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META 2.0

Meta-Analysis of U.S. Economy-Wide Decarbonization Studies

Executive Summary

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Meta 2.0: Meta-Analysis of U.S. Economy-Wide Decarbonization Studies

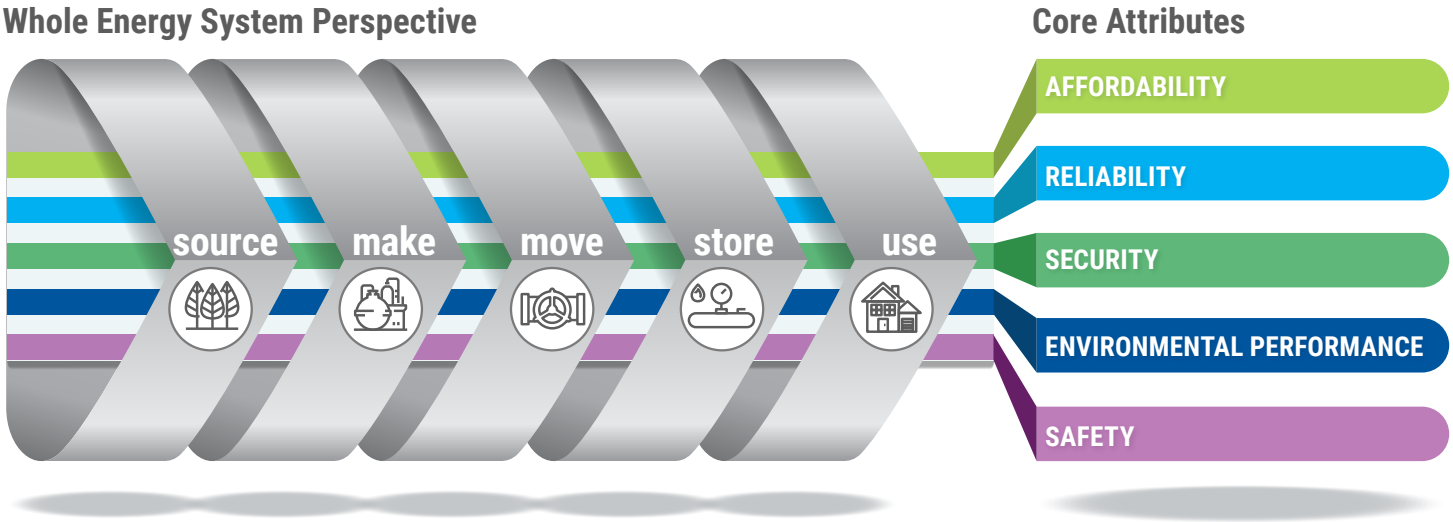
Meta 2.0, the second edition of GTI Energy's meta-analysis of U.S. economy-wide decarbonization studies, builds upon insights from the 2023 Meta NZ study. By harmonizing results across ten analyses and 109 net-zero scenarios, it places studies with different teams, methods, and assumptions on a common basis for side-by-side comparison. Developed in consultation with the modeling teams behind each study, Meta 2.0 draws together a broad range of expertise, analytical approaches, and data to offer an updated look at designs for net-zero energy systems.

The Spotlight Shifts. The Foundations Remain.

The spotlight shifts. Over the decades, attention has shifted among the attributes of affordability, reliability, security, environmental performance, and safety. When the Meta NZ study was published, decarbonization held the spotlight. Today, rising energy bills, resource adequacy, surging electricity demand, and supply-chain risks dominate the headlines. The spotlight will continue to shift, but the core attributes of affordability, reliability, security, environmental performance, and safety will continue to matter.

The foundations remain. The foundations of a well-designed energy system remain constant, regardless of where the spotlight is currently focused. Delivering on any single core attribute depends on a whole-system perspective: how energy is sourced, made, moved, stored, and used. And because they are interconnected, no single attribute can be pursued in isolation. Gains in one can come at the expense of another. For example, improved environmental performance can come with higher costs, and vice versa. Effective long-term planning weighs these attributes together, with the whole energy system in view.

The stakes are high for long-lived infrastructure. Power plants, pipelines, transmission lines, and industrial facilities built this decade will still be operating at mid-century, under conditions that will continue to evolve. Planning for these assets benefits from understanding a broad array of possible futures, including those at the frontier of deep decarbonization. Meta 2.0 brings together ten economy-wide analyses that map this frontier across the whole energy system to evaluate cost-optimal pathways to net-zero emissions by 2050, providing insight into the balance between environmental performance and affordability. Wherever the spotlight falls next, this frontier view offers a durable reference point for the decisions being made today.



Many Independent Lenses. One Harmonized View.

Economy-wide models offer a whole energy system perspective. The economy-wide analyses in Meta 2.0 span energy value chains from *source*, through *make, move, store*, and *use*. They weigh a broad range of options for carbon management (e.g., emissions abatement and removal), energy sources (e.g., renewable, nuclear, and fossil), and energy carriers (e.g., electricity, hydrogen, and biofuels) for cost-optimal solutions under a net-zero emissions constraint. That breadth makes them uniquely suited to revealing how tradeoffs in one part of the energy system ripple through the rest. For example, they can weigh the competitiveness of electrification against low-carbon fuels, accounting for both the power generation and grid buildout that supports electrification and the supply chains and infrastructure that support low-carbon fuels.

Multiple perspectives bring the clearest patterns into focus. Each individual economy-wide study offers a robust view of U.S. energy systems. But while one study offers a view, a comparison of multiple studies—a meta-analysis—reveals the patterns. And the broader the range of perspectives gathered, the more confidence we can place in the patterns that emerge. To the best of the authors' knowledge, every U.S. economy-wide, net-zero scenario set released since Meta NZ was considered for Meta 2.0—a total of 34 analyses.[1] Objective, consistent selection criteria were applied to arrive at the ten analyses and 109 scenarios included in this meta-analysis (Table ES-1).[2] With teams spanning academia, national laboratories, government, and nonprofit and private research organizations, these ten largely independent analyses encompass a broad range of modeling approaches, vantage points, and assumptions.[3]

Table ES-1: Analyses Included in Meta 2.0

Publication	Team	Year	Model	Analysis Label	Net-Zero Scenarios
US economy-wide decarbonization: Sectoral and distributional impacts	Becker et al. (EPA, MIT, RTI, Mines)	2025	USREP-ReEDS	USREP	12
Diverse Decarbonization Pathways Under Near Cost-Optimal Futures	Open Energy Outlook (OEO); Sinha et al.	2024	Temoa	OEO	3[4]
LCRI Net Zero Scenarios 2.0	Low-Carbon Resources Initiative (LCRI); EPRI	2024	US-REGEN	LCRI	11
Annual Decarbonization Perspective 2024	Evolved Energy Research (EER)	2024	EnergyPATHWAYS & RIO	EER	10
Similarities and contrasts: Comparing U.S. and Canadian paths to net-zero	Starke et al. (Simon Fraser, Navius Research)	2024	gTech	gTech	4
The role of electrification and the power sector in U.S. carbon neutrality	O'Keefe et al. (UMD, PNNL, Peking Univ., KAIST)	2024	GCAM-USA	GCAM-USA	9
Net-zero CO2 by 2050 scenarios for the United States in the Energy Modeling Forum 37 study[5]	Browning et al.; EPA	2023	EPA-TIMES	TIMES	19
	Browning et al.; UMD, PNNL	2023	GCAM	GCAM	16
	Browning et al.; NETL	2023	MARKAL-NETL	MARKAL	18
	Browning et al.; NREL, Esmia Consultants	2023	NATEM	NATEM	7
Total			**10 analyses**		**109**

"Analysis Label" is the identifier used in Figures ES-1 to ES-3.

Varied Perspectives. Shared Patterns.

Net-zero energy systems are *"and"* energy systems. The defining pattern of net-zero energy systems is a combination rather than substitution: ***"and"*** rather than "or." This was evident in Meta NZ. It remains evident in Meta 2.0, where all 109 scenarios rely on both halves of the pairings below.

- **Emissions reductions *and* carbon removal.** All 109 scenarios cut gross emissions deeply, through adoption of low-carbon energy sources and/or abatement of fossil emissions via carbon capture and sequestration (CCS). ***And*** all 109 rely on removing carbon from the atmosphere to balance residual emissions, through land sinks, bioenergy with CCS, and/or direct air CCS (Figure ES-3).[6]
- **Non-fuel *and* fuel-based energy sources.** All 109 scenarios expand non-fuel energy sources, led by wind and solar. ***And*** all 109 leverage fuel-based energy sources: bioenergy, nuclear, and/or fossil fuels (Figure ES-1).
- **Electricity *and* fuel-based energy carriers.** All 109 scenarios expand the delivery of electricity to energy customers, rising from about 18% of final energy today to between 30% and 68% in 2050. ***And*** all 109 continue to leverage fuels to meet end-use demands in buildings, industry, and transportation, accounting for the remaining 32% to 70% of final energy in 2050 (Figure ES-2).

The features of *"and"* energy systems endure as the landscape changes. Meta NZ drew on five analyses and 23 net-zero scenarios. Meta 2.0 draws on ten analyses and 109 net-zero scenarios. Across this expanded dataset, all key findings from Meta NZ endure.[7] This consistency is remarkable given all that has changed since Meta NZ was published: new modeling approaches and teams, significant shifts in energy policy, higher expectations for future energy demand, and updated technology insights. It provides compelling evidence that these findings reflect the cornerstone features of net-zero energy systems.

What *"and"* energy systems look like can vary widely. While these analyses and scenarios share a common pattern of ***"and"*** features, there remains ample room in how net-zero energy systems could be designed. For example, nuclear energy in 2050 ranges from well below to well above today's level, and hydrogen production spans from roughly today's volume to an order of magnitude more. These differences can be traced to each analysis's assumptions about energy demand and the cost, performance, and availability of resources and technologies. Together, those assumptions set the balance within each pairing: emissions reductions ***and*** carbon removal; non-fuel ***and*** fuel-based energy sources; and electricity ***and*** fuel-based energy carriers.

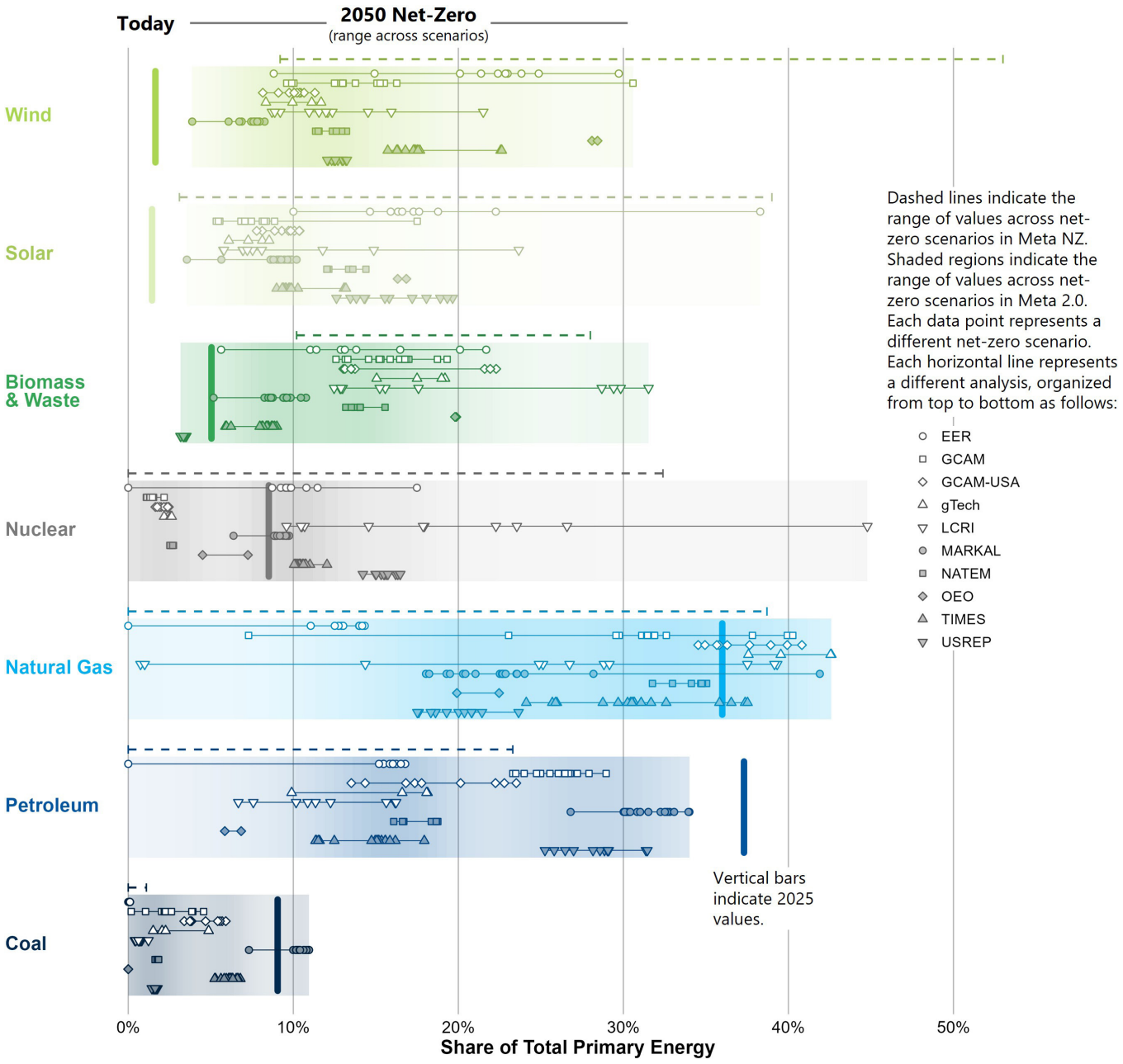
Both insights matter as we look to the future. The shared ***"and"*** features are the cornerstone: they hold across models, teams, and assumptions, offering a firm foundation for long-term planning. The breadth of possible designs provides a range of options: no single analysis, and no single scenario, holds "the" answer. Planning that remains open to multiple pathways retains the flexibility to adapt as technologies, costs, and conditions evolve.

Key Findings from Meta NZ
(five analyses, 23 net-zero scenarios)

1. Renewables grow the supply of low-carbon energy
2. Electricity expands across sectors
3. Fuels diversify and serve multiple markets
4. Efficiency reduces energy consumption while enabling economic growth
5. Carbon dioxide removal balances remaining emissions

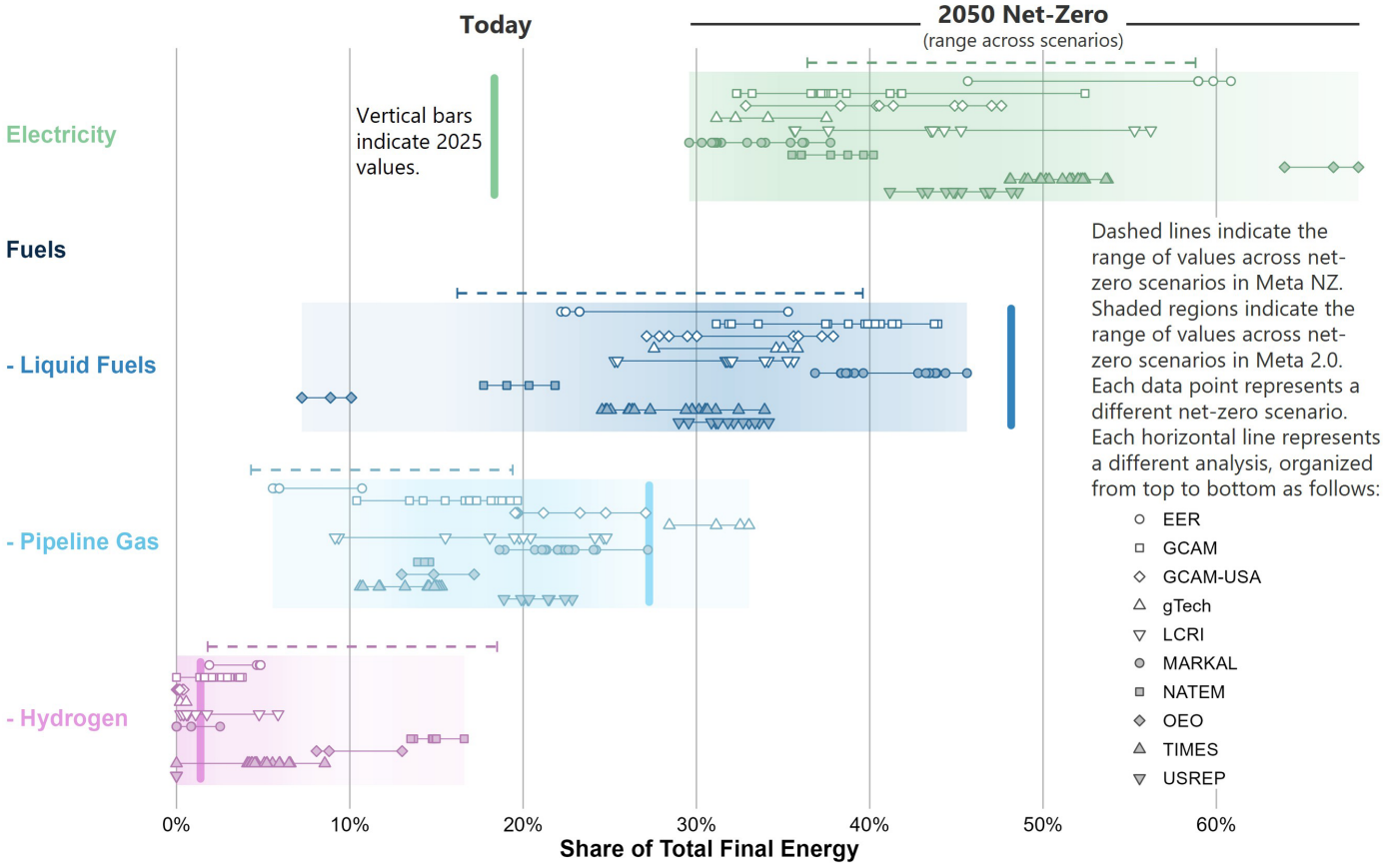
All five findings endure across Meta 2.0's ten analyses and 109 net-zero scenarios.

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



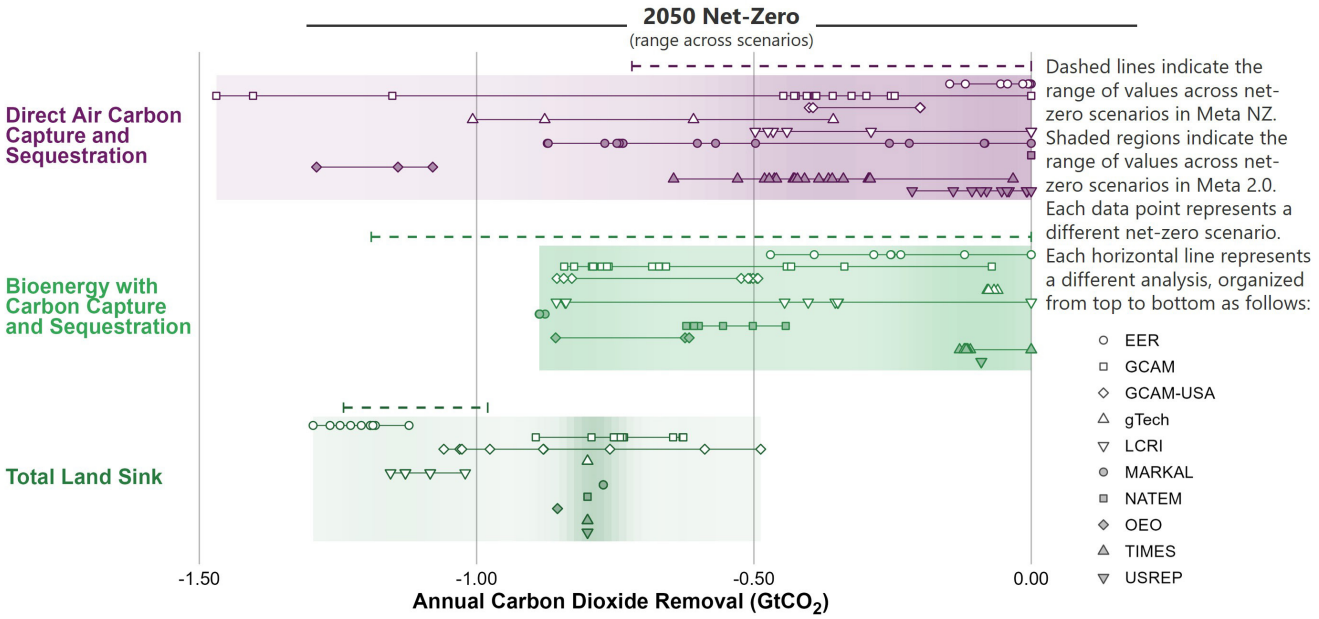
Primary energy (the sources from which energy is drawn) shifts in every net-zero scenario. Renewables expand relative to today. Nuclear and fossil energy sources remain a part of the energy mix in most scenarios. Geothermal and hydro energy, not shown in this figure, typically account for a small share of primary energy in most scenarios.

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



Electricity supplies a larger share of final energy (the energy consumed by end-use customers) in every net-zero scenario than today, while liquid fuels, pipeline gas, and hydrogen continue to meet a meaningful share of end-use demand. Coal, biomass, and geothermal, not shown in this figure, typically account for a small share of final energy in most scenarios. These final energy results include both energy and non-energy use of fuels for all analyses except OEO.

Figure ES-3: Annual Carbon Dioxide Removal by Approach



Every net-zero scenario relies on removal of carbon from the atmosphere, though the mix of approaches and their scale vary widely.[6]

Reflecting on the Patterns. Looking to the Future.

Peaks drive infrastructure planning, and net-zero systems are peaky. Consistent with Meta NZ, these results point to sustained, large-scale investment in energy infrastructure. For example, most scenarios roughly double to triple the installed electricity capacity, led by solar and wind, with corresponding growth in the grid that delivers it. As variable wind and solar account for a larger share of energy supply, energy systems become *peakier*. Today, most energy assets are firm and flexible: available to deliver peak energy throughput whenever called upon. In net-zero systems, firm and flexible assets may run less often, yet remain essential when wind and solar output falls and/or demand spikes. This paradigm holds true for both electricity and fuels infrastructure. It holds for the firm power plants and electric grid that make and move electricity to meet peak demands. And it holds for the fuels infrastructure that stores and moves the fuel to supply those power plants at peak conditions. With hybrid electric-fuel end-use equipment, electricity-based fuels production, and other cross-sector integration, *peakiness* is likely to manifest throughout net-zero energy systems. Thoughtful planning for long-lived electricity and fuels infrastructure therefore rests on a systems-level understanding of the role those assets play in meeting both annual and peak energy demands.

The full value of economy-wide models depends on full reporting. Economy-wide analyses are uniquely suited to assess the ***"and"*** of energy systems, yet many analyses thinly report and/or represent fuel systems and overall cost information. All ten analyses report the annual electricity supply mix, and nine report installed power capacity (i.e., the combined size of the installed power plants) (Table ES-2). The composition of the fuel supply is reported less consistently, particularly for liquid fuels and pipeline gas, which are reported by only four and three of the ten analyses, respectively. None of the analyses reports the peak capacity of hydrogen, liquid fuel, or pipeline gas infrastructure (i.e., the size of the pipe). Cost reporting is similarly inconsistent, such that Meta 2.0 cannot fully test Meta NZ's finding that more highly constrained scenarios are more costly—a notable gap given that affordability is central to the energy conversation today. Looking ahead to future economy-wide modeling efforts, more comprehensive consideration and reporting of the fuels supply mix, peak capacity, and cost information would unlock far more of the insight these models have to offer.

Table ES-2: Energy Carrier Supply Mix and Capacity Reporting

Energy Carrier	Annual Supply Mix (composition of the annual energy supply)	Peak Capacity (peak level of energy that can be supplied)
Electricity	10 of 10	9 of 10
Hydrogen	8 of 10	2 of 10
Liquid Fuels	4 of 10	0 of 10
Pipeline Gas	3 of 10	0 of 10

Number of the ten Meta 2.0 analyses reporting each type of result. Darker shading indicates more complete reporting.

The spotlight will shift. The foundations will remain. Across ten analyses and 109 scenarios, net-zero energy systems are ***"and"*** energy systems: emissions reductions ***and*** carbon removal, non-fuel ***and*** fuel-based sources, electricity ***and*** fuels-based energy carriers. These features have held even as policy, technology, and demand expectations have changed. Long-range planning grounded in these cornerstone features, and in a whole-system view of how energy is sourced, made, moved, stored, and used, can help ensure that decisions made today will hold up as conditions evolve into the future.

ENDNOTES

[1] Meta NZ included studies and datasets published through August 2023. Meta 2.0 considered all U.S. economy-wide, net-zero analyses and datasets released after that cutoff and through August 2026.

[2] Selection criteria: U.S. economy-wide net-zero scenarios with results for 2050; documented scenario types and definitions; publication between August 2023 and August 2026; and data publicly available or freely obtainable upon request. If a model and/or modeling team published multiple analyses, either the standalone and/or newest analysis has been included. The full list of 34 analyses considered appears in the main report.

[3] The ten analyses included in Meta 2.0 were largely developed independently of one another. One partial exception is the four analyses performed as part of Energy Modeling Forum 37 (TIMES, GCAM, MARKAL, NATEM), which were run as part of a coordinated model comparison such that there may be some level of interdependence between them.

[4] OEO scenarios include the deterministic net-zero pathway, and a low-hydrogen pathway (contrasting in terms of including higher carbon capture), and a near-cost-optimal scenario (MGA_010_80_6) whose key metrics generally lie closer to the medians of the distribution of 1,100 near optimal runs than the deterministic pathway.

[5] Four Energy Modeling Forum 37 models (TIMES, GCAM, MARKAL, NATEM) are included; other Energy Modeling Forum 37 participants were represented by more recent standalone analyses already in Meta 2.0. Only the "R2" model runs were used, following consultation with the modelers.

[6] Net-zero is defined differently across analyses: all EER scenarios and two NATEM scenarios balance greenhouse gases, while the other nine analyses balance carbon dioxide only. OEO excludes the land sink; LCRI counts only growth in the land sink relative to today as part of the net-zero balance.

[7] The efficiency finding carries added nuance. Final energy (the energy delivered to buildings, transportation, and industry) declines from about 82 EJ today to 38–79 EJ in 2050 in every net-zero scenario, led by electric vehicles, heat pumps, and other efficient end-use technologies. Primary energy also declines in most scenarios, partly because wind, solar, and other non-combustion generation are reported in terms of the electricity they output; the MARKAL scenarios and four scenarios across EER, GCAM, and gTech are the exceptions.

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Operations Technology Development (OTD) is a member-controlled, not-for-profit organization advancing technologies that improve the safety, reliability, and efficiency of natural gas systems.

About Low-Carbon Resources Initiative (LCRI)

The Low-Carbon Resources Initiative (LCRI), created by GTI Energy and EPRI, advances low- and zero-carbon energy technologies to support economy-wide decarbonization.

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