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LCRI LOW-CARBON RESOURCES INITIATIVE

NOVEMBER 2023

EXECUTIVE SUMMARY

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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Funding

This work was supported by funding from GTI Energy and the Low Carbon Resources Initiative which was designed by GTI Energy and the Electric Power Research Institute (EPRI) to address the need to accelerate development and demonstration of low-and-zero-carbon energy technologies.

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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

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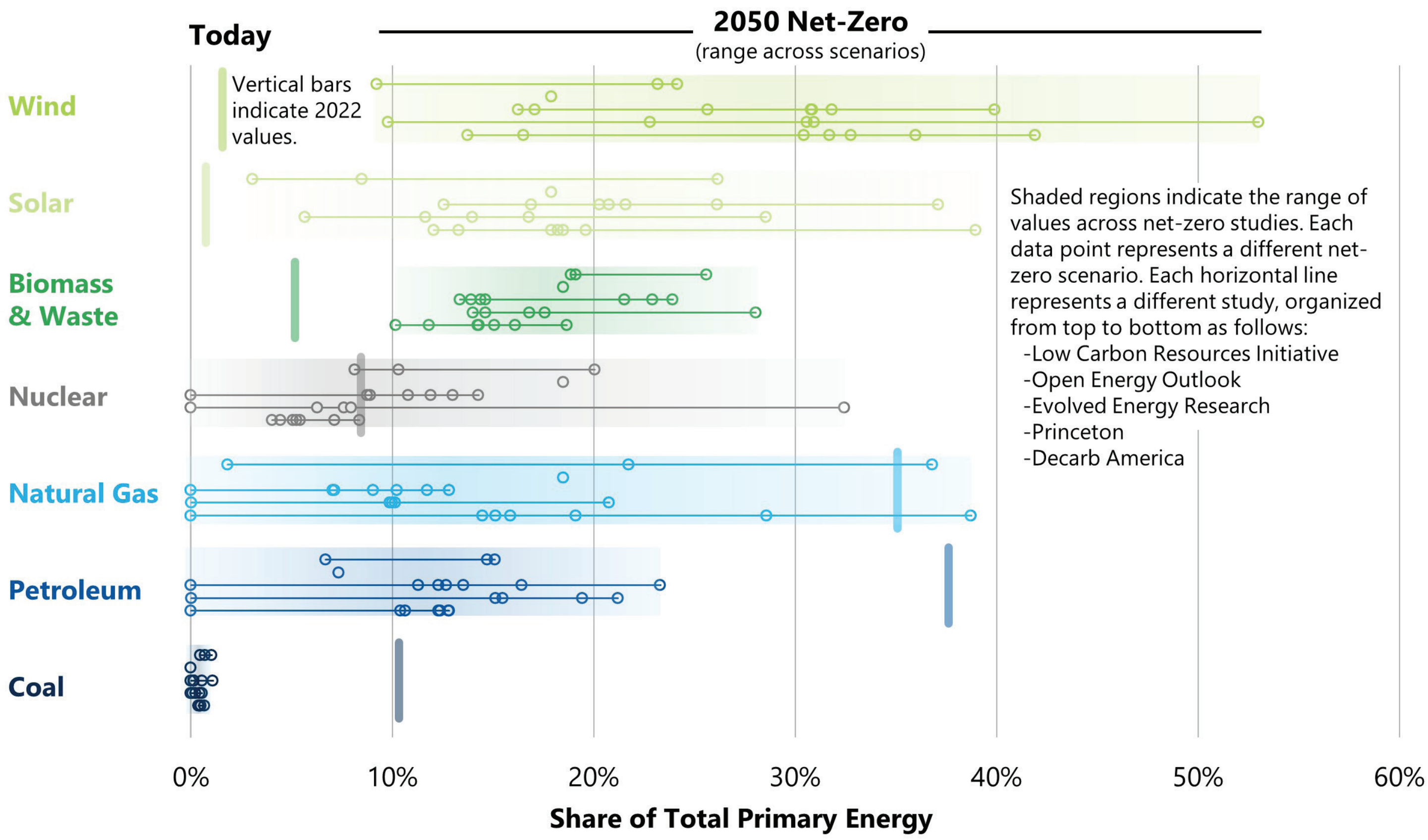
Commonalities Across U.S. Economy-Wide, Net-Zero Studies

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.

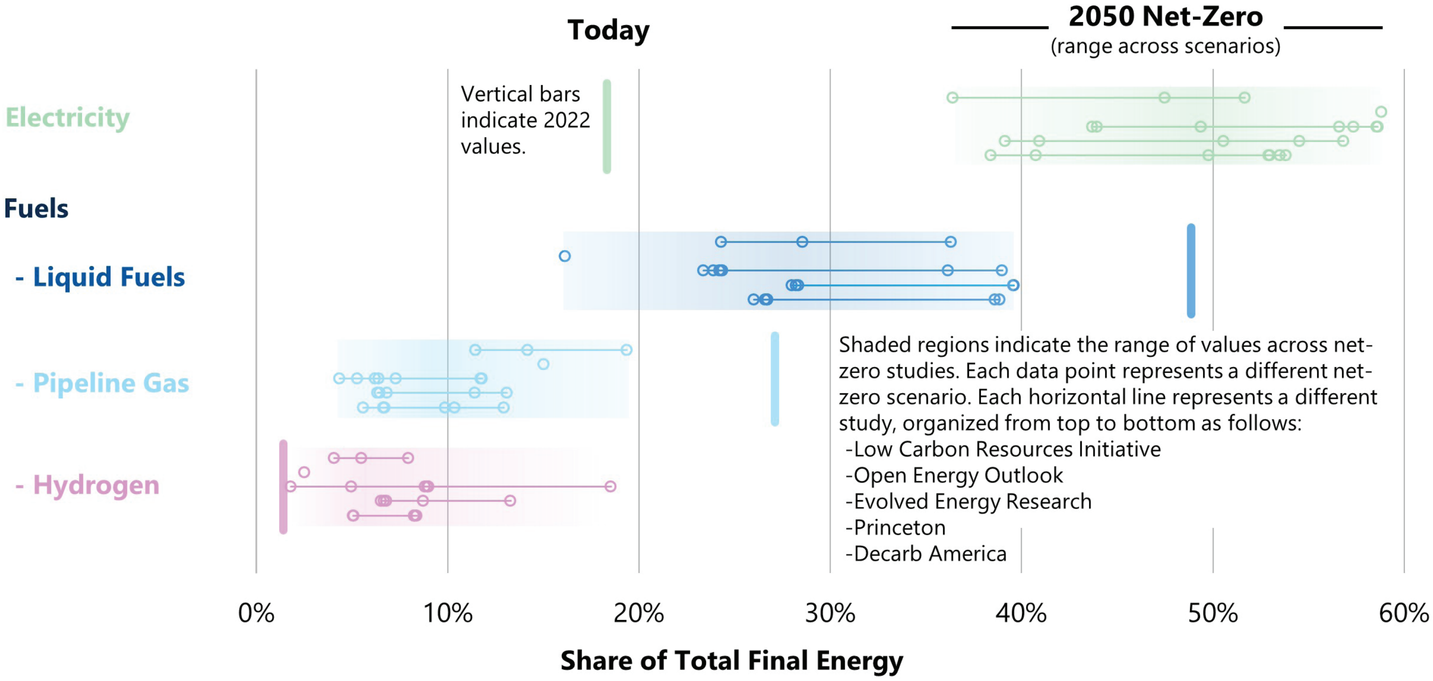
Fuels diversify and serve multiple markets. Fuels continue to have a sizeable role in these net-zero systems, accounting for between 41 and 64% of final energy (Figure ES-2). In all net-zero scenarios, fuels are used across all end-use sectors—transportation, industry, and buildings. Liquid fuels and 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



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

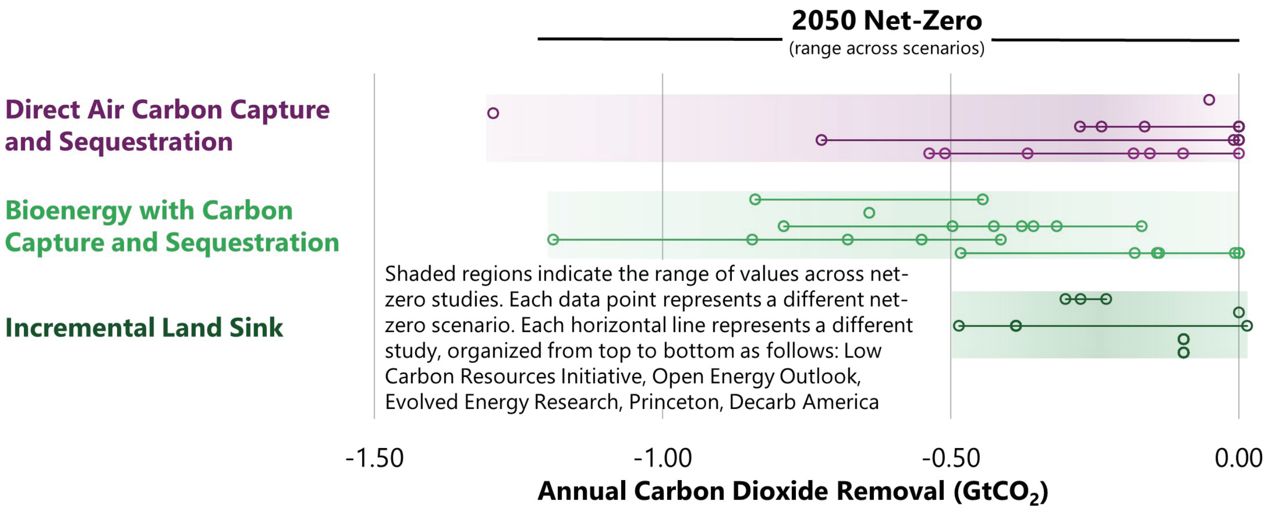


Final energy, the form of energy used by end-use customers in the buildings, transportation, and industrial sectors, transforms in net-zero scenarios relative to today. The share of final energy supplied by electricity grows in all scenarios. Gaseous and liquid fuels continue to serve across sectors, 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



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.

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.

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About GTI Energy

GTI Energy is a leading technology development organization. Our trusted team works to scale impactful solutions that shape energy transitions by leveraging gases, liquids, infrastructure, and efficiency. We embrace systems thinking, innovation, and collaboration to develop, scale, and deploy the technologies needed for low-carbon, low-cost energy systems.

About Low-Carbon Resources Initiative (LCRI)

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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Thanks to GTI Energy colleagues who supported this effort: Zane McDonald, Christy Michals, Kristin Cone, Alessandra Reilly.

This version of the executive summary was updated in February 2024.

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