dioxide. Once energy carriers are delivered to end-use markets, these models consider a range of end-use technology options to meet energy service demands—vehicles, appliances, and equipment.

Economy-wide, net-zero models include several low-carbon technologies that are still at relatively early stages of development and deployment, which carry uncertainty regarding their cost, performance, and emissions. These models apply forward-looking estimates for these early-stage technologies based on the information available today. This information—the costs and performance of these technologies, and the energy sources they leverage—will evolve in progressing towards net-zero. Technological breakthroughs and other disruptions could significantly alter the net-zero energy system designs projected by these models. Nonetheless, these modeling approaches provide some of the most comprehensive and analytically grounded tools available to inform the designs of net-zero systems.

Table 1: Studies Considered in this Meta-Analysis

Study	Team	Date Published	Primary Energy	Final Energy	Transportation	Industry	Buildings	Electricity Capacity	Electricity Generation	Hydrogen Production	Pipeline Gas Supply	Liquid Fuel Supply	GHG Emissions
New Energy Outlook U.S. (report)	Bloomberg New Energy Finance	August 2023	🟦	🟦	🟦	🟦	🟦	🟦	🟩	🟦	🟦	🟦	🟩
BP Energy Outlook 2023[10] (report)	BP	July 2023	🟩	▨	▨	▨	▨	▨	▨	▨	▨	🟦	🟩
Net-zero CO_2 by 2050 scenarios for the United States in the Energy Modeling Forum 37 study (report)	Energy Modeling Forum (EMF)[11]	April 2023	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟦	🟦	🟩
Shell Scenarios Sketch: A U.S. Net-Zero CO_2 Energy System by 2050 (report)	Shell	March 2023	🟩	🟩	🟦	🟦	🟦	🟦	🟩	🟦	🟦	🟦	🟩
Pathways to Net-Zero for the U.S. Energy Transition (report)	Energy Pathways USA[12]	November 2022	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
LCRI Net-Zero 2050: U.S. Economy-wide Deep Decarbonization Scenario Analysis (report)	Low-Carbon Resources Initiative (LCRI)[13]	September 2022	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
An Open Energy Outlook: Decarbonization Pathways for the USA (report)	Open Energy Outlook (OEO)[14]	September 2022	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Annual Decarbonization Perspective: Carbon-Neutral Pathways for the United States (report)	Evolved Energy Research (EER)	August 2022	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Navigating America's net-zero frontier: A guide for business leaders (report)	McKinsey Sustainability	May 2022	🟦	🟦	🟦	🟦	🟩	🟦	🟩	🟩	🟦	🟦	🟩
The Long-Term Strategy of The United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050 (report)	U.S. Executive Office of the President	November 2021	🟦	▨	▨	▨	▨	▨	🟩	🟦	🟦	🟦	🟩
Net-Zero America: Potential Pathways, Infrastructure, and Impacts (report)	Princeton University	October 2021	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Pathways to Net-Zero Emissions (report)	Decarb America (DA)[15]	February 2021	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

🟩 *Data publicly available* ▨ *Data partially publicly available* 🟦 *Data not publicly available*

Studies Considered

Several U.S. decarbonization studies have been considered in this meta-analysis, as summarized in Table 1 below. The studies considered here align with the following criteria: (1) the study is focused on the U.S. economy; (2) at least one scenario in the study is targeted at achieving economy-wide, net-zero emissions; and (3) the results of the study are freely and publicly available.[16] To the authors' knowledge, Table 1 contains all such studies published to date.[17,18,19]

The scope of results reported varies across these studies. At present, this meta-analysis focuses on the five studies with the most comprehensive set of publicly available results. Future efforts, extending beyond the publication of this study, will seek to perform a detailed evaluation of a broader subset of the studies listed in Table 1.

Two studies listed in Table 1 are comparative in nature. The Energy Pathways USA study compared the results of two 2050 analyses—U.S. Energy Information Administration (EIA)'s Annual Energy Outlook (AEO) and the Princeton study—similar to this meta-analysis. The EMF 37 study investigated how different energy systems modeling platforms perform when given the same objective and guidelines for evaluating U.S. economy-wide deep decarbonization, providing granular insights into the impact of analytical methodology on model results. The meta-analysis presented here offers a broad comparison across five U.S. economy-wide, net-zero studies, encompassing different modeling approaches, input assumptions, and scenario definitions.

Studies Evaluated

Five of the 12 considered studies were evaluated in detail in this meta-analysis (Table 2). All five studies set a target of achieving U.S. economy-wide, net-zero emissions by 2050. These studies assumed continued economic growth over the next three decades, with increasing energy service demands. Projections of these energy service demands—such as the number of miles driven by given vehicle class, or the square footage of buildings heated and cooled in a given region—were based on estimates from the EIA's AEO for all five studies.

Table 2: Studies Evaluated in this Meta-Analysis

Study	Team	Net-Zero Target	Model	Service Demands	Demand Decisions	Supply Decisions	Scenarios
Net-Zero 2050: U.S. Economy-Wide Deep Decarbonization Scenario Analysis (report)	Low-Carbon Resources Initiative (LCRI)	net-zero CO_2 by 2050	US-REGEN	AEO 2020	model output	model output	3 net-zero 1 BAU 0 other
An Open Energy Outlook: Decarbonization Pathways for the USA (report)	Open Energy Outlook (OEO)	net-zero CO_2 by 2050	TEMOA	AEO 2022	model output	model output	1 net-zero 1 BAU 2 other
Annual Decarbonization Perspective 2022 (report)	Evolved Energy Research (EER)	net-zero GHGs by 2050	Energy PATHWAYS	AEO 2022	user input	model output	7 net-zero 1 BAU 0 other
Net-Zero America: Potential Pathways, Infrastructure, and Impacts (report)	Princeton University	net-zero GHGs by 2050	Energy PATHWAYS	AEO 2019	user input	model output	5 net-zero 1 BAU 0 other
Pathways to Net-Zero Emissions (report)	Decarb America (DA)	net-zero GHGs by 2050	Energy PATHWAYS	AEO 2019	user input	model output	7 net-zero 1 BAU 1 other

There are key differences across these studies, such as the way the net-zero target is defined. The LCRI and OEO studies targeted net-zero CO_2 emissions, whereas the EER, Princeton, and DA studies targeted net-zero emissions of several GHG emissions, including activities not directly associated with energy (e.g., agricultural livestock production).[20] This difference in definition has a meaningful impact on the total emissions burden to be abated.

All studies analyzed a multitude of technology options and pathways across sectors, solving for energy systems designs that achieve economy-wide net-zero emissions. All studies applied cost-optimization as part of the analytical framework, although the methodology applied varied across different studies.

The EER, Princeton, and DA studies used Evolved Energy Research's EnergyPATHWAYS model, and Evolved Energy Research participated in all three studies. In the EnergyPATHWAYS model, the demand-side technology mix is defined as based upon user-defined values. For example, the share of light-duty vehicle types—gasoline internal combustion vehicle, battery electric vehicle, hydrogen fuel cell vehicle, etc.—is defined by the user. The supply-side technology mix is optimized within the EnergyPATHWAYS model to achieve the lowest possible cost while satisfying the economy-wide emissions target. That is, the mix of technologies for making, moving, and storing electricity, hydrogen, and other fuels is optimized to provide the least cost set of supply-side technologies to meet energy demands, while satisfying the net-zero target.

The LCRI and OEO studies also optimize the supply-side technology mix. Additionally, these studies incorporate the demand-side technology mix and associated costs into the analytical framework. In these models the technology decisions at the point of end-use—for example, whether to heat a building with an electric heat pump, a gas-fired unit, or a hybrid electric-gas system—are solved as a model output, rather than being defined as a user input.

A wide range of scenarios were evaluated across these five studies.[21] These scenarios evaluate the trajectory of energy systems under different sets of assumptions and constraints, characterizing the impacts of various parameters on possible future outcomes. This range stems partly from intentioned efforts within these studies to evaluate corner point scenarios as a means for highlighting the dynamics and tradeoffs of different net-zero designs. Each study included a business-as-usual (BAU) scenario to evaluate the possible trajectory of the U.S. energy system under current policies. None of the studies evaluated incorporated the Inflation Reduction Act (IRA) incentives because the modeling activities were completed before the legislation passed.[22] Some studies, such as OEO and DA, included 'other' scenarios, which introduced emissions targets, but not net-zero targets. While these 'other' scenarios offer useful insights, they are not incorporated into the results of this meta-analysis. Rather, this meta-analysis primarily focuses on the results of net-zero scenarios.

Comparison of Net-Zero Results

The economy-wide, net-zero studies evaluated here differed in their reporting of results, making it difficult to make direct comparisons across studies. In this meta-analysis, the results of these different studies have been harmonized through a process of collaboration with the teams from each of the five studies to ensure accurate interpretation and representation. The results have been aligned to a consistent reporting basis across the following metrics: **total energy consumption, end-use sectors, energy carriers, greenhouse gas emissions,** and **cost**.

This meta-analysis seeks to identify insights when comparing across economy-wide, net-zero conditions. Thus, this report highlights the results of net-zero scenarios, specifically the 2050 end point of these scenarios—**the designs of U.S. economy-wide, net-zero energy systems**. The results presented here enable like-for-like comparisons of these net-zero designs, both across different studies and scenarios, and relative to today's energy systems.[23]

Total Energy Consumption

primary and final energy

End-Use Sectors

transportation, industry, and buildings

Energy Carriers

electricity, hydrogen, pipeline gas, and liquid fuels

Greenhouse Gas Emissions

positive and negative emissions

Cost

total cost of deploying and operating future energy systems

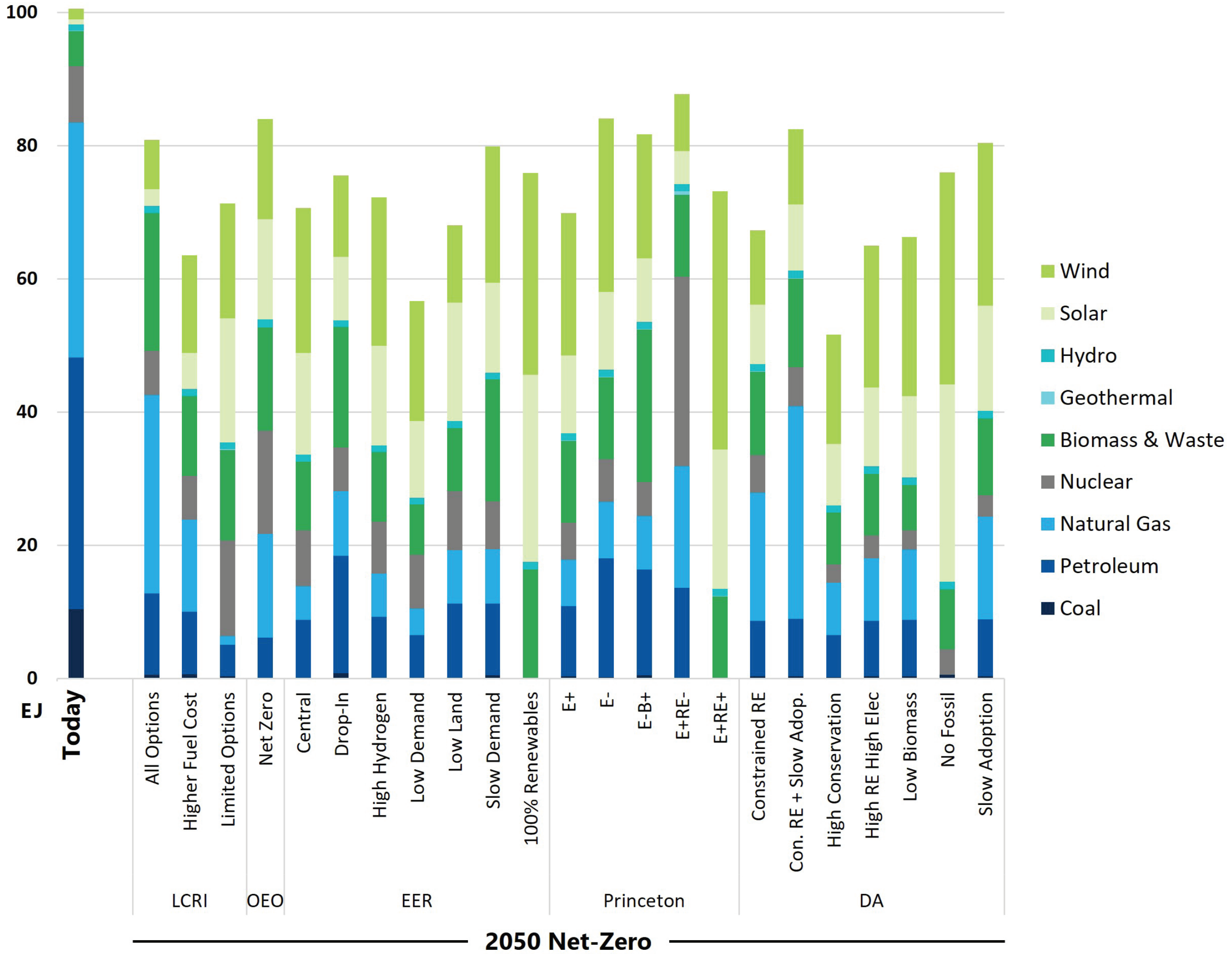
Total Energy Consumption

The net-zero studies evaluated here all assume continued economic growth from now until reaching net-zero in 2050, leveraging information from the EIA to project future energy service demands (e.g., vehicle miles driven of a given vehicle class, building square footage heated and cooled, etc.). Even with growing service demand, final energy consumption is reduced from 81 EJ today to between 40 and 62 EJ in 2050 across net-zero scenarios.[24,25] Similarly, primary energy consumption is reduced from 100 EJ today to between 52 and 88 EJ in 2050 (Figure 2). These reductions are achieved through efficiency improvements across sectors. The reported reduction in primary energy consumption is also an artifact of the reporting convention employed here for wind and solar technologies, where the produced energy is directly reported (e.g., the electricity generated from a solar panel) rather than the available energy (e.g., the sunlight energy impinging on a solar panel).

Many net-zero scenarios suggest that renewables could supply the majority of energy in a net-zero U.S. economy. Wind and solar deployments increase considerably from today's levels, contributing to large shares of electricity generation. Wind contributes more primary energy than solar in most scenarios. Energy from biomass and waste increases from 5% today to 10–28% in 2050. Bioenergy resources, such as cellulosic biomass, grow substantially to serve a range of markets, especially low-carbon fuels production. Hydro energy is similar to today across scenarios. Geothermal energy is nearly zero in all but two scenarios.

Fossil energy resources continue to play a role across these net-zero systems. Coal is largely eliminated, other than for uses in heavy industrial applications like steel and cement. Consumption of petroleum and natural gas decreases but is non-zero unless it is explicitly excluded under the constraints of a given scenario. Petroleum contributes 7–23% of primary energy and natural gas contributes 7–39% in net-zero scenarios where fossil fuels and carbon sequestration are allowed within the scenario definition. Carbon capture and sequestration (CCS) is deployed to abate fossil emissions across many scenarios. Unabated use of fossil fuels is also present

Figure 2: Annual Primary Energy Consumption by Source (EJ)



Primary energy consumption decreases relative to today in all net-zero scenarios as a result of efficiency improvements across energy value chains. Renewable energy deployment grows considerably. Fossil fuel consumption decreases but remains, except for scenarios that explicitly prohibit their use.

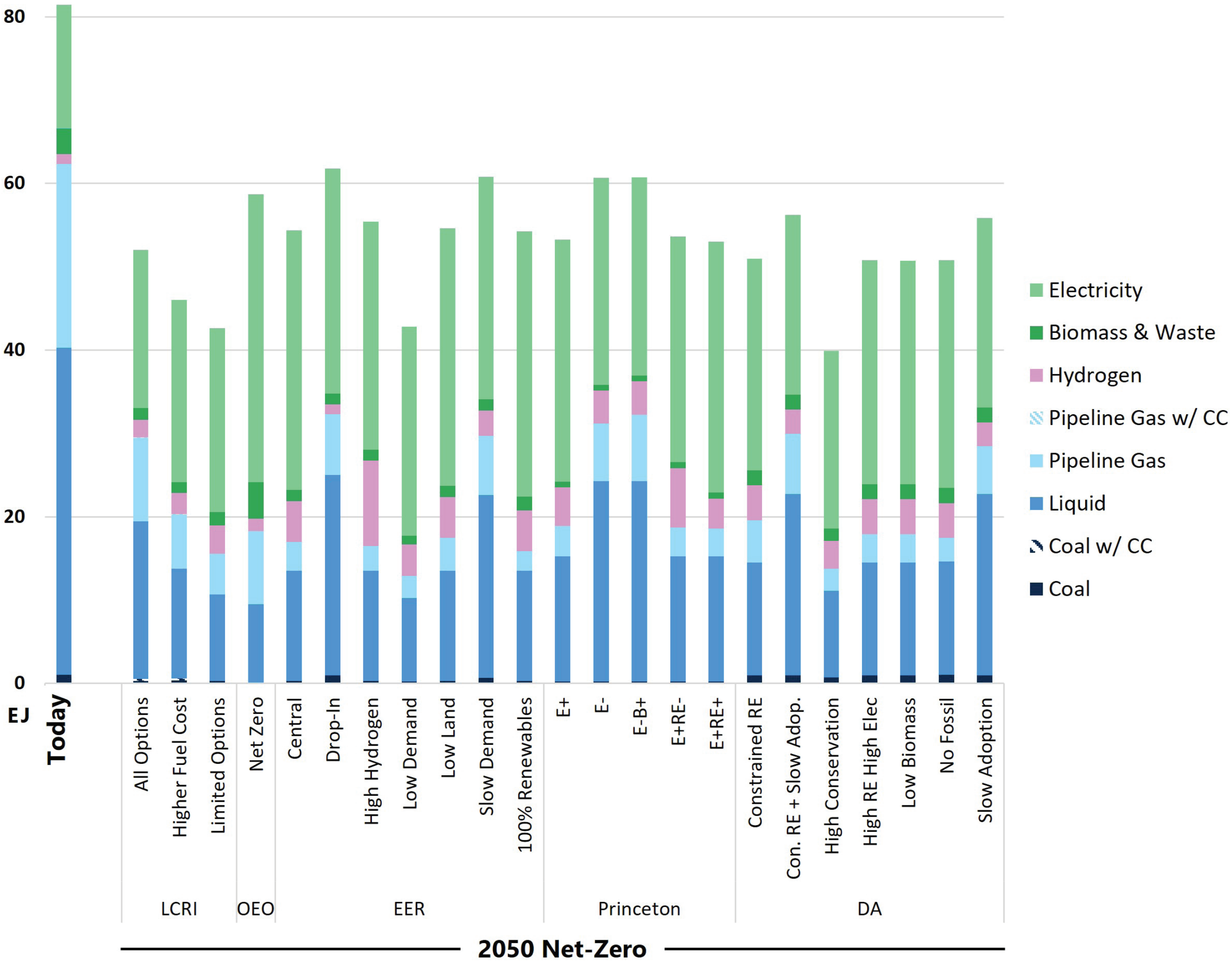
across all scenarios where fossil fuels are allowed, with associated emissions offset by carbon dioxide removal (CDR) approaches to achieve the economy-wide, net-zero target. Fossil resources also continue to be leveraged for non-energy purposes as feedstock for production of chemicals and materials.

Nuclear energy is used for power generation in all scenarios unless it is explicitly excluded under the constraints of a given scenario.[26] Some net-zero scenarios point to declines in nuclear energy relative to today, whereas other scenarios point to increases in nuclear energy through growing deployment of small modular reactors.

Final energy also decreases in all scenarios relative to today due to efficiency improvements across end-use sectors. Electricity use expands, with increasing shares in transportation, buildings, and industry. Electric vehicles and heat pumps particularly arise as cost-competitive technologies with substantial efficiency gains, driving increases in electricity consumption and decreases in overall final energy consumption. Today, 18% of energy supplied to end-use customers is in the form of electricity. This share grows to between 36 and 59% of all final energy under these net-zero scenarios, serving an even larger share of energy service demands as a result of the relatively higher efficiencies achieved for electricity-based equipment.

Solid, liquid, and gaseous fuels continue to be supplied to end-use markets in these net-zero systems, accounting

Figure 3: Annual Final Energy Consumption by Energy Carrier (EJ)



Final energy supplied to end-use consumers decreases in all net-zero scenarios relative to today as a result of efficiency improvements in vehicles, appliances, and other equipment. Electricity expands across sectors, with total consumption growing considerably from today's levels. Energy delivered to consumers as a fuel decreases but still makes up roughly half of final energy consumed in most net-zero scenarios.

for between 41 and 64% of final energy. Fuels are used across all end-use sectors—transportation, industry, and buildings—in all net-zero scenarios. Liquid fuels and pipeline gas are increasingly produced via low-carbon approaches such as bioenergy and synthetic fuel production, where hydrogen and carbon dioxide are used as feedstocks to produce fuels.[27,28] Hydrogen grows considerably from zero today to 2–19% of final energy in 2050, with production through a variety of low-carbon pathways including electrolysis, natural gas with carbon capture and sequestration (CCS), and bioenergy with carbon capture and sequestration (BECCS).[29] Liquid fuels, particularly petroleum-derived liquids, are also leveraged as feedstocks for non-energy uses and included in the results reported in Figure 3.[30]

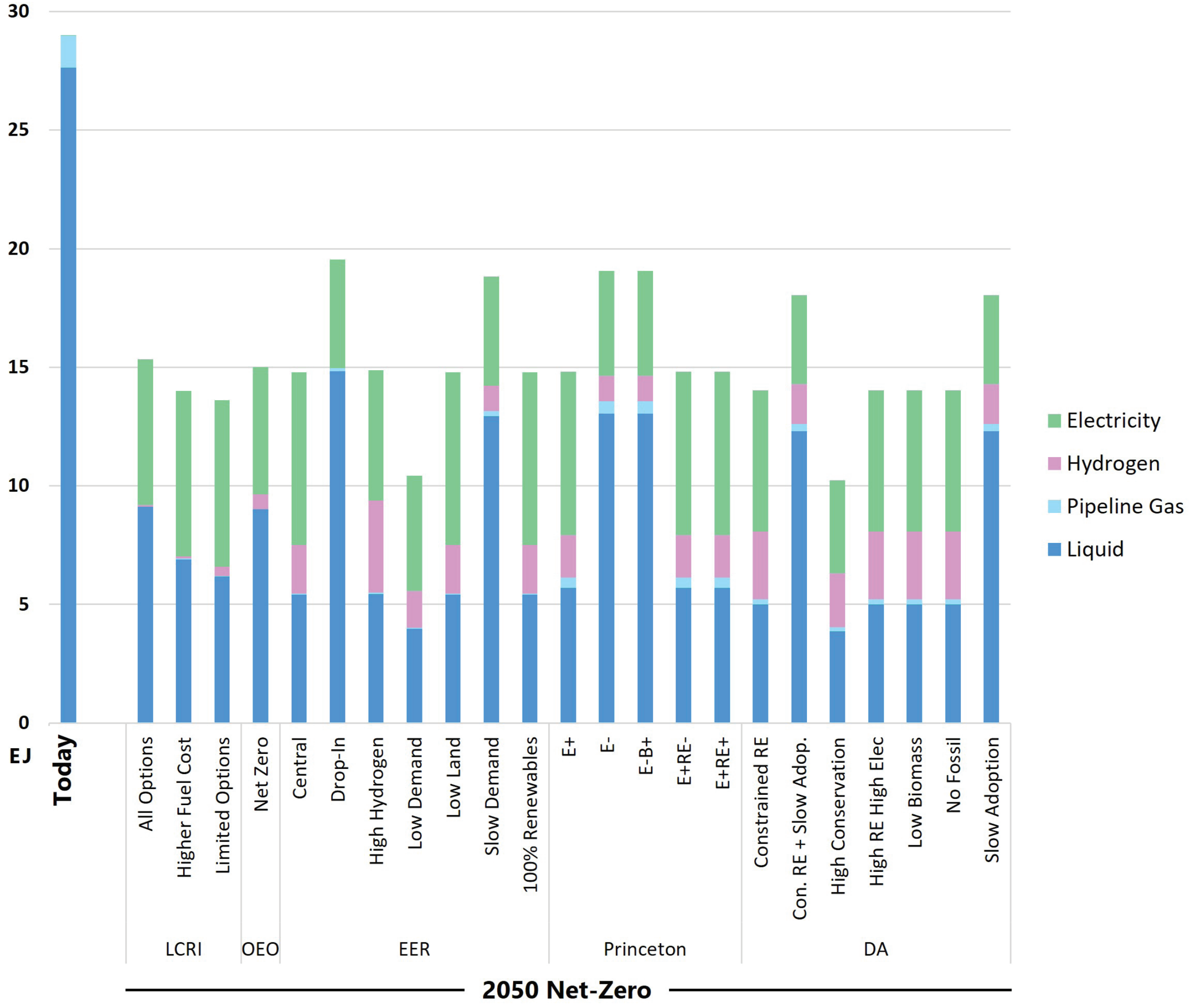
End-Use Sectors

Energy systems are built to serve the myriad of end-use customer needs across the economy. In the transition to net-zero energy systems, energy **use** will also evolve to meet the needs of the evolving U.S. economy. Across the net-zero energy system designs envisioned in these studies, increasing shares of electric and hydrogen-fueled vehicles, appliances, and equipment are adopted, while hydrocarbon fuels continue to serve end-use markets.

Transportation

In the transportation sector (Figure 4), electric vehicle adoption increases considerably relative to today in all net-zero scenarios, especially in the light-duty, on-road market. Given the efficiency gains of electric vehicles

Figure 4: Annual Transportation Energy Consumption by Energy Carrier (EJ)



Increased deployment of efficient electric vehicles drives rising electricity consumption and falling energy consumption relative to today. Hydrogen vehicles are adopted across all net-zero scenarios, while liquid fuels continue to serve long-haul and heavy-duty sectors.

as compared to conventional fuels-based vehicles, this increased adoption drives steep declines in total energy consumption in the transportation sector, even as the total number of vehicle miles traveled per year rises from now to 2050. Note that these efficiencies for transport electrification mean that electricity's share of service demand exceeds its share of final energy. Fuels—which are capable of storing large quantities of energy per unit weight and volume—continue to serve, especially in sectors with more stringent on-board storage requirements. Liquid fuels remain a large share of the energy supply, particularly for aviation, maritime, and heavy-duty sectors. Hydrogen is also adopted in the transport sector, with a range of potential deployments across studies and scenarios. Hydrogen vehicle deployment is lower in the LCRI and OEO studies, as compared to the EER, Princeton, and DA studies. In the LCRI and OEO studies the demand-side decisions regarding which vehicle type to deploy were incorporated as part of the overall cost optimization, whereas the vehicle types were provided as user-defined inputs in the other studies. Ammonia is adopted as a fuel for the maritime sector in the LCRI, EER, and DA studies. Pipeline gas continues to serve a small share of the transportation sector in some net-zero scenarios, primarily for medium- and heavy-duty vehicles.

Industry

Industrial energy consumption falls across net-zero scenarios (Figure 5), driven by efficiency improvements. For example, the LCRI Limited Options scenario—where

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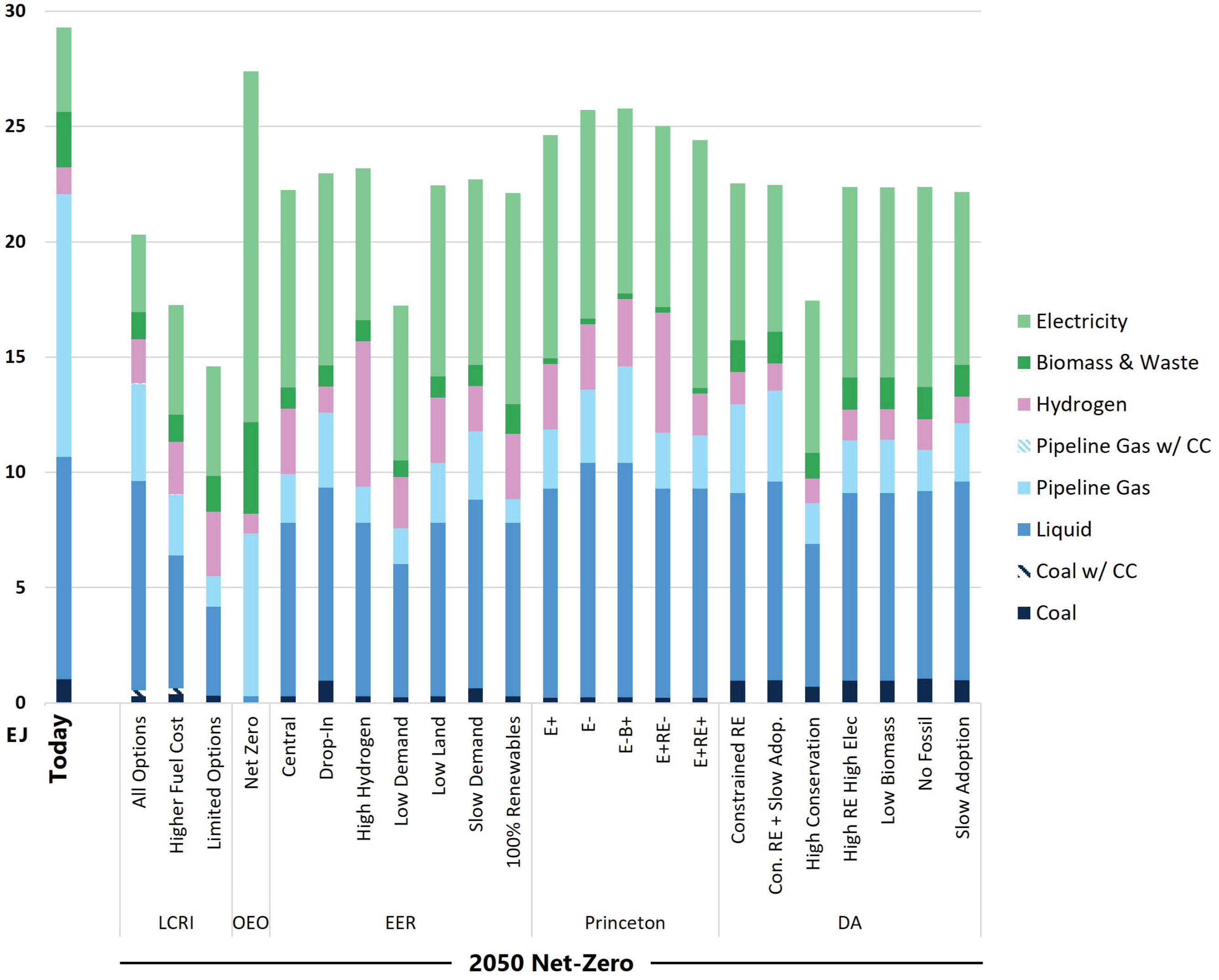
Figure 5: Annual Industrial Energy Consumption by Carrier (EJ)



Electricity and hydrogen expand across industry relative to today. Fuels comprise a large share of industrial energy consumption under net-zero conditions, with liquid fuels continuing to serve as feedstocks for non-energy uses.

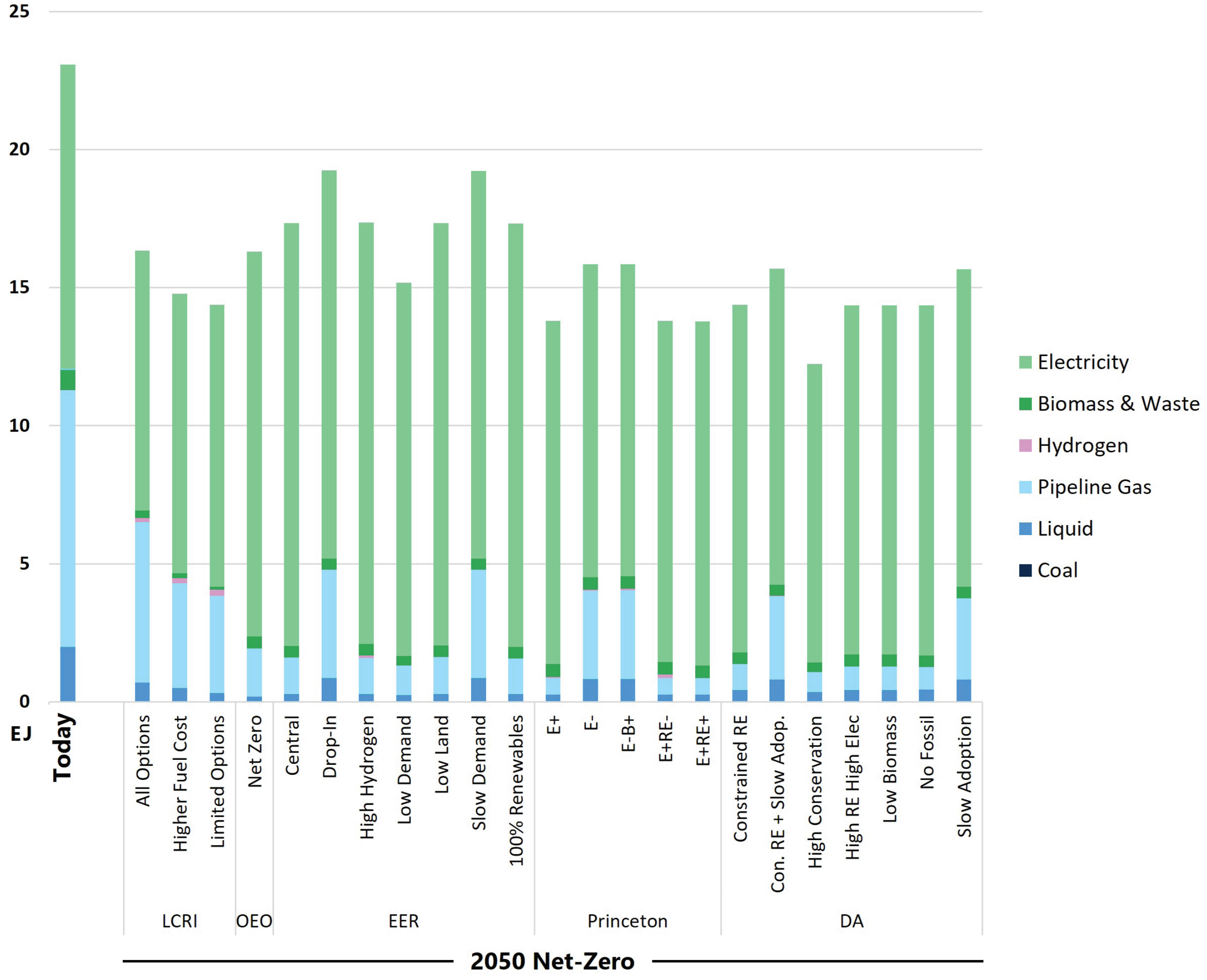
there were constraints on the technology options available—adopted higher efficiency technologies as part of the least-cost solution, driving down overall energy consumption in the industrial sector. EER's Low Demand scenario and DA's High Conservation scenario assumed lower energy service demand in general, which also led to lower industrial energy consumption.

Electricity grows considerably relative to today, comprising more than a third of energy consumption in most net-zero scenarios. Fuels continue to have a significant role, accounting for more than half of industrial energy consumption in all net-zero scenarios. Hydrogen grows from today's levels where it continues to serve as a non-energy feedstock for chemicals production, as well as a fuel for process heating.[29] Pipeline gas usage declines but remains non-zero in all scenarios. Liquid fuel consumption remains similar to today's levels, in part, because these fuels continue to serve as feedstocks for non-energy uses.[30] Coal declines across most scenarios but continues to serve the steel and cement industry with carbon capture and sequestration deployed in some scenarios.

Buildings

In the buildings sector (Figure 6), as with the transportation and industrial end-use sectors, electricity expands to provide a large share of energy consumption. A range of electric appliances and equipment are adopted, with substantial deployment of electric heat pumps for space

Figure 6: Annual Building Energy Consumption by Energy Carrier (EJ)



Electric appliance adoption expands throughout the buildings sector as compared to today. Pipeline gas and liquid fuels decline but continue to supply energy to buildings in all net-zero scenarios.

heating. The high efficiencies of these technologies lead to reductions in the total energy consumed in the buildings sector, even as the total square footage of buildings is projected to increase from today to 2050. The LCRI and EER studies allowed the option to deploy electric heat pumps as part of a hybrid approach in which a fuel-fired heating unit is coupled with the electric heat pump, particularly in cooler climate zones. This hybrid approach avoids the need to size the electric heat pump to satisfy peak heating demands on the coldest degree days, offering a cost-competitive approach for reducing emissions.[31] Whether as part of a hybrid electric-gas heating system or a standalone gas-fired unit, pipeline gas continues to serve the buildings sector across all net-zero scenarios, particularly for cooler climate regions with peak winter space heating demands.

Liquid fuels, including propane, decrease drastically across scenarios but are never eliminated. They—along with biomass resources like firewood—continue to be used for cooking and heating in places where it may be costly to build or upgrade distribution infrastructure, such as in rural communities.

Energy Carriers

While energy systems are built to serve customer needs, much of the energy infrastructure is built to **make**, **move**, and **store** the energy carriers supplied to end-use markets. Today, electricity is made in a variety of ways, whereas the liquid and gaseous fuels leveraged are primarily linked to petroleum and natural gas, respectively. These economy-wide net-zero studies open the aperture, considering a diverse set of pathways for producing low-carbon liquid and gaseous fuels relative to other potential decarbonization options. The cost-optimized net-zero energy system designs in these studies point towards increased production of low-carbon electricity coupled with a mix of fuels that is increasingly produced through low-carbon pathways.

Electricity

Electricity generation capacity significantly increases relative to today in all net-zero scenarios to meet the demands of increased electrification across sectors (Figure 7). Wind and solar power dominate new capacity in all scenarios, increasing four to 26 times that of today's level. New solar deployments outpace wind in all but two scenarios. Hydropower capacity remains largely unchanged relative to today's levels across all scenarios. Geothermal installations remain at their current levels, increasing only in OEO's Net Zero scenario and Princeton's E+RE- and E+RE+ scenarios.

Electric storage technologies, including batteries, pumped hydro, compressed air energy storage, and other storage systems are available as deployable options across these net-zero studies. Batteries dominate the share of new storage capacity across all scenarios, while other storage technologies have relatively little to no new deployment. The substantial increase in battery capacity complements the substantial increase in wind and solar capacity, serving to balance the short-duration (hourly, intraday) variability of these resources.

Fuels-based generation—fossil, nuclear, biomass, and hydrogen—provides firm capacity to balance long-duration (multiday, seasonal) renewables and demand variations. Total fuels-based power capacity varies across net-zero scenarios, ranging from 40% to 117% of today's fuels-based generation capacity. Coal power capacity is largely retired across net-zero scenarios. Limited levels of biomass power capacity are deployed in some scenarios, and in some cases with carbon capture.

Gas-fired capacity ranges from roughly 200 to 800 GW across net-zero scenarios, spanning a wide range as compared to the 500 GW installed today. The majority of gas-fired capacity in net-zero scenarios is deployed as peaking plants without carbon capture, providing firm, flexible operation to meet peak load demands. It is noteworthy that gas-fired generation without carbon capture is leveraged even in net-zero scenarios that exclude fossil fuels. A low-carbon pipeline gas fuel blend is used for gas-fired power plants in EER's 100% Renewables scenario, Princeton's E+RE+ scenario, and DA's No Fossil scenario.

Gas-fired power generation units with carbon capture are deployed in several scenarios. These units operate at higher capacity factors as compared to gas-fired units without carbon capture, offering firm, low-carbon power capacity. Correspondingly, higher deployment levels of carbon-capture enabled gas-fired generation tends to occur in scenarios with lower deployment levels of wind and solar generation. The relative competitiveness of carbon-capture enabled gas-fired generation depends on a multitude of factors, including the costs of the power plant and CO_2 transport and sequestration, as well as the ability of these systems to flexibly operate in response to fluctuations in renewables availability and load demand.

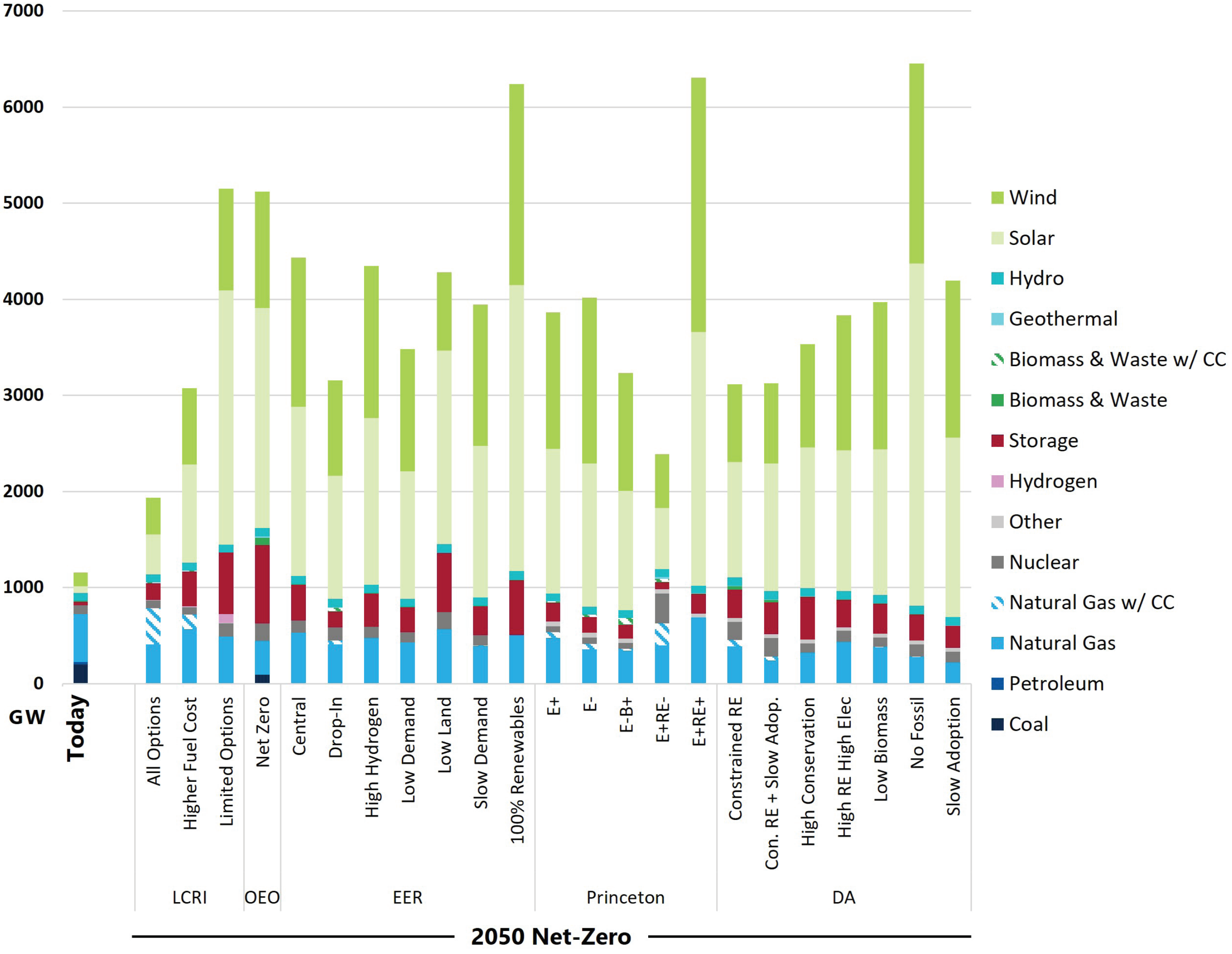
Nuclear power capacity is present in all net-zero scenarios except those that explicitly exclude it (EER's 100% Renewables scenario and Princeton's E+RE+ scenario). In scenarios that allow nuclear, a sizeable share of the existing capacity is maintained through 2050. New nuclear capacity buildout tends to leverage advanced technologies like small modular reactors. The highest level of nuclear deployment occurs in scenarios where other options are constrained.

Hydrogen-fired power capacity is only deployed in the LCRI study, predominately in the Limited Options scenario.[32] These units leverage hydrogen as a form of long-duration energy storage (multiday, seasonal), dispatching to meet peak demands when other generation is insufficient: for example, when wind and solar availability is limited.

Electricity production increases significantly in these net-zero systems, with total generation of between two- and three-times today's levels across most scenarios (Figure 8). This generation serves the increased electricity demands across end-use sectors, as well as electrolysis-based hydrogen production, and the synthetic fuels derived from that hydrogen.

Wind and solar contribute the majority of power generation in nearly all net-zero scenarios, providing more than two-thirds of total generation in most scenarios. In net-zero scenarios where fossil fuels and nuclear are allowed, wind and solar account for as much as 90% of all primary generation. This share increases to as high as 98% in scenarios where fossil and nuclear resources are excluded. When generation from these units exceeds

Figure 7: Electricity Generation Capacity by Source (GW)



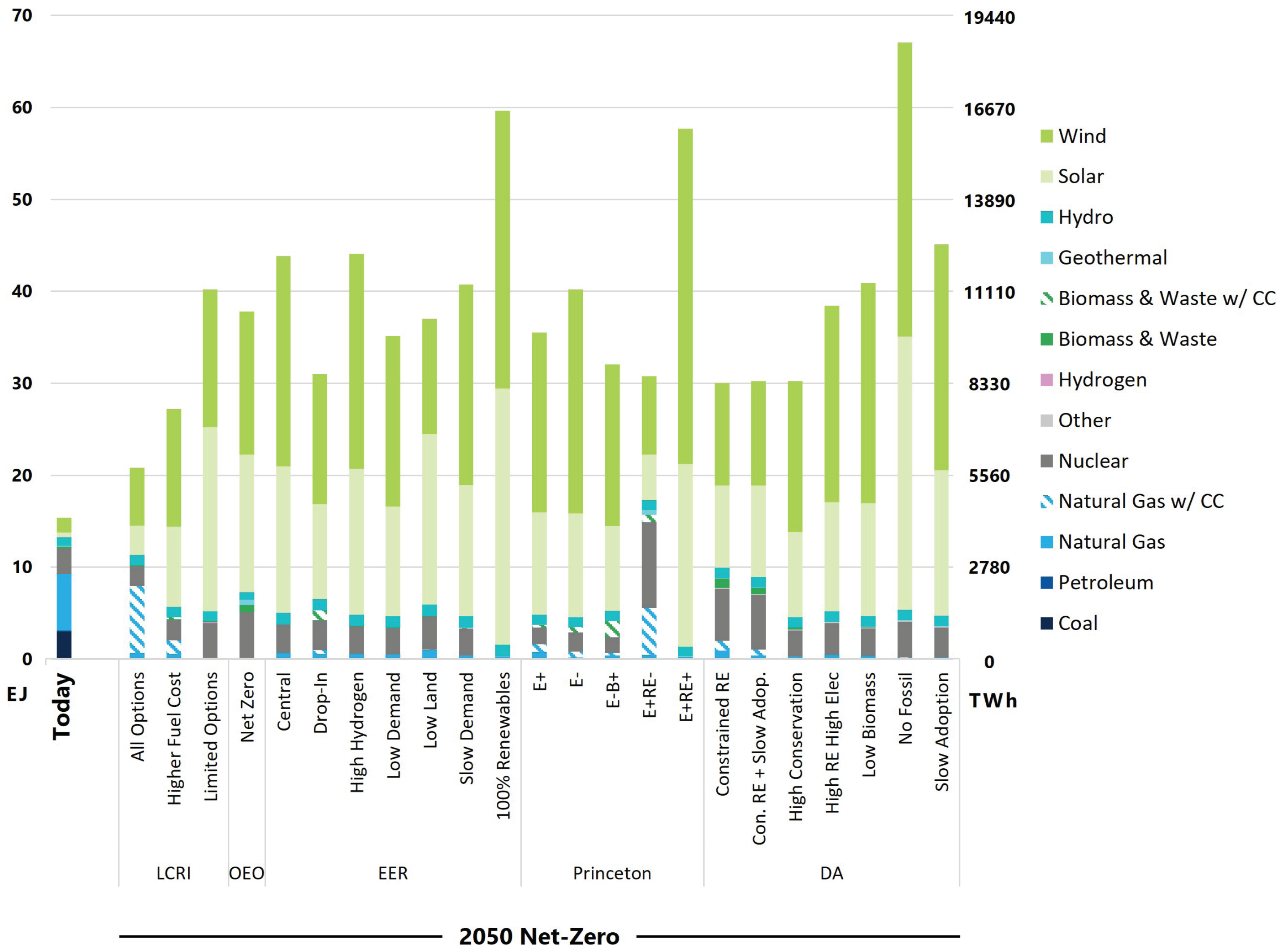
Electricity generation capacity grows multifold relative to today and is dominated by wind and solar across most net-zero scenarios, with storage and fuels-based capacity deployed to balance the variability of these renewable resources.

end-use electricity demands, this excess energy is either stored for dispatch at a later time, leveraged to produce hydrogen via electrolysis, curtailed or used to support direct air capture in some scenarios.

Nuclear energy provides the largest share of electricity after wind and solar in most scenarios (Figure 8). Nuclear-based generation contributes between 5 and 20% of total generation in all scenarios where nuclear is allowed. The Princeton E+RE-scenario is an exception, where nuclear contributes 30% of total generation. While the total installed capacity is relatively small (Figure 7), these units operate as baseload generation, providing a meaningful contribution to total electricity production.

Gas-fired generation contributes only a small amount of electricity across most net-zero scenarios, despite the relatively large capacity deployed (Figure 7). Natural gas-fired generation without carbon capture accounts for less than 3% of generation across all scenarios. These generators operate as peaking plants, with fleet-average capacity factors of roughly 2–5% for most scenarios.[33] Although used infrequently, the firm, flexible capacity offered by these units serves to provide high rates of power production to address peak events when renewables availability is low (e.g., low wind speeds due to atypical weather conditions) and/or demand is high (e.g., peak building cooling loads associated with a heat wave). In scenarios where

Figure 8: Annual Electricity Generation by Source (EJ)



The substantial wind and solar capacity deployed in these net-zero systems is leveraged to provide the vast majority of power generation in most net-zero scenarios.[34] The variability of these resources is balanced by low-carbon dispatchable generation—batteries, hydro, and carbon-captured enabled gas generation—and gas-fired peaking plants. Nuclear, and to a lesser extent biomass-fueled power, provide baseload generation.

fossil fuels are excluded, these 'natural gas' units are fueled by a mix of low-carbon fuels. Hydrogen-fired generation is also leveraged to meet peak demands in the LCRI Limited Options scenario.

Carbon-captured enabled natural gas generation contributes a small share of power production in several net-zero scenarios, accounting for at least 1% of total generation in seven scenarios (Figure 8). These units operate with fleet-average capacity factors of roughly 30 to 70% across scenarios, offering dispatchable power to balance renewables intermittency and load demands. Carbon-capture enabled gas-fired units tend to generate more electricity in scenarios where wind and solar generation is lower.

Hydropower generation is dispatched in all net-zero scenarios, leveraging a fleet of generation units with total installed capacity similar to today. In most scenarios, these units are leveraged at somewhat higher capacity factors in 2050, producing roughly 10–20% more power as compared to today. These units serve as a dispatchable source of power to balance grid demands, with fleet-average capacity factors of 40–45% in most scenarios.

Deployment of biomass-fueled power generation capacity is relatively small across net-zero scenarios (Figure 7). However, these plants tend to operate with high-capacity factors, making them a relevant share of the total generation mix. Biomass-fueled electricity accounts for at least 2% of total generation in six of the net-zero scenarios, spanning all studies except LCRI. Biomass-fuel power generation offers a source of low-carbon power. When coupled with carbon capture and sequestration, biomass-fueled power generation provides a pathway for achieving carbon dioxide removal (see Greenhouse Gas Emissions section). In some scenarios, carbon captured from these facilities provides a source of biogenic CO_2 feedstock for synthetic fuels production.

Geothermal generation is near zero in all scenarios except OEO's Net Zero scenario and Princeton's E+RE- scenario, which account for 1.5% and 1.8% of total generation, respectively. Geothermal units are leveraged as baseload power in those two scenarios.

The way electricity is **made** and **stored** in net-zero energy systems is central to delivering a robust supply of low-carbon electricity to end-use sectors: so too is the infrastructure required to **move** that electricity from where it is made and stored, to where it is used. Each of these studies incorporated the cost of expanding the electric grid as part of the overall analytical framework. The electricity generation capacity (Figure 7) offers a proxy for the electric grid infrastructure required in these net-zero scenarios. The grid must be sized to capture the peak output of wind and solar resources, as well as that of batteries and other firm generation. In some scenarios, this can include buildout of long-distance transmission infrastructure to move electricity from regions with high production to regions with high demand. In all net-zero scenarios where electric transmission results were reported, the transmission infrastructure is expanded relative to today. Distribution infrastructure must also be expanded considerably to meet growing demands across end-use sectors. With increased electrification of space heating, peak electric grid loads can grow considerably in cooler regions, with peak demands shifting from the summer cooling season to the winter heating season.

Hydrogen

Hydrogen has been part of the U.S. economy for decades, primarily for non-energy uses as a feedstock in petroleum refining and chemical production. Hydrogen offers great potential as a low-carbon energy carrier in that it offers the intrinsic storability and transportability characteristics of fuels, while emitting no CO_2 emissions at point of end-use. There are multiple pathways for producing low-carbon hydrogen, including electrolysis coupled with low-carbon electricity, natural gas conversion coupled with CCS, and biomass conversion with or without carbon capture. These low-carbon production pathways, as well as the systems and equipment required for moving, storing, and using hydrogen at scale, are still in the early stages of development and deployment.

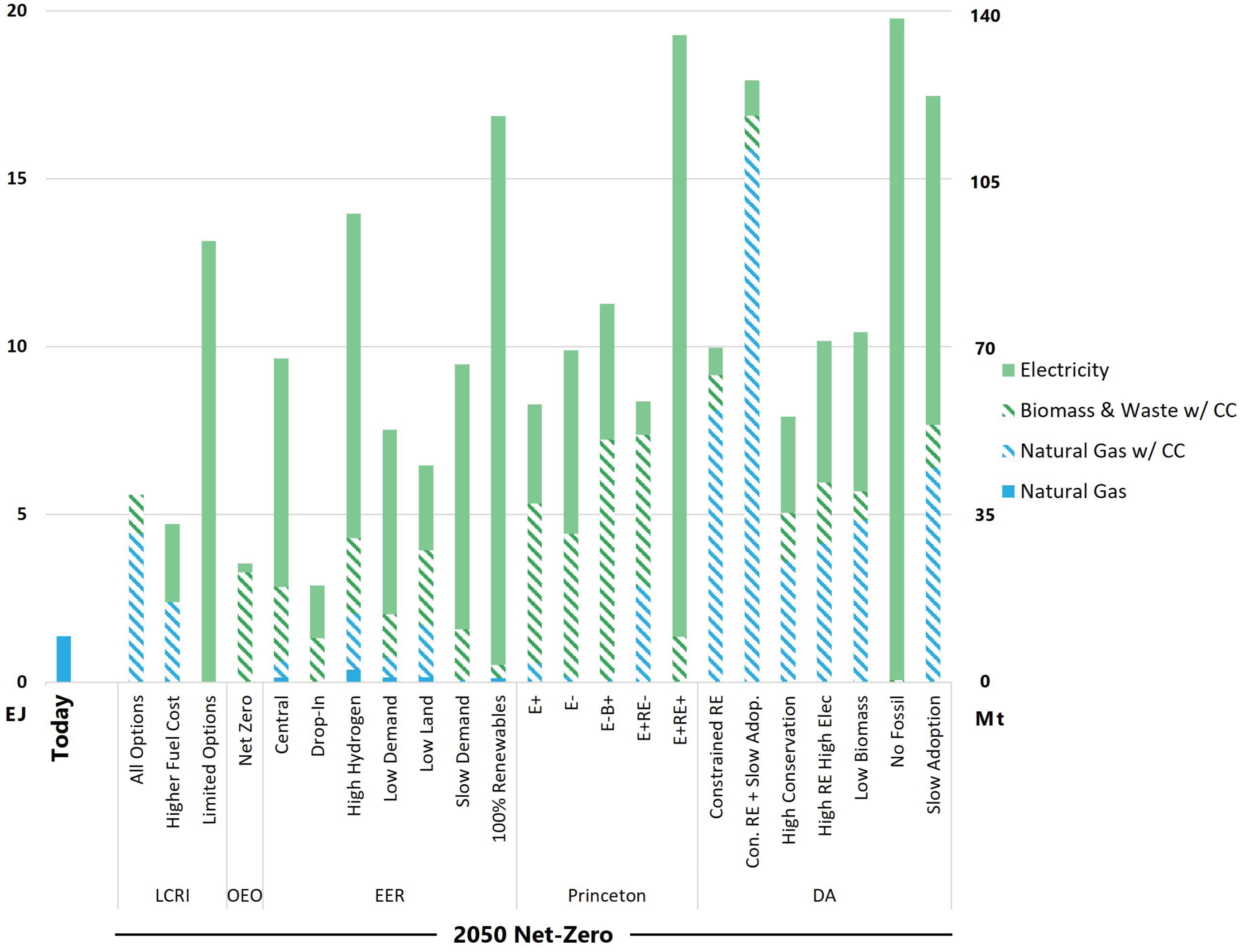
Hydrogen production increases sharply in all net-zero scenarios, growing three to 20 times relative to today (Figure 9). The wide range of production levels across scenarios is driven, in part, by the nascency of the low-carbon hydrogen industry and the associated uncertainty of technology costs and performance assumptions.[35] It is noteworthy that the LCRI and OEO studies tend to have lower levels of hydrogen production and consumption, relative to the other three studies.[36] This may be attributed in part to the fact that demand side decisions—for example, whether to deploy a battery electric vehicle versus a hydrogen-fueled vehicle—are solved for as part of the overall cost optimization in the LCRI and OEO studies, whereas these decisions are framed as part of the input assumptions in the other studies.

In addition to differences in production levels, there is a range of results across net-zero studies and scenarios regarding the type of hydrogen production deployed. Electrolysis—where electricity is used to produce hydrogen from water—is leveraged across a wide range of production levels, with deployment in all net-zero scenarios except LCRI's All Options scenario. Electrolysis, and hydrogen production overall, becomes especially pronounced in scenarios where fossil resources are constrained such as LCRI's Limited Options scenario,[37] EER's 100% Renewables scenario, Princeton's E+RE+ scenario, and DA's no-fossil scenario. Across net-zero scenarios, electrolysis leverages generation from intermittent wind and solar, such that these hydrogen production facilities are considered to operate with a high degree of flexibility to utilize the variable supply of electricity from these resources.

Hydrogen production from biomass and/or waste with carbon capture and sequestration arises across many scenarios, in part, as this provides means for both producing hydrogen and for achieving negative carbon emissions flows. By capturing and sequestering the carbon in the biomass—carbon which was removed from the atmosphere during the biomass growth cycle—atmospheric CDR can be achieved. Additionally, biomass conversion with carbon capture and utilization is adopted in some scenarios, where the captured carbon is utilized as a feedstock to produce drop-in hydrocarbon fuels via synthetic fuel production pathways (hydrogen and carbon dioxide converted to hydrocarbon fuels).

Today, there is a limited level of hydrogen pipeline and underground storage infrastructure, with installations centralized in the U.S. gulf refining region. To leverage hydrogen as an energy carrier at the scale envisioned in these net-zero scenarios, the infrastructure required to **store** and **move** hydrogen must be deployed in parallel with the facilities to **make** hydrogen. These studies evaluated blending hydrogen in natural gas pipelines along with the deployment of dedicated hydrogen

Figure 9: Annual Hydrogen Production by Production Pathway (EJ)



Low-carbon hydrogen grows considerably from today's levels, with a range of projections for production levels and pathways across net-zero studies and scenarios.

pipeline networks and large-scale underground storage, incorporating the costs of these facilities into the overall cost optimization analysis. Additionally, options for trucking hydrogen and above-ground storage tanks were also evaluated. Scenarios that leverage high levels of wind- and solar-based electrolytic hydrogen production tend to deploy higher levels of hydrogen storage to balance the variability of production with demand.

Pipeline Gas

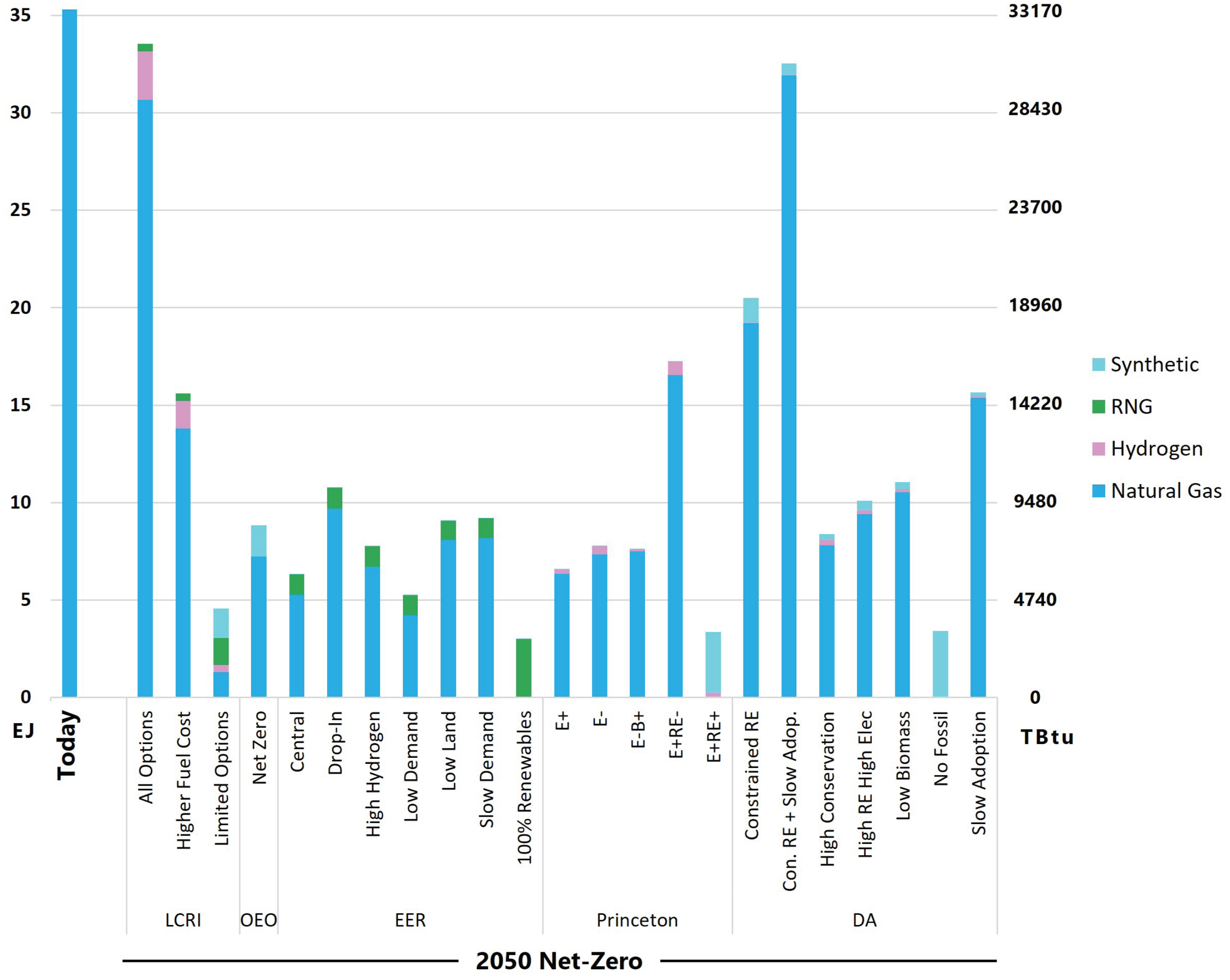
Large quantities of energy are stored and moved within the U.S. natural gas pipeline infrastructure today, supplying both power generation as well as end use customers. As energy systems transition towards net-zero, there is the potential to leverage this infrastructure for use with low-carbon gas molecules including renewable natural gas (RNG), synthetic natural gas (SNG), and blended hydrogen.

Pipeline gas continues to serve in all net-zero scenarios, but consumption declines to less than a third of today's levels across most scenarios (Figure 10). The steepest declines arise where fossil resources are constrained such as LCRI's Limited Options scenario,[37] EER's 100% Renewables scenario, Princeton's E+RE+ scenario, and DA's No Fossil scenario. Gas consumption remains the highest in scenarios where pipeline gas is leveraged with higher levels carbon capture and sequestration, such as in LCRI's All Options scenario and DA's Con. RE + Slow Adoption scenario.

Fossil natural gas remains the dominant share of pipeline gas supply in all net-zero scenarios except for those in which fossil resources are constrained either directly or indirectly.[37] RNG and SNG pathways provide a means for producing gas with a nearly identical composition to fossil natural gas.[38] They supply a small share of gas across all net-zero scenarios, with the highest shares present in net-zero scenarios where fossil fuel resources are constrained. Hydrogen is blended into the pipeline gas supply at low levels in the LCRI, Princeton, and DA studies.

The way pipeline gas is **made** in these net-zero systems evolves relative to today, whereas the way it is **moved** and **stored** is similar to today, i.e., by leveraging the existing natural gas infrastructure. These net-zero studies include the transport and storage capacity of pipeline gas infrastructure in the analysis, incorporating the costs to operate and maintain this infrastructure as part of the overall cost optimization. Although pipeline gas consumption

Figure 10: Annual Pipeline Gas Consumption by Production Pathway (EJ)



Pipeline gas consumption decreases relative to today but continues to serve in all net-zero scenarios—particularly for peak electric and winter heating demands—with increasing shares of gas produced through low-carbon pathways.

decreases for net-zero scenarios, peak gas demands can remain relatively high. For example, gas-fired power generation capacity is deployed across all net-zero scenarios (Figure 7), but these generation assets only account for a small level of total generation (Figure 8). In many scenarios, these gas-fired generation units are only used during periods when variable renewable energy resources (e.g., wind and solar) or other generators are insufficient to meet electric demands. Hence, these gas-fired generators are used infrequently, but when called upon, they may operate at high loads, requiring a relatively high rate of pipeline gas delivery. This operating characteristic—infrequent use of pipeline gas infrastructure at relatively high throughput capacity—also arises for hybrid electric-gas heat pump systems that leverage gas-fired heating for peak heating demands during the coldest days and weeks of the year (see Buildings section in End-Use Sectors). These net-zero studies leverage the seasonal storage capacity and gas throughput capacity of gas infrastructure at relatively high levels as compared to the lower levels of pipeline gas consumption.

Liquid Fuels

Liquid hydrocarbon fuels dominate today's energy systems, both as a primary energy source and as a final form of energy to serve end-use markets. These fuels are energetically dense, enabling relatively low-cost storage and transport of these molecules—characteristics which have led to widespread adoption of these fuels in the transportation sector (where vehicle on-board energy storage is required) and large-scale deployment of pipeline and distribution networks to move these energy carriers to market. Low-carbon drop-in fuels capable of substituting petroleum-derived fuels provide a means to leverage these networks as part of an economy-wide net-zero energy system.

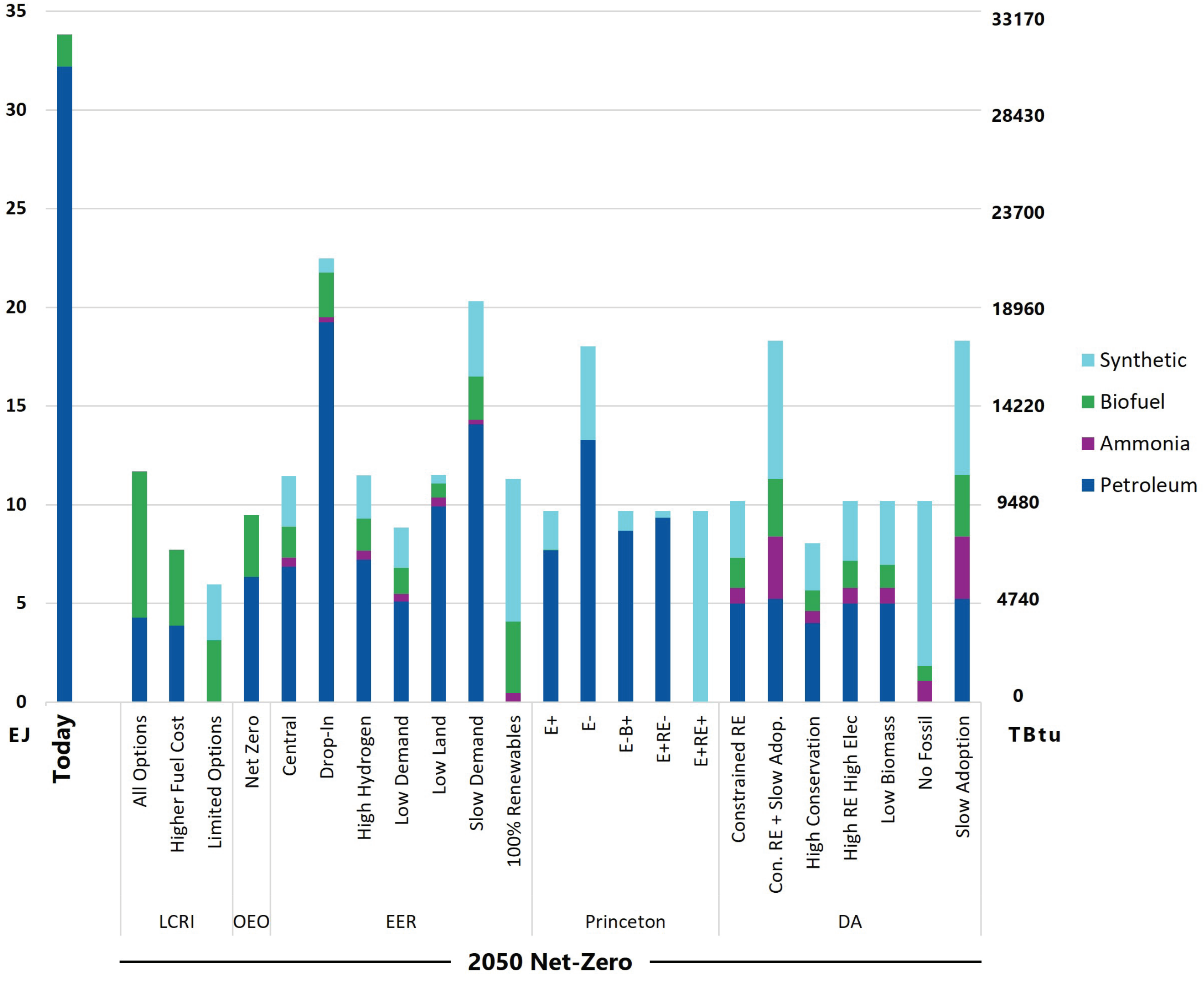
Liquid fuels serve multiple markets, especially transportation, across all net-zero scenarios, but at much lower levels of consumption relative to today. In terms of the energy uses for liquid fuels, as shown in Figure 11 here,[39] consumption levels drop to roughly a quarter of today's levels across most scenarios. Higher levels of liquid fuels consumption tend to occur in scenarios with lower levels of transportation electrification (Figure 4).

Conventional petroleum-based fuels comprise a large share of the liquid fuel mix across net-zero scenarios, albeit with significant decreases relative to today. Advanced biofuel technologies capable of converting a variety of cellulosic biomass materials into drop-in liquid hydrocarbon fuels—especially low-carbon aviation and diesel fuels—expand across net-zero scenarios, substituting petroleum fuels and first-generation biofuels, such as corn-based ethanol.[39] Synthetic fuel technologies, which utilize carbon dioxide and hydrogen as feedstocks for low-carbon fuel production, also expand across net-zero scenarios. These pathways tend to leverage CO_2 originally absorbed from the atmosphere, including CO_2 from direct air capture and CO_2 captured from biofuels production processes. Deployment of biofuels and synthetic fuels technologies is most prevalent in net-zero scenarios where fossil fuels are constrained, either directly within the definition of the scenario, or indirectly as a result of other aspects of the scenario definition.[37]

Ammonia is produced through low-carbon pathways in all net-zero scenarios to serve non-energy purposes, such as fertilizer and chemical applications. In the LCRI,[40] EER, and DA studies ammonia is leveraged as a low-carbon fuel to serve end-use energy needs—specifically as a fuel for marine sectors.

Today's liquid fuels are delivered to market through widespread pipeline and distribution networks. Many of the low-carbon liquid fuels **made** in these net-zero systems can leverage the existing infrastructure and networks to **move** and **store** these energy carriers. Drop-in liquid hydrocarbon fuels are energetically dense, making them relatively inexpensive to move and store as compared to other energy carriers. Given this, and the availability of existing infrastructure, the costs of moving and storing liquid hydrocarbon fuels has a relatively low impact on the results of the studies. Where ammonia production grows to accommodate a larger share of final energy as a transportation fuel, the buildout of associated storage and transport infrastructure is included in the overall cost optimization.

Figure 11: Annual Liquid Fuel Consumption by Production Pathway (EJ)



Liquid fuels continue to serve energy uses in all net-zero scenarios,[41] but at much lower levels of consumption as compared to today. Drop-in liquid hydrocarbons produced through bioenergy and synthetic fuels pathways increasingly serve as substitutes for petroleum-based fuels. Ammonia arises as a fuel for the maritime sector in some net-zero scenarios.

Greenhouse Gas Emissions

Getting to net-zero across the U.S. economy entails sharp declines from today's emissions levels. In addition to deeply reducing positive emissions, economy-wide, net-zero analyses consistently point to expanding negative emissions approaches, CDR, as a part of the cost-optimal design for achieving net-zero. Across the studies evaluated here, the net-zero target has been framed differently. In the LCRI and OEO studies, the net-zero target encompasses only CO_2 emissions. In the EER, Princeton, and DA studies, several greenhouse gas emissions across the economy are balanced out as part of the net-zero target.[20] Therefore, non-CO_2 emissions are only reported for the EER, Princeton, and DA in Figure 12.

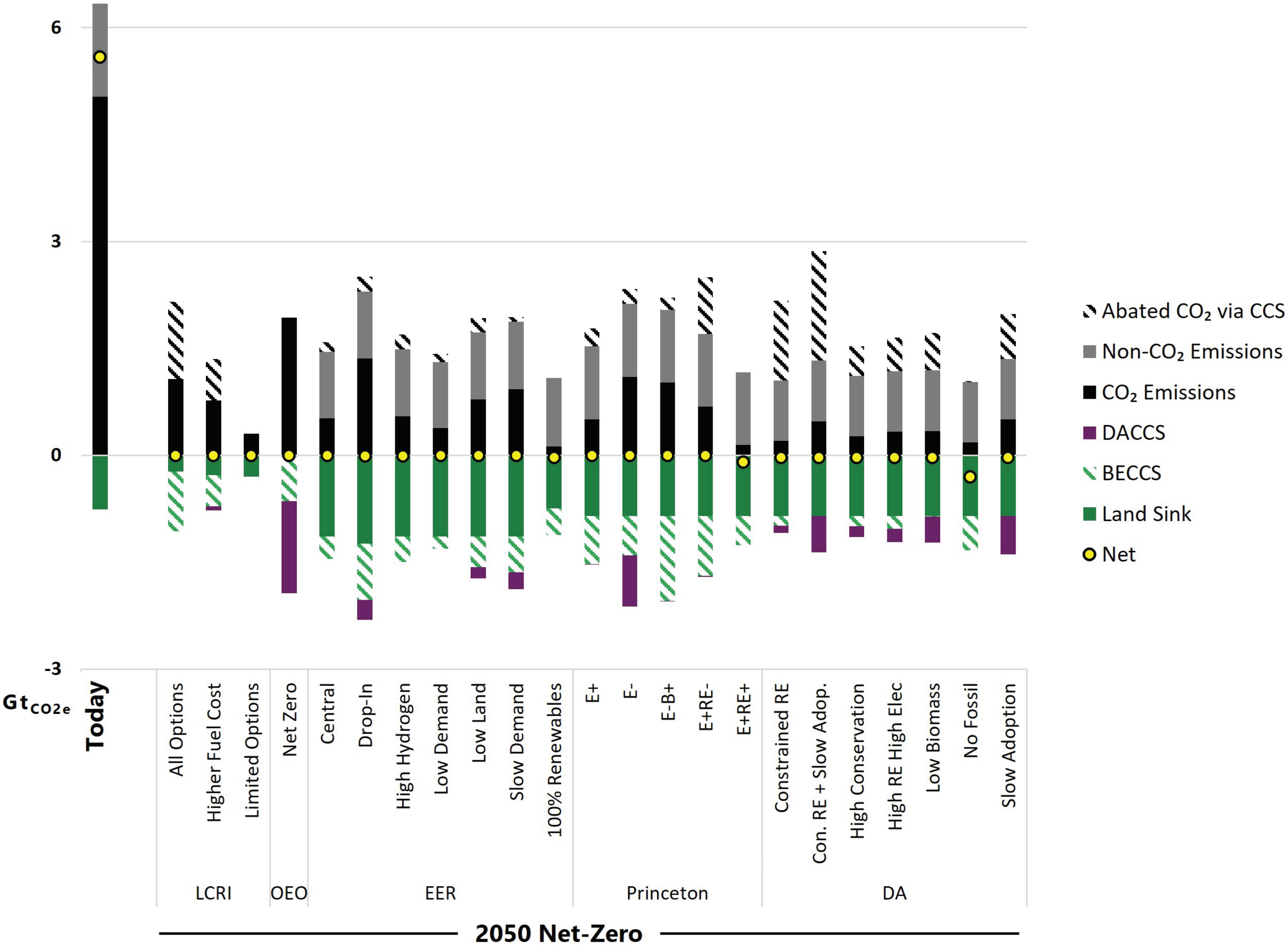
Total positive emissions levels include unabated CO_2 and non-CO_2 emissions. Fossil-based emissions that are abated through CCS are also shown in Figure 12 below to illustrate the relative scale of these activities. However, these abatements do not contribute to the total positive emissions level. Positive emissions are balanced by negative emissions approaches, where CO_2 is removed from the atmosphere and durably stored. CDR can be achieved through adjustments in agriculture, forestry, and other practices that further expand the natural land sink, i.e., terrestrial absorption of atmospheric CO_2 into the land. The existing U.S. land sink absorbs 0.75 $GtCO_2$ from the atmosphere each year. This land sink grows in net-zero scenarios relative to today.[42]

Bioenergy pathways combined with carbon capture and sequestration (BECCS) also provide a means for achieving CDR. As bioenergy feedstocks are leveraged for energy purposes, such as power production or fuels generation, CO_2 is typically emitted. By capturing this CO_2—which was originally absorbed from the atmosphere during the biomass growth cycle—and durably sequestering it, negative emissions flows can be achieved. These BECCS pathways are leveraged in every study and every net-zero scenario, except for the LCRI Limited Options scenario, where carbon sequestration was explicitly excluded as part of the scenario definition. The level of BECCS deployment varies across studies.

Direct air capture systems, energy-consuming technologies that extract CO_2 directly from the atmosphere, are also leveraged across net-zero scenarios. Coupling direct air capture with carbon sequestration (DACCS) provides another pathway for achieving negative emissions flows. Although DACCS is a relatively costly approach for abating emissions, it offers a pathway to offset positive emissions from the most difficult-to-abate activities elsewhere in the economy. Given this, DACCS tends to arise as a backstop in these net-zero scenarios. DACCS technologies tend to be deployed later in the time horizon (i.e., closer to 2050) and the costs of these systems tend to ultimately set the marginal cost of CO_2 emissions under net-zero conditions in 2050. Given the multitude of factors that converge around the DACCS deployment decision within these optimization analyses, as well as the uncertainties in the costs and performance of this nascent technology, there is a wide range of estimates for the level of DACCS deployed across these net-zero studies.

To realize the BECCS, DACCS, and CCS-based abatements envisioned in these net-zero systems, infrastructure to **move** and **store** CO_2 at scale must be deployed. These studies include the costs associated with building new

Figure 12: Annual Greenhouse Gas Emissions ($GtCO_{2e}$)



Deep emissions reductions are achieved relative to today across all net-zero scenarios, with remaining positive emissions balanced by carbon dioxide removal (Updated February 2024).

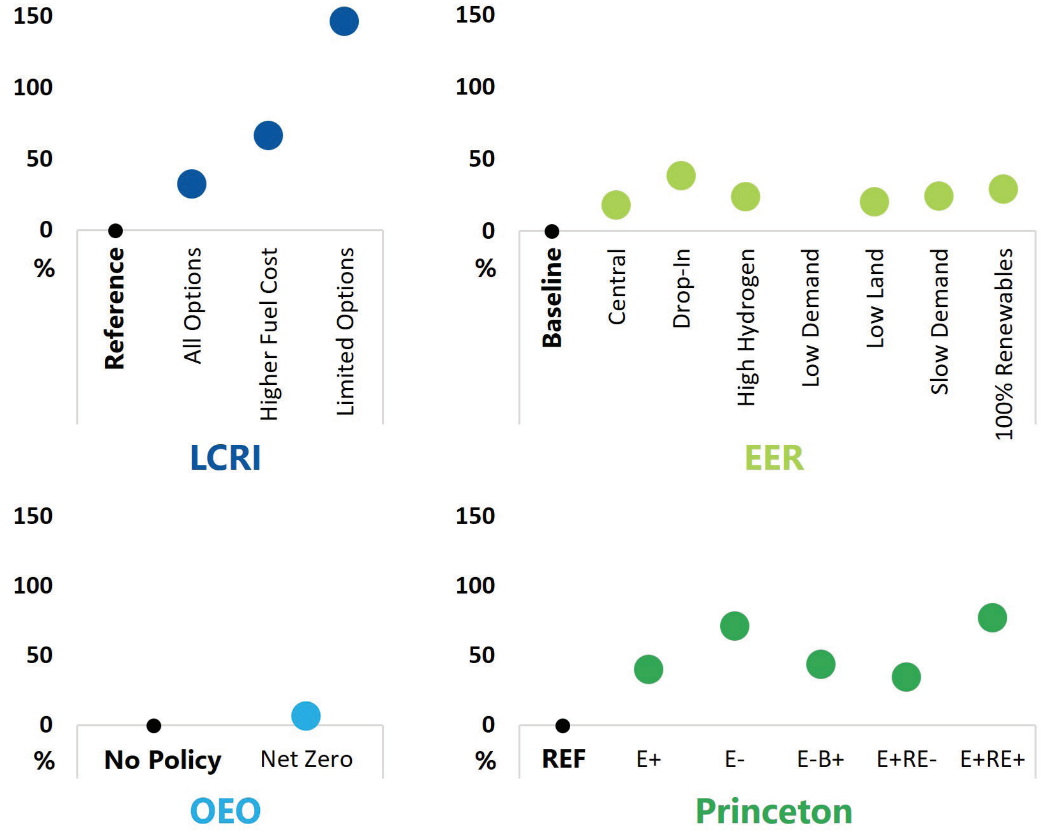
CO_2 transport networks and sequestration facilities as part of the overall cost-optimization analysis. Additionally, for scenarios that leverage CO_2 utilization, these studies include buildout of the networks for transporting CO_2 from the places where it is captured to the places where it is used, such as synthetic fuels production facilities.

Costs

All evaluated studies solved for least-cost pathways to achieve U.S. economy-wide, net-zero emissions by 2050. While each of the energy system designs envisioned across these studies reach net-zero targets, the total cost associated with transitioning to these systems varies as a function of input assumptions and scenario constraints. These studies differ in their framing and approach to characterizing the total cost of deploying these future energy systems.[43] It is thus tenuous to attempt to directly compare costs between different studies. Nonetheless, insights can be attained by comparing relative changes in cost across different scenarios within a single study. To this end, net-zero scenario costs for a given study are shown relative to that study's business as usual (BAU) scenario in Figure 13. For example, the LCRI All Options scenario costs 33% more than the LCRI BAU scenario, and the EER 100% Renewables scenario costs 29% more than the EER BAU scenario. In all studies and scenarios, achieving net-zero by 2050 results in higher cost as compared to continuing under business-as-usual conditions.[44]

The relative costs of reaching net-zero can vary across scenarios for a multitude of reasons. This can include changes in projected resource supply assumptions for a given scenario. For example, LCRI's Higher Fuel Cost and Limited Options scenarios assume lower biomass supply relative to the All Options scenario leading to higher costs, whereas Princeton's E-B+ scenario assumes higher biomass supply relative to other scenarios leading to lower costs. This can also include variations in technology assumptions such as higher CCS costs as in LCRI's Higher Fuel Cost scenario. In general, the highest costs tend to correspond to scenarios which introduce the most constraints. Examples of such constraints are: LCRI's Limited Options scenario does not allow CO_2 to be sequestered, EER's 100% Renewables scenario and Princeton's E+RE+ scenarios only allow renewable energy sources to be used, and EER's Drop-In scenario and Princeton's E- scenario constrain the adoption of electric technologies.

Figure 13: Cost of Net-Zero Systems Relative to Business as Usual (%)[45]



The total cost of deploying and operating these net-zero energy systems increases as compared to proceeding on a business-as-usual trajectory. The relative costs vary depending on the assumptions and constraints of a given net-zero scenario. The highest costs tend to correspond to scenarios with the most constraints.

Designs for a Net-Zero U.S. Economy

Transitioning to net-zero requires an informed view of net-zero energy system designs. In recent years, a growing number of researchers, modelers, and analysts have begun to evaluate energy system designs capable of achieving economy-wide, net-zero emissions by mid-century. The energy system models leveraged in these studies consider a comprehensive set of sectors, value chains, and energy carriers, offering detailed assessments of least-cost pathways to deep decarbonization—the technologies, infrastructure, investments, and integration needed to enable a growing, net-zero U.S. economy.

The designs envisioned in these economy-wide, net-zero studies point to a transformation in the way energy is sourced, made, moved, stored, and used. These net-zero designs are built on the energy systems of today, deploying new technologies and expanding the energy infrastructure with an increasing degree of integration across electricity, fuels, and carbon management value chains. These economy-wide studies point to a common set of features in the design of net-zero energy systems. While these studies were performed prior to passage of the Inflation Reduction Act, the commonalities across these studies are consistent with the incentives in this legislation. These common approaches, now further supported by the IRA, can inform decision-making and planning efforts to drive the transition to a net-zero U.S. economy.

- **Renewables grow the supply of low-carbon energy.** Wind and solar electricity generation expands dramatically from today's levels, while biomass resources are increasingly leveraged for low-carbon fuels production.
- **Electricity expands across sectors.** Increasing numbers of electric vehicles, equipment, and appliances are adopted across sectors, with total electricity generation doubling or more than tripling today's levels.
- **Fuels diversify and serve multiple markets.** Fuels continue to supply roughly half of all energy delivered to end-use customers, with growing shares of hydrogen, and increased deployment of bioenergy and synthetic fuels technologies for producing liquid fuels and pipeline gas.
- **Efficiency reduces energy consumption while enabling economic growth.** Efficiency gains across energy value chains, particularly for electric vehicles and heat pumps, drive reductions in total energy consumption while satisfying the growing demands of an expanding U.S. economy.
- **Carbon dioxide removal balances remaining emissions.** Emissions are greatly reduced, with remaining positive emissions balanced by negative emissions approaches, such as growing the land sink, or deploying bioenergy and/or direct air capture technologies with carbon sequestration.

There is no single design for net-zero energy systems. Each of these studies points to a wide array of energy carriers, technologies, and regionally specific solutions to meet the energy demands of an expanding U.S. economy. The range of results across these studies highlights a range of perspectives and possibilities for the design of net-zero systems. This range stems partly from intentioned efforts within these studies to evaluate corner point scenarios as a means for highlighting the dynamics and tradeoffs of different net-zero designs. Despite their differences, these studies are consistent in finding that constrained scenarios—where certain technologies or pathways are explicitly excluded or limited—have higher costs than unconstrained scenarios. There is value in considering a range of options to reach net-zero, particularly in these early stages of energy transitions when there is a lot of learning yet to come. At the same time, the insights shared across these studies can inform the decisions made today.

Net-zero systems entail net-zero infrastructure. Large-scale investment in energy infrastructure is needed to achieve the unprecedented level of transformation projected across these studies. These models point to expansion of the electric grid to accommodate increasing wind and solar deployments and growing electricity demands. Infrastructure to move and store gaseous molecules at scale is required to employ hydrogen as a versatile low-carbon energy carrier and to enable carbon dioxide removal and sequestration. The existing liquid hydrocarbons and pipeline gas infrastructure will need to be leveraged where it supports the net-zero system designs envisioned in these studies.

Innovation is a foundation for transformation. The net-zero designs envisioned in these studies all rely on large-scale deployment of new technologies. This includes investing in innovations already proven out at scale, such as wind, solar, and battery technologies. It also includes investing in a broad portfolio of nascent solutions, such as hydrogen, bioenergy, carbon capture, and sequestration. The net-zero systems projected in these studies are based on the information available today. The understanding of these systems is certain to evolve as progress is made towards net-zero. Innovation in a variety of forms—technologies, operating models, market frameworks, and beyond—will be central to enabling the transition to net-zero economies.

Acronyms

AEO	Annual Energy Outlook
BAU	Business As Usual
BECCS	Bioenergy with Carbon Capture and Sequestration
CC	Carbon Capture
CCS	Carbon Capture and Sequestration
CDR	Carbon Dioxide Removal
CO_2	Carbon Dioxide
DA	Decarb America
DAC	Direct Air Capture
DACCS	Direct Air Capture with Carbon Sequestration
EER	Evolved Energy Research
EIA	Energy Information Administration
EPRI	Electric Power Research Institute
GHG	Greenhouse Gas
IRA	Inflation Reduction Act
LCRI	Low-Carbon Resources Initiative
OEO	Open Energy Outlook
RNG	Renewable Natural Gas
SNG	Synthetic Natural Gas

Units

EJ	exajoule
GW	gigawatt
Gt	gigatonne (billion metric tons)
Mt	megatonne (million metric tons)
TBtu	trillion British thermal units
TWh	terawatt-hour

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Endnotes

1 See Table 1 in the main report for the complete list of studies considered.

2 The Evolved Energy Research, Princeton University, and Decarb America studies all employed a common analytical framework—the EnergyPATHWAYS model, developed by EER.

3 Liquid fuels include ammonia and hydrocarbon fuels derived from petroleum, bioenergy, and synthetic pathways.

4 Pipeline gas includes fossil natural gas, renewable natural gas, synthetic natural gas, and blended hydrogen.

5 Three exceptions are: (1) the Open Energy Outlook study did not report non-energy uses of fuels, hence the results shown here are for energy uses only, (2) the hydrogen data for today is based on 2020 data, rather than 2022, and (3) the Open Energy Outlook Net-Zero scenario had 7% of final energy as biomass.

6 The reported reduction in primary energy consumption is also an artifact of the reporting convention employed here for wind and solar technologies, where the produced energy is directly reported (e.g., the electricity generated from a solar panel) rather than the available energy (e.g., the sunlight energy impinging on a solar panel).

7 Land sinks were not included in the Open Energy Outlook analysis.

8 As based on government commitments tracked by Climate Watch.

9 Facilities that leverage bioenergy resources for power generation or fuel production may emit CO_2 released from carbon that was originally within the bioresource. The carbon in these bioresources was absorbed from the atmosphere during growth. By capturing and sequestering this CO_2 from bioenergy facilities, this creates an overall negative flow of CO_2 from the atmosphere.

10 The BP study, despite being global in scope, was still considered for this meta-analysis because it had a section with U.S. data.

11 The Energy Modeling Forum (EMF), coordinated by Stanford, brings together experts and decisionmakers to study important energy and environmental issues. Each EMF study is organized through a working group to design the study, compare each model's results, and discuss key conclusions.

12 Energy Pathways USA is a partnership between Duke Nicholas Institute for Energy, Environment & Sustainability and Energy Transitions Commission.

13 The Low-Carbon Resources Initiative (LCRI) is a joint collaboration between GTI Energy and Electric Power Research Institute (EPRI) focused on accelerating the development and deployment of low-carbon energy technologies required for deep decarbonization.

14 The Open Energy Outlook is joint initiative between the Wilton E. Scott Institute for Energy Innovation at Carnegie Mellon University and North Carolina State University to examine U.S. energy futures to help inform energy and climate policy efforts.

15 The Decarb America Research Initiative is a collaboration between the Bipartisan Policy Center, Clean Air Task Force, and Third Way to analyze policy and technology pathways for the United States to reach net-zero greenhouse gas emissions by 2050.

16 The data assessment in Table 1is based on an evaluation of publicly and freely available data. It is possible that additional data is available behind a paywall for some studies.

17 As of September 2023. Some teams publish studies on an annual basis, such as BP, Shell, and EER. Only the most recent publication has been considered here.

18 Pathways to 2050 by the Center for Climate and Energy Solutions was initially considered for this meta-analysis but ultimately not included because none of its scenarios targeted net-zero emissions. The most aggressive scenario stopped at an 80% reduction in GHG emissions.

19 Many global net-zero studies have been published over the past few years, such as the International Energy Agency's *Net Zero Roadmap*. However, these studies sometimes lack publicly available U.S.-specific data. Comparisons of global decarbonization studies have been published by Resources for the Future (report) and others (report, report).

20 Non-CO_2 greenhouse gases in the EER, Princeton, and DA studies include methane, oxides of nitrogen, fluorinated gases, and others and are represented as carbon dioxide equivalent (CO_{2e}).

21 A more detailed summary of studies and scenarios is provided in the Supporting Material.

22 A recent multimodal study provides a comparison of how the Inflation Reduction Act could shape energy systems and emissions (report).

23 Information for the current U.S. energy system was derived from EIA; current U.S. emissions data was obtained from the Environmental Protection Agency (EPA). Detailed discussion on the methodologies applied in this meta-analysis are provided in the Supporting Material.

24 Final energy is calculated by summing the energy consumption of the three end-uses: transportation, industry, and buildings. It does not show energy consumed in direct air capture or in interim stages like electricity and fuel production.

25 Energy values for fuels are reported on a higher heating value (HHV) basis in this report.

26 The EER study also used heat from thermal nuclear power plants for direct air capture systems.

27 Liquid fuels include ammonia and hydrocarbon fuels derived from petroleum, bioenergy, and synthetic pathways.

28 Pipeline gas includes fossil natural gas, renewable natural gas, synthetic natural gas, and blended hydrogen.

29 Hydrogen is reported as a final energy carrier when it is used directly as an end-use fuel or as a non-energy feedstock for chemicals production (including non-energy uses of ammonia). Hydrogen is reported in pipeline gas when it is blended into the pipeline gas supply. Hydrogen is reported in liquid fuels when it is used to produce synthetic fuels or ammonia used as an end-use fuel.

30 The OEO study did not include non-energy uses of fuels.

31 Air-source heat pump efficiencies decrease as outside air temperatures become colder. To meet the heating requirements with a heat pump alone, the heating unit would need to be sized larger than a unit sized for a hybrid mode. This standalone heat pump approach is more costly in terms of the heating equipment itself, but also in terms of the associated infrastructure requirements. Electrification of space heating can increase and shift peak annual electric loads to the coldest winter days, such that additional electric transmission and distribution capacity is required, along with additional electric generation capacity. This cost stacking through the electric value chain for standalone heat pumps can lead to higher overall costs for achieving economy-wide net-zero targets in comparison to hybrid electric-gas heating systems. This complex set of cost tradeoffs is incorporated into the analyses of the LCRI and EER studies, which allow for this hybrid heating option. The results of these studies point to broad adoption of hybrid electric-gas heating systems in net-zero scenarios.

32 Although hydrogen is blended into the pipeline gas mixture used for gas-fired power generation in some scenarios across studies, pure hydrogen is only leveraged as a fuel for power generation in the LCRI study.

33 Capacity factor is a measure how intensively a generating unit is operated. Capacity factors are calculated here by dividing the electricity generated in 2050 by the maximum possible electrical energy that could have been produced if the generator were continuously operated at maximum capacity. A capacity factor of 100% indicates that a generating unit is continuously operated at its maximum output.

34 Figure 8 reports the primary source of generation from wind and solar, rather than the secondary generation from storage, which originally stored power from excess wind and solar capacity. This is consistent with the reporting convention of all five studies evaluated here.

35 Electrolysis costs in 2050 were assumed to be lower in the Princeton and EER studies as compared to the LCRI study, and correspondingly, the Princeton and EER studies trend towards higher deployment of electrolytic hydrogen production. Regarding natural gas with carbon capture pathways, Princeton and EER assumed higher costs in 2050 than LCRI, and correspondingly the Princeton and EER studies trended towards lower deployment of natural gas-based hydrogen production. LCRI assumed a 55% carbon capture rate for biomass pathways, whereas Princeton assumed an 87% capture rate.

36 For OEO, the lower level of hydrogen could be attributed to the study excluding non-energy uses of resources.

37 LCRI's Limited Options scenario does not explicitly exclude fossil fuels, but it explicitly excludes carbon sequestration. This constraint ultimately translates to substantial reductions in fossil fuel consumption in the LCRI Limited Options scenario.

38 There are differences in how certain low-carbon pipeline gas pathways are labeled across different studies. In all studies, landfill gas and anaerobic digestion-based gas are considered as sources for renewable gas. Similarly, across all studies, pipeline gas generated through conversion of captured CO_2 and hydrogen is treated as synthetic natural gas. For gas produced via biomass gasification this is treated as RNG in the LCRI study, whereas it is treated as SNG in EER, Princeton, and DA. OEO did not include RNG but included SNG.

39 The Princeton study included biofuels as part of the production of liquid fuels and pipeline gas. However, in the Princeton dataset utilized for this meta-analysis, biofuels are reported as synthetic fuels. Hence, the synthetic fuels results in Figure 10 and Figure 11 are indicative of both biofuels and synthetic fuels.

40 For LCRI, ammonia is used as a transportation fuel at very low levels (0.04 EJ) in the Limited Options scenario.

41 Figure 11 shows energy uses of liquid fuels, such as heating buildings and fueling vehicles. Non-energy use of liquid fuels as feedstock chemicals and materials is not shown here but is included in the total final energy values reported in Figure 3.

42 The land sink values reported for LCRI scenarios only include the incremental land sink change relative to the 2020 level evaluated in that study. Hence these values appear smaller in magnitude as compared to the 2022 levels shown in Figure 12. In the EER 100% Renewables scenario, the 2050 land sink is slightly lower than the 2022 level, but the overall net-zero target is still achieved despite this slight land sink reduction. OEO did not include the land sink in their analysis.

43 The cost information reported here is described in greater detail in the Supporting Material.

44 Costs for the EER Low Demand scenario are not reported here as based on guidance from the authors of the EER study. The framing for the Low Demand scenario is such that it is tenuous to compare costs for this scenario relative to other EER scenarios.

45 Decarb America did not report cost information.

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GTI Energy and EPRI are together addressing the need to accelerate development and demonstration of low- and zero-carbon energy technologies.

The Low-Carbon Resources Initiative (LCRI) will focus on large-scale deployment to 2030 and beyond. Fundamental advances in a variety of low-carbon electric generation technologies and low-carbon chemical energy carriers—such as clean hydrogen, bioenergy, and renewable natural gas—are needed to enable affordable pathways to economy-wide decarbonization.

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