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

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Meta 2.0 is the second edition of GTI Energy's meta-analysis of U.S. economy-wide decarbonization studies, building 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.

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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.

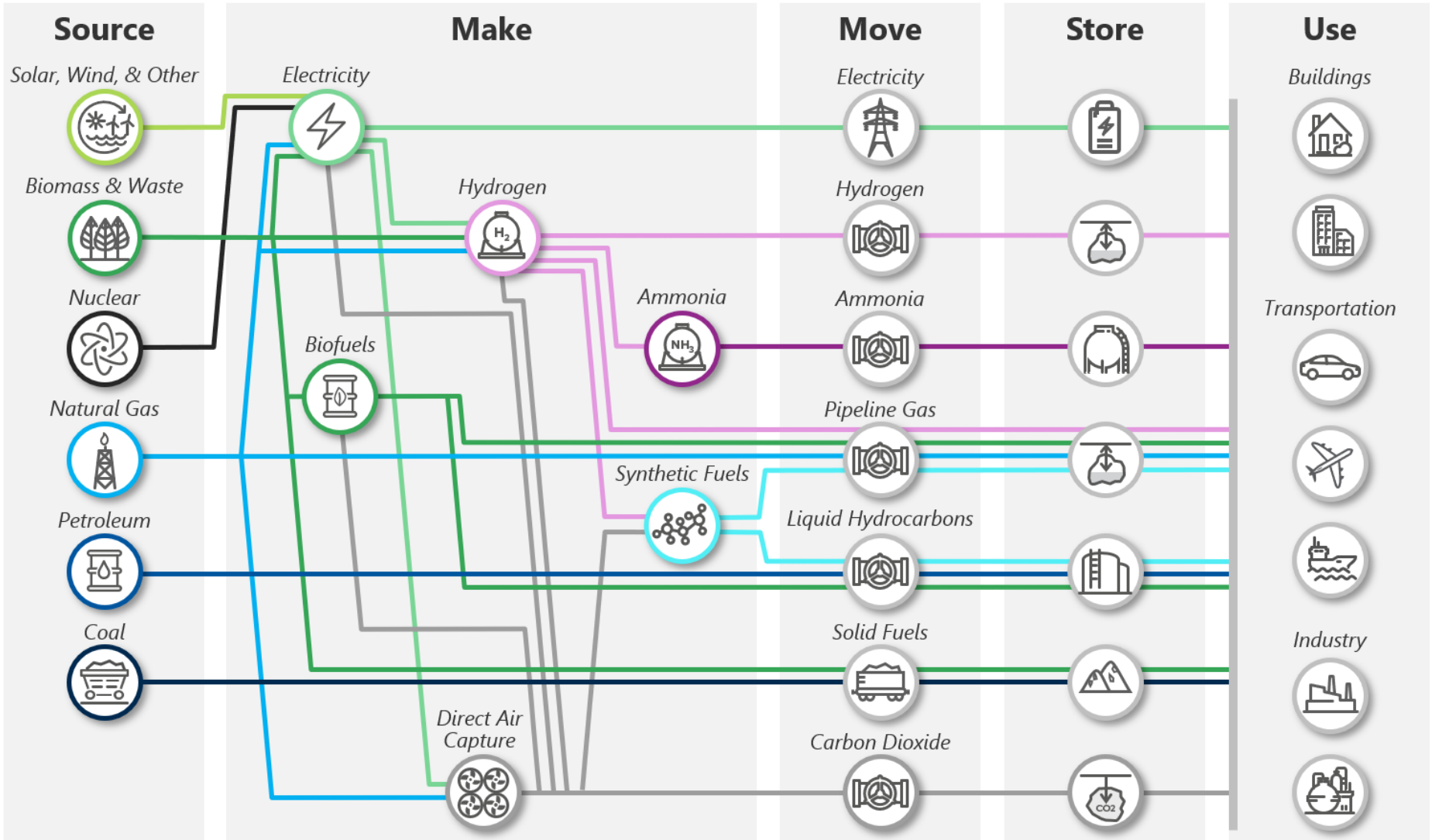
The foundations remain. The foundations of a well-designed energy system remain constant, regardless of where the spotlight is currently focused. Delivering on any single core attribute depends on a whole-system perspective: how energy is sourced, made, moved, stored, and used. And because they are interconnected, 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.

Long-run planning benefits from assessing a **broad array of possible futures**, including the **frontier of decarbonization**.

Meta 2.0 brings together ten economy-wide analyses that map this frontier across the **whole energy system.**

This frontier view offers a durable reference point for today's decisions, **wherever the spotlight shines in the future**.

Economy-Wide Analyses. Whole Energy System Perspective.



The **economy-wide analyses** in this Meta 2.0 study 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 carbon 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 **whole energy system perspective** 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.

Many Independent Lenses. One Harmonized View.

Many Independent Lenses. 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 identified**. Objective, consistent selection criteria were applied to arrive at the **10 analyses selected** and **109 scenarios included** in this meta-analysis. 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.



One Harmonized View. Results from the **109 scenarios** have been aligned to a consistent reporting basis across primary source energy, final end-use energy, energy carriers, and greenhouse gas emissions.

Methodology | Identification, Selection, & Inclusion

34 **Analyses Identified**

↓

10 **Analyses Selected**

↓

109 **Scenarios Included**

Identification Criteria

- U.S. economy-wide decarbonization analysis
- Published after August 2023 (Meta NZ cutoff)

Core Selection Criteria

- U.S. economy-wide, net-zero scenario(s)
- Economy-wide energy systems data/results for 2050
- Traceability to scenario and results definitions
- Data available publicly or freely upon request

Additional Considerations

- *Data for a year prior to 2025 to validate actuals applied*
- *Incorporates recent policies and trends (e.g. IRA, OBBBA, data centers)*
- *If a model was used for multiple analyses, either the standalone and/or newest analysis was included*

August 2023 was the cutoff date for publication of relevant scenario data for inclusion in Meta NZ. Meta 2.0 considers analyses from August 2023 through August 2026.

Methodology | 34 Analyses Identified

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Year	Title		Authors	Energy System Model Used
2026	Annual Energy Outlook 2026	1	U.S. Energy Information Administration (EIA)	NEMS
2026	Bloomberg New Energy Outlook 2026	2	Bloomberg New Energy Finance (BNEF)	Proprietary
2025	US economy-wide decarbonization: Sectoral and distributional impacts	3	**Becker et al. (EPA, MIT, RTI, Mines)**	**USREP-ReEDS**
2025	World Energy Outlook 2025	4	International Energy Agency (IEA)	Global Energy and Climate (GEC) Model
2025	Annual Energy Outlook 2025	5	U.S. Energy Information Administration (EIA)	NEMS
2025	bp Energy Outlook 2050: September 2025	6	bp	Proprietary
2025	Bloomberg New Energy Outlook 2025	7	Bloomberg New Energy Finance (BNEF)	Proprietary
2025	Policy implications of net-zero emissions: A multi-model analysis of United States emissions and energy system impacts	8	Bistline et al.	(multiple)
2024	Diverse Decarbonization Pathways Under Near Cost-Optimal Futures	9	Sinha et al. (Open Energy Outlook: Carnegie Mellon, NC State)	Temoa
2024	LCRI Net Zero Scenarios 2.0	10	**EPRI**	**US-REGEN**
2024	Annual Decarbonization Perspective 2024	11	**Evolved Energy Research (EER)**	**EnergyPATHWAYS & RIO (EP-RIO)**
2024	World Energy Outlook 2024	12	International Energy Agency (IEA)	Global Energy and Climate (GEC) Model
2024	Similarities and contrasts: Comparing U.S. and Canadian paths to net-zero	13	**Starke et al. (Simon Fraser, Navius Research)**	**gTech**
2024	An Energy Systems Model Approach to US Decarbonization: Technological Solutions, Policy Pathways, and Equity Outcomes	14	**Katherine H. Jordan (OEO, CMU)**	**Temoa**
2024	A deep decarbonization framework for the United States economy – a sector, sub-sector, and end use based approach	15	Kar et al.	Decarbonization Scenario Analysis Model
2024	Drivers and implications of alternative routes to fuels decarbonization in net-zero energy systems	16	Mignone et al.	Unknown
2024	Uses and limits of national decarbonization scenarios to inform net-zero transitions	17	Bistline et al.	(multiple)
2024	bp Energy Outlook 2050: July 2024	18	bp	Proprietary
2024	Climate Progress 2024: REPEAT Project's Annual U.S. Emissions Pathways Update Summary Report	19	Princeton & EER	EP-RIO
2024	The role of electrification and the power sector in U.S. carbon neutrality	20	**O'Keefe et al. (UMD, PNNL, Peking Uni, KAIST)**	**GCAM-USA**
2023	State-by-state energy-water-land-health impacts of the US net-zero emissions goal	21	Ou et al. (Peking Uni, PNNL, UMD, EPA)	GCAM-USA
2023	Net-zero CO2 by 2050 scenarios for the United States in the Energy Modeling Forum 37 study		Browning et al. (part of EMF37 for NCA5)	(multiple)
		22	***EPA***	***EPA-TIMES***
		23	***UMD, PNNL***	***GCAM***
		24	***NETL***	***MARKAL-NETL***
		25	***NREL, Esmia Consultants***	***NATEM***
		26	*MIT*	*USREP-ReEDS*
		27	*EER*	*EP-RIO*
		28	*UMD, PNNL*	*GCAM-USA*
		29	*Simon Fraser, Navius Research*	*gTech*
		30	*OEO*	*Temoa*
		31	*EPRI*	*US-REGEN*
2023	Clean Energy Now For A Safer Climate Future: Pathways To Net Zero In The United States By 2050	32	NRDC & EER	EP-RIO
2023	Insights from Adding Transportation Sector Detail into an Economy-Wide Model: The Case of the ADAGE CGE Model.	33	Cai et al.	ADAGE
2023	Modeling the energy mix and economic costs of deep decarbonization scenarios in a CGE framework	34	Gilmore et al.	GCAM & EC-MSMR

*Rows in **blue text** indicate analyses selected for Meta 2.0.*

Methodology | 10 Analyses Selected 109 Scenarios Included

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Publication		Label	Model	Net-Zero Target	Service Demands	Demand Decisions	Supply Decisions	Geography	Equilibrium Approach	Scenarios Included
US economy-wide decarbonization: Sectoral and distributional impacts	1	USREP	USREP-ReEDS	Economy-wide NZ by 2050, CO_2 only	Not AEO-based	model output	model output	50 US states as 12 regions	General, myopic	12
Diverse Decarbonization Pathways Under Near Cost-Optimal Futures	2	OEO	Temoa	Economy-wide NZ by 2050, CO_2 only	Some from AEO 2022	model output	model output	50 US states as 9 regions	Partial, perfect	3 (of ~1100)
LCRI Net Zero Scenarios 2.0	3	LCRI	US-REGEN	Economy-wide NZ by 2050, CO_2 only	Not AEO-based	model output	model output	48 US states as 16 regions	Partial, perfect	11
Annual Decarbonization Perspective 2024	4	EER	EnergyPATHWAYS	Economy-wide NZ by 2050, All GHGs	Some from AEO 2023	user input	model output	50 US states as 27 regions	Partial, perfect	10
Similarities and contrasts: Comparing U.S. and Canadian paths to net-zero	5	gTech	gTech	Economy-wide NZ by 2050, CO_2 only	Not AEO-based	model output	model output	50 US states as 9 regions	General, myopic	4
The role of electrification and the power sector in U.S. carbon neutrality	6	GCAM-USA	GCAM-USA	Economy-wide NZ by 2050, CO_2 only	Some from AEO 2022	model output & user input	model output	50 US states as 51 region (+DC)	Partial, myopic	9
Individual model scenarios from Browning et al. EMF37 NCA5	7	TIMES	EPA-TIMES	Economy-wide NZ by 2050, CO_2 only	EPAUS9rT Database	user input	model output	50 US states as 9 regions	Partial, perfect	19
	8	GCAM	GCAM	Economy-wide NZ by 2050, CO_2 only	Not AEO-based	model output & user input	model output	50 US states as 1 region	Partial, myopic	16
	9	MARKAL	MARKAL-NETL	Economy-wide NZ by 2050, CO_2 only	EPAUSr2017 Database	user input	model output	50 US states as 9 regions	Partial, myopic	18
	10	NATEM	NATEM	Economy-wide NZ by 2050, CO_2 only for 5 scenarios and all GHGs for 2 scenarios	Some from AEO 2018	user input	model output	50 US states as 12 regions	Partial, perfect	7

"Label" is the identifier used in the results figures.

Methodology | Data Harmonization

Standardized scope, units, categories, and accounting conventions are applied, converting diverse net-zero scenario outputs into a consistent, like-for-like comparison dataset

Consultation with authors of the included analyses to resolve unclear source definitions, outliers, duplicate records, and category mismatches

1 Scope & Scenario Alignment
U.S. economy-wide scenarios, common 2050 endpoints, duplicate scenario/subtotal removal, completeness checks.

2 Units & Accounting
Common units, higher heating value (HHV) fuel basis, and reconciled primary energy reporting conventions.

3 Metric, Sector & Energy Carrier Mapping
Shared structures for energy, end-use sectors, electricity, hydrogen, gaseous fuels, liquid fuels, ammonia, and emerging carriers.

4 Study-Specific Reconciliation
Resolve "other" categories, feedstocks, non-energy fuel uses, reporting gaps, and author interpretation questions.

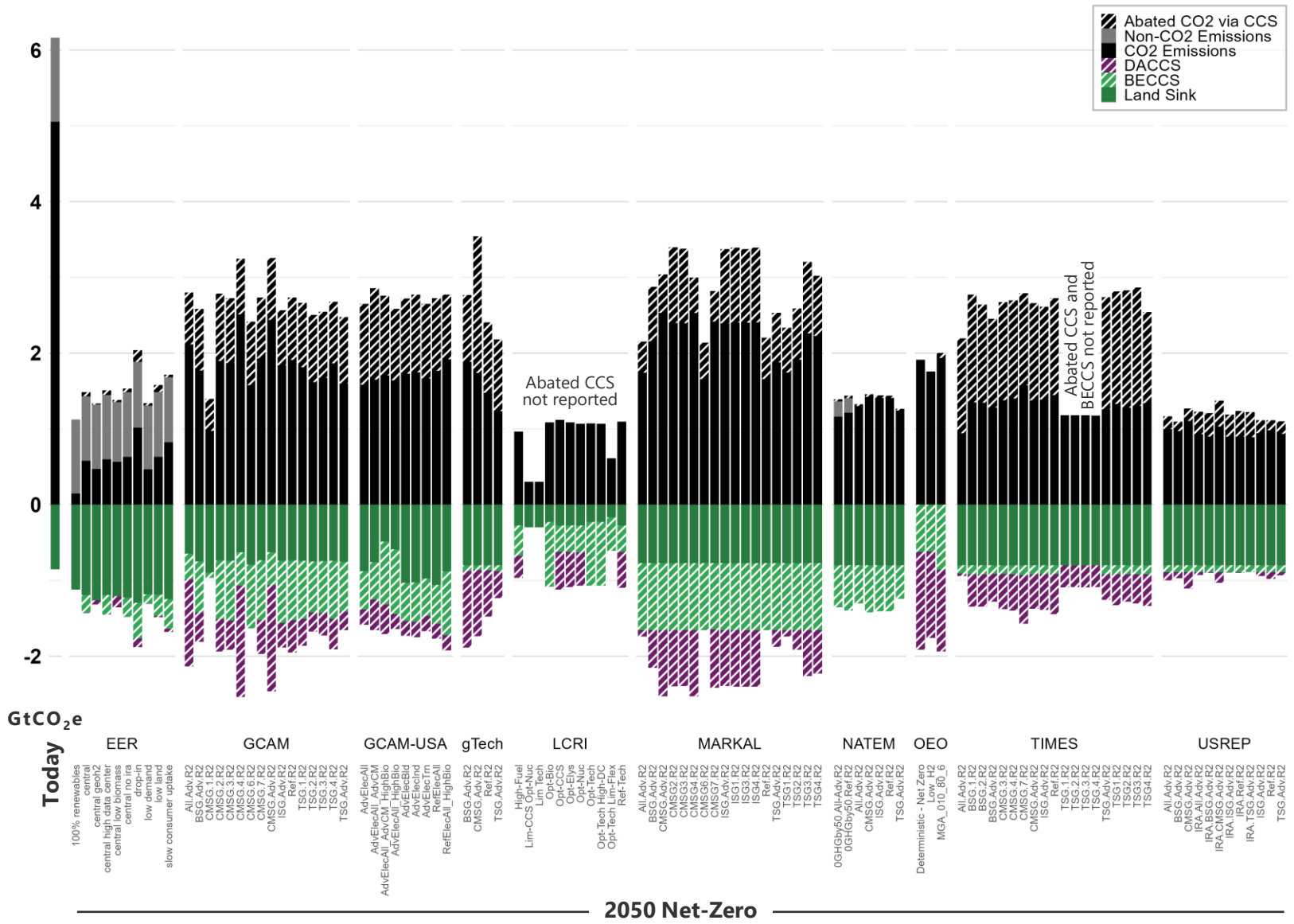
5 Carbon Management & Emissions
Comparable treatment of abated, positive and negative CO_2 emissions, land sinks, non-CO_2.

6 Consistency Verification
Outlier review, category checks, group orders, palettes, legends, and author feedback.

Meta 2.0 Dataset
consistent reporting across standardized categories

- **Primary Source Energy**
- **Final End-Use Energy**
- **Energy Carriers**
- **Greenhouse Gas Emissions**

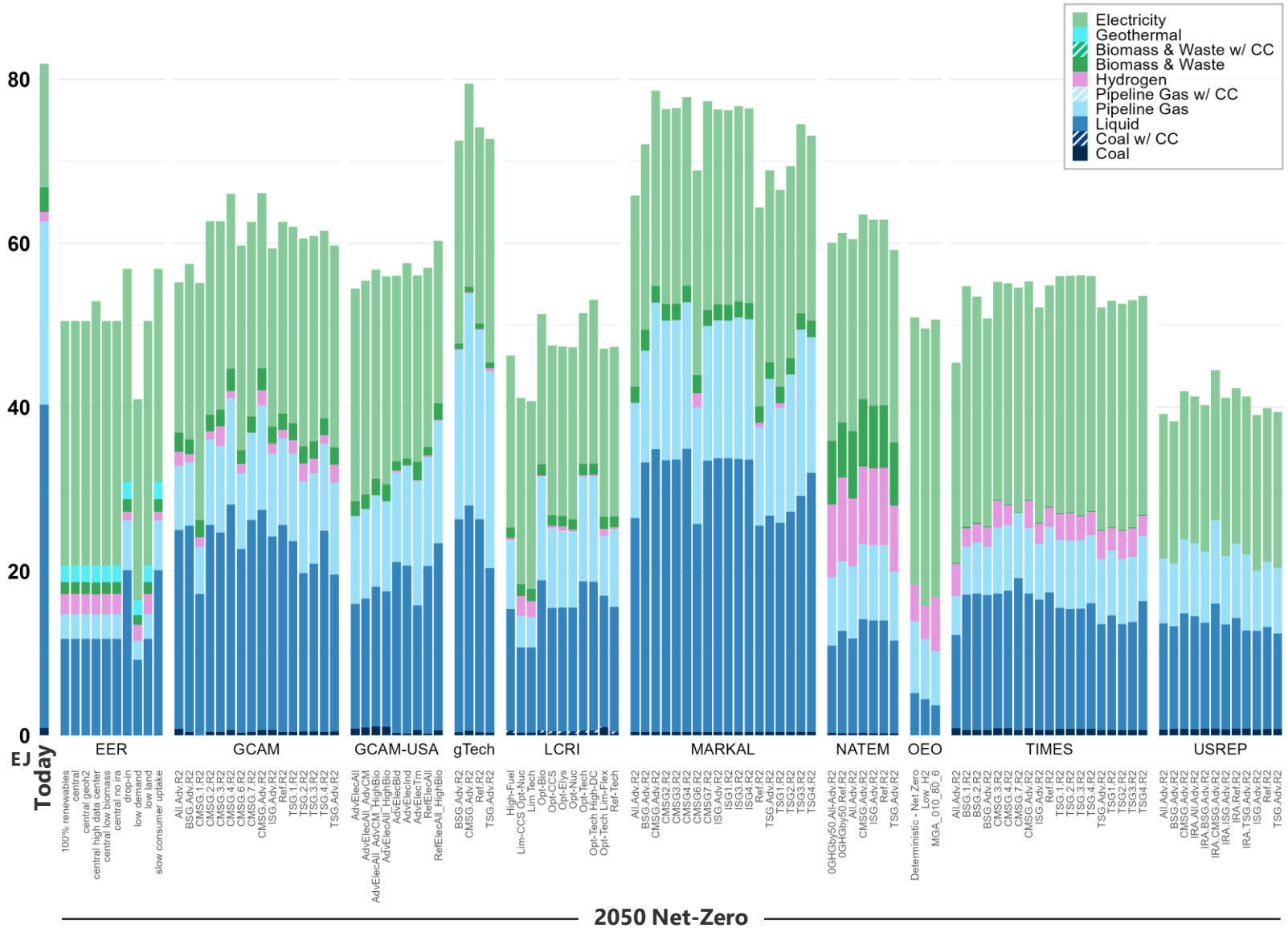
Results | Annual Greenhouse Gas Emissions ($GtCO_2e$)



- **All NZ scenarios achieve deep cuts in gross greenhouse gas (GHG) emissions but do not eliminate them entirely.** Every scenario retains residual carbon dioxide (CO_2) and non-CO_2 emissions (if included) from sectors that are difficult or expensive to fully decarbonize.
- **Net-zero is achieved through a combination of emissions reductions and carbon removals.** Every NZ scenario leverages some combination of land sink enhancement and/or sequestration of carbon directly captured from the air (DACCS) or from bioenergy sources (BECCS).
- **Net-zero is defined differently in different analyses**, with nearly all analyses considering only CO_2 as part of the positive emissions balance (except EER and two NATEM scenarios) and some analyses not accounting for the land sink as part of the emissions offset (OEO) or only accounting for growth in the land sink beyond today's levels (LCRI).
- **Differences across analyses are driven by the net-zero definition applied and assumptions** regarding energy demand and resource and technology pathway availability, cost, emissions characteristics, and operating profiles. Scenarios that retain higher levels of fossil fuel consumption generally employ higher levels of carbon capture and/or carbon dioxide removal to achieve a net-zero emissions balance.

LCRI included only the incremental land sink whereas OEO excluded the land sink. Carbon capture and utilization is not shown explicitly here: fossil-carbon fuels appear as positive CO_2 emissions when re-released, while biogenic-carbon fuels appear as zero. CO_2 abated via CCS is not positive but appears here to show its scale relative to other emissions. LCRI did not report abated CO_2 emissions.

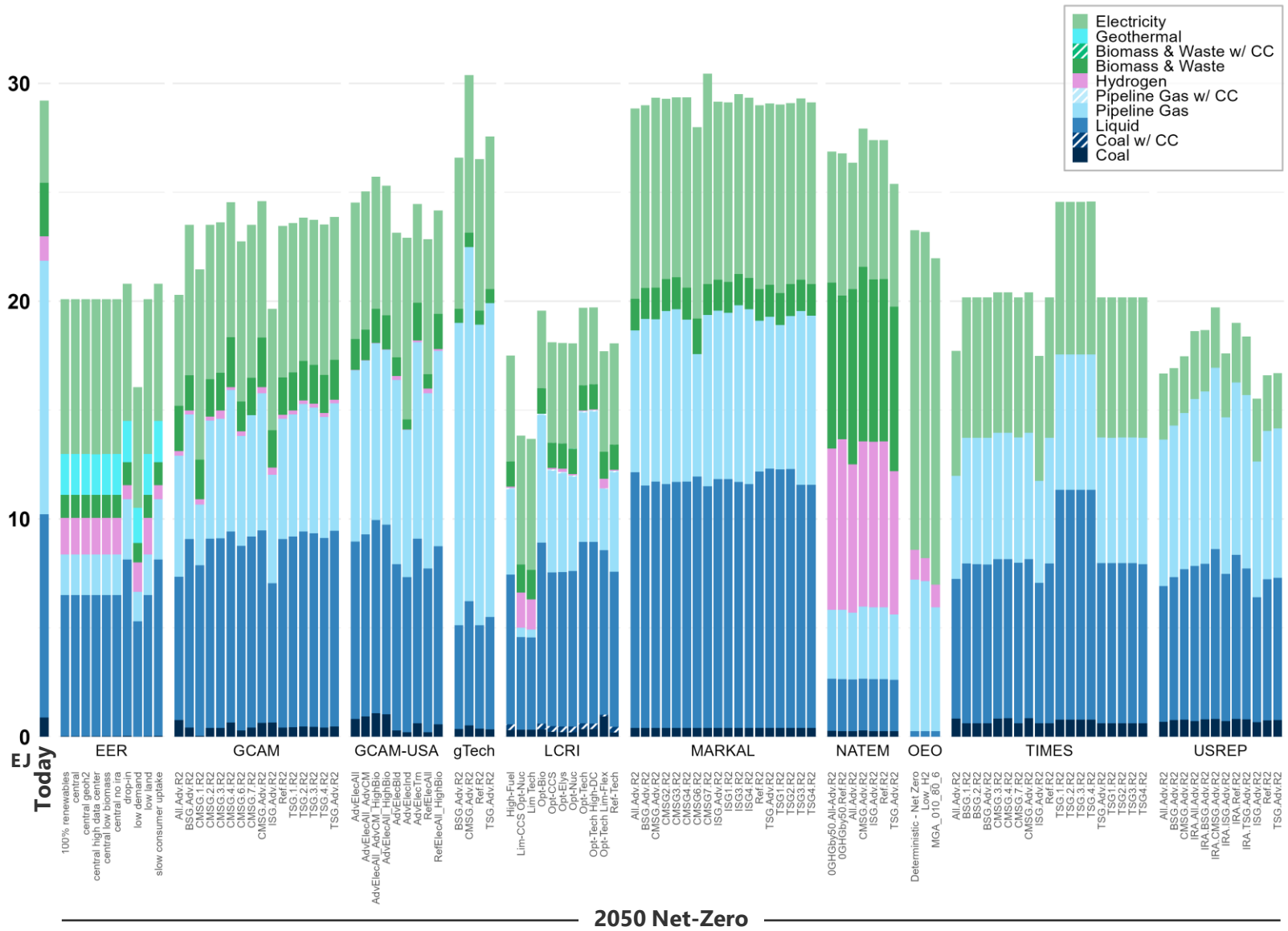
Results | Annual Final Energy Consumption by Carrier [EJ]



- **Final energy consumption declines in all NZ scenarios relative to today**, reflecting end-use efficiency gains that enable economic growth with lower total energy demand, even for scenarios that consider sharp growth in data center-driven power demand.
- **Electricity use increases in absolute and relative terms across all NZ scenarios**. Efficient electrification, particularly via heat pumps and electric vehicles, is a key driver of final energy demand reductions.
- **End-use fuel consumption declines relative to today, but fuels remain a part of the final energy mix in all NZ scenarios** even in scenarios that explicitly constrain fossil fuels. Low-carbon fuels such as biofuels, synthetic fuels, and hydrogen provide a means to directly abate emissions. Unabated fossil fuels continue to serve end uses in many scenarios, with their emissions offset by carbon dioxide removal.
- **Differences across analyses and scenarios are driven by the balance between low-carbon electricity, low-carbon fuels and carbon abatement/removal**, all of which ultimately depend on assumptions regarding energy demand and resource and technology availability, cost, emissions characteristics, and operating profiles.

Final energy results include both energy and non-energy use of fuels for all analyses except OEO. All fuels reported on a higher-heating-value basis. Biomass & Waste refers to solid bioenergy only. Liquid and gaseous biofuels are grouped in Liquid and Pipeline Gas, respectively. Only EER reported geothermal explicitly.

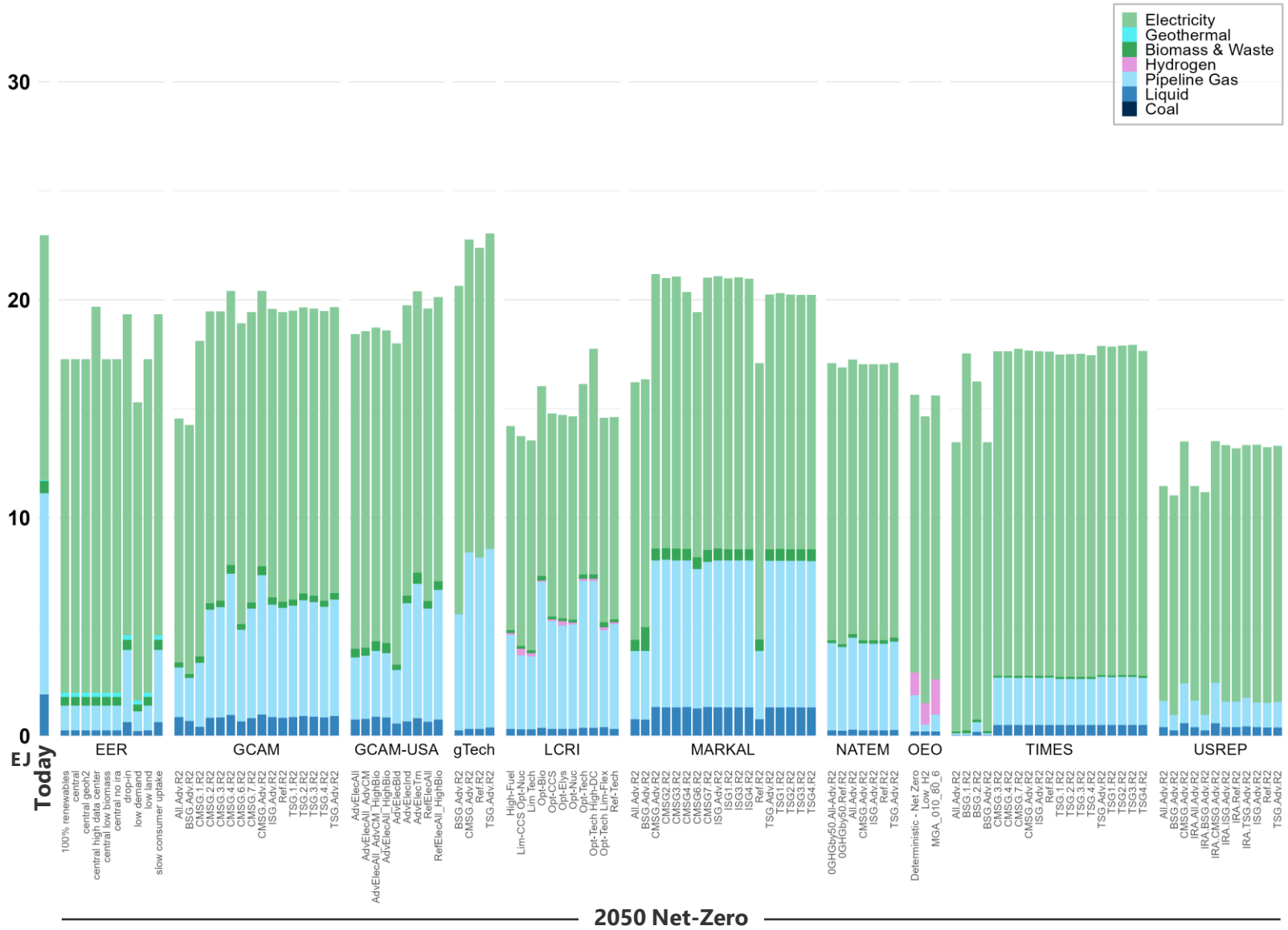
Results | Annual Industrial Energy Consumption by Carrier [EJ]



- **Industrial energy consumption declines relative to today in most NZ scenarios**, reflecting efficiency gains. MARKAL and one gTech scenario remain near or slightly above today's level.
- **Electricity use increases in most NZ scenarios,** typically supplying roughly one-third or less of industrial energy. The largest shares occur in OEO scenarios (63–68%) and two LCRI scenarios that limit carbon capture (43–44%), whereas USREP industrial electricity use is below today's level.
- **Fuels remain a part of the industrial energy mix in all NZ scenarios**, even where fossil fuels are constrained, serving high-temperature processes and non-energy feedstocks (e.g., chemicals). Low-carbon fuels directly abate emissions. Where unabated fossil fuels remain, their emissions are offset by carbon dioxide removal.
- **Pipeline gas remains a significant industrial energy carrier in most NZ scenarios**, with levels ranging between 50% and 75% of today's level in roughly half the scenarios. Use is lowest in EER, NATEM, and LCRI scenarios that constrain carbon capture, but above today's level in gTech.
- **Liquid fuels continue to serve industry in NZ scenarios**, with levels ranging from roughly 50% to 120% of today's level in most scenarios. The NATEM and OEO scenarios are exceptions with less than 26% and 3% of today's level, respectively.
- **Hydrogen use varies widely across analyses**. It is highest in NATEM, followed by EER, OEO, and LCRI scenarios that limit carbon capture, and is minimal or absent in the other analyses.
- **Geothermal energy is used in EER,** supplying roughly 10% of industrial energy.
- **Solid bioenergy use remains near or below today's level in most NZ scenarios**. NATEM is well above today's level, while OEO, TIMES, and USREP are minimal or absent.
- **Coal persists at modest levels in many NZ scenarios**, including with carbon capture in several LCRI scenarios, but is minimal or absent in EER and OEO.

Industrial energy results include both energy and non-energy use of fuels for all analyses except OEO. All fuels reported on a higher-heating-value basis. Biomass & Waste refers to solid bioenergy only. Liquid and gaseous biofuels are grouped in Liquid and Pipeline Gas, respectively.

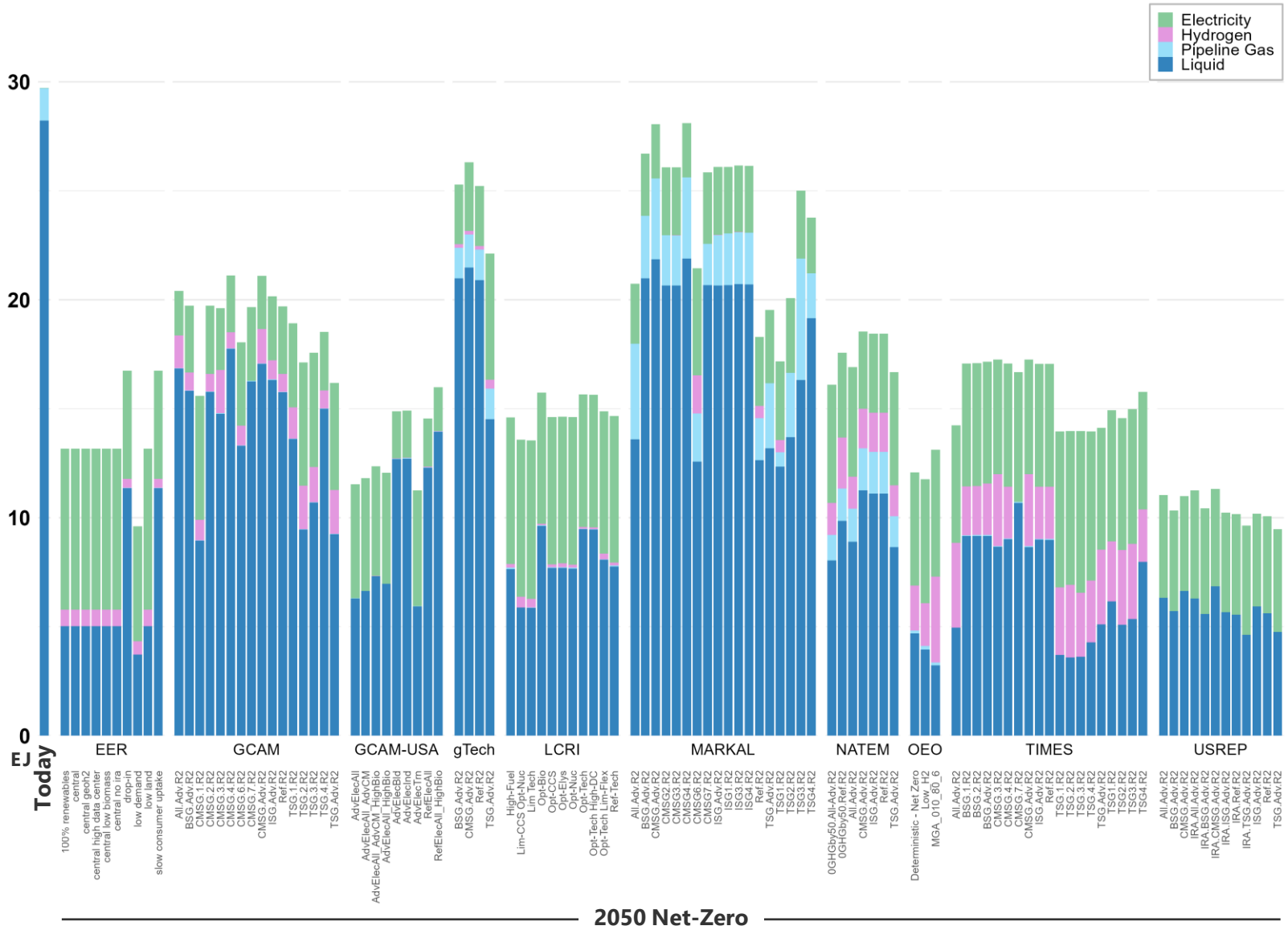
Results | Annual Building Energy Consumption by Carrier [EJ]



- **Building energy consumption declines relative to today in nearly all NZ scenarios**, reflecting efficiency gains, including those associated with efficient electric heat pumps. The gTech scenarios are the exception with future building energy consumption near today's level.
- **Electricity's share of building energy increases in all NZ scenarios**. Absolute electricity use increases in most NZ scenarios but remains near or below today's level in some (e.g., LCRI and USREP).
- **Direct fuel consumption declines in all NZ scenarios but remains part of the building energy mix**, primarily as pipeline gas. A few TIMES scenarios approach full electrification. In scenarios that explicitly constrain fossil fuels, remaining fuel demand is met by low-carbon fuels such as biofuels, hydrogen, and/or synthetic fuels.
- **Hydrogen use in buildings is minimal or absent in most analyses**. OEO and LCRI are exceptions, with hydrogen supplying up to 10% and 2% of building energy, respectively.
- **Geothermal provides a small share energy in EER**, accounting for less than 0.5% of building energy consumption across scenarios.

All fuels reported on a higher-heating-value basis. Biomass & Waste refers to solid bioenergy only. Liquid and gaseous biofuels are grouped in Liquid and Pipeline Gas, respectively.

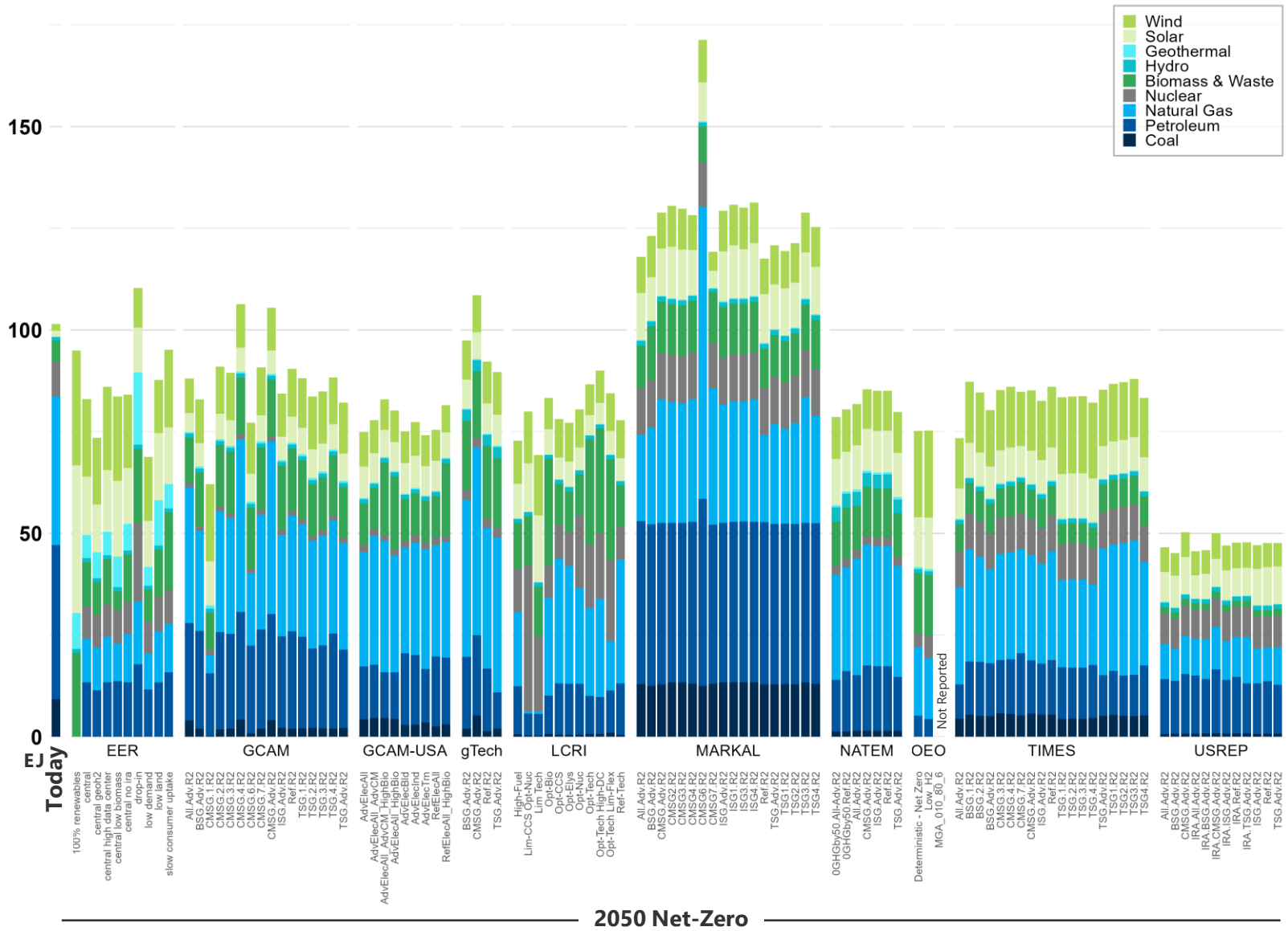
Results | Annual Transportation Energy Consumption by Carrier [EJ]



- **Transportation energy consumption declines relative to today in all NZ scenarios**, driven by efficiency gains, including those associated with efficient electric vehicles. Declines range from modest (e.g., some MARKAL and gTech scenarios) to more than 50% below today's level (e.g., EER, OEO, USREP).
- **Electricity grows from near zero today to an appreciable share of transportation energy in all NZ scenarios**, reaching roughly half in several analyses (e.g., EER, LCRI, TIMES, USREP) but remaining well below that in others (e.g., GCAM, gTech, MARKAL).
- **Liquid fuel consumption declines but remains a sizeable share in all NZ scenarios**, including those that explicitly constrain fossil fuels (e.g., EER 100% Renewables), reflecting demand for hard-to-electrify applications such as aviation, shipping, and heavy-duty transport. Liquid fuels can include petroleum products, biofuels, synthetic liquid fuels, and ammonia.
- **Hydrogen use varies widely across analyses**, reaching roughly a quarter or more of transportation energy in some OEO and TIMES scenarios. It is minimal or absent in GCAM-USA, USREP, and most MARKAL scenarios.
- **Pipeline gas is a notable contributor in three analyses** (gTech, MARKAL, NATEM), primarily for freight vehicles, with levels similar to or higher than today's in most scenarios. It is minimal or absent in the other seven analyses.

All fuels reported on a higher-heating-value basis. Liquid and gaseous biofuels are grouped in Liquid and Pipeline Gas, respectively.

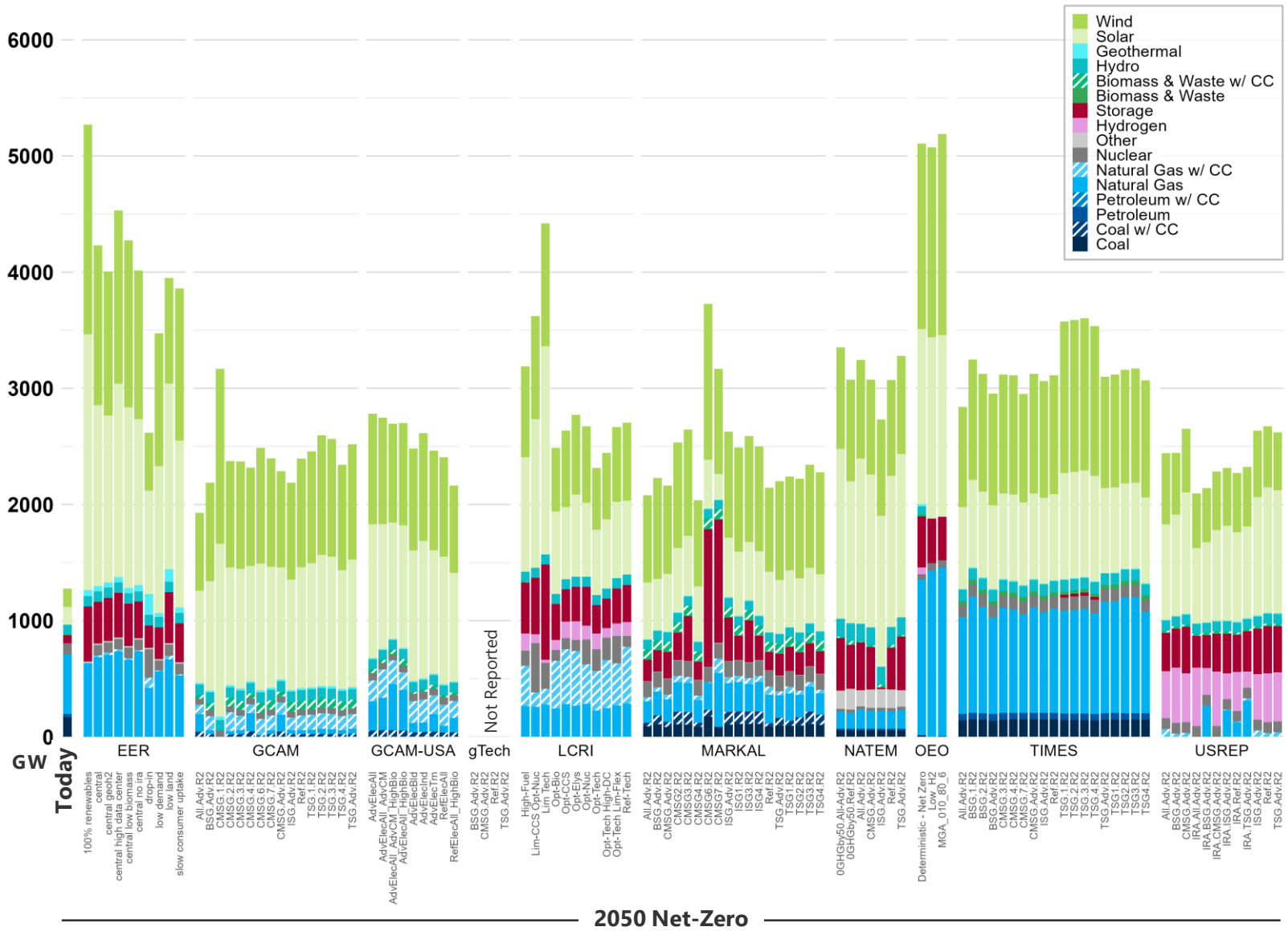
Results | Annual Primary Energy Consumption by Source [EJ]



- **Total primary energy declines relative to today in most NZ scenarios** due to efficiency gains across value chains and the output-based reporting convention for wind, solar, and other non-biomass renewables. Notable exceptions where primary energy increases are the MARKAL scenarios and four scenarios across EER, GCAM, and gTech.
- **Renewable energy sources expand substantially across NZ scenarios,** with significant growth of solar and wind across all scenarios and growth of biomass in most scenarios.
- **Nuclear energy varies widely across NZ scenarios**, with values ranging from considerably lower, to considerably higher, than today.
- **Fossil fuel consumption declines in almost every NZ scenario but remains a part of the energy supply** unless explicitly constrained in the scenario definition. Coal and petroleum generally experience larger percentage reductions than natural gas. MARKAL is a notable exception with coal and petroleum above today's levels in all scenarios and total fossil consumption above today's levels in two scenarios.
- **Differences across analyses and scenarios are driven by the balance between low-carbon resources, abatements for fossil resources, and carbon dioxide removal**, all of which ultimately depend on assumptions regarding energy demand and resource and technology availability, cost, emissions characteristics, and operating profiles.

All fuels reported on a higher-heating-value basis. OEO did not report primary energy for MGA scenarios. Non-biomass, non-hydro renewables in gTech were split among wind (56.9%), solar (41.5%), and geothermal (1.6%) based on their average ratio across the other nine studies and author agreement.

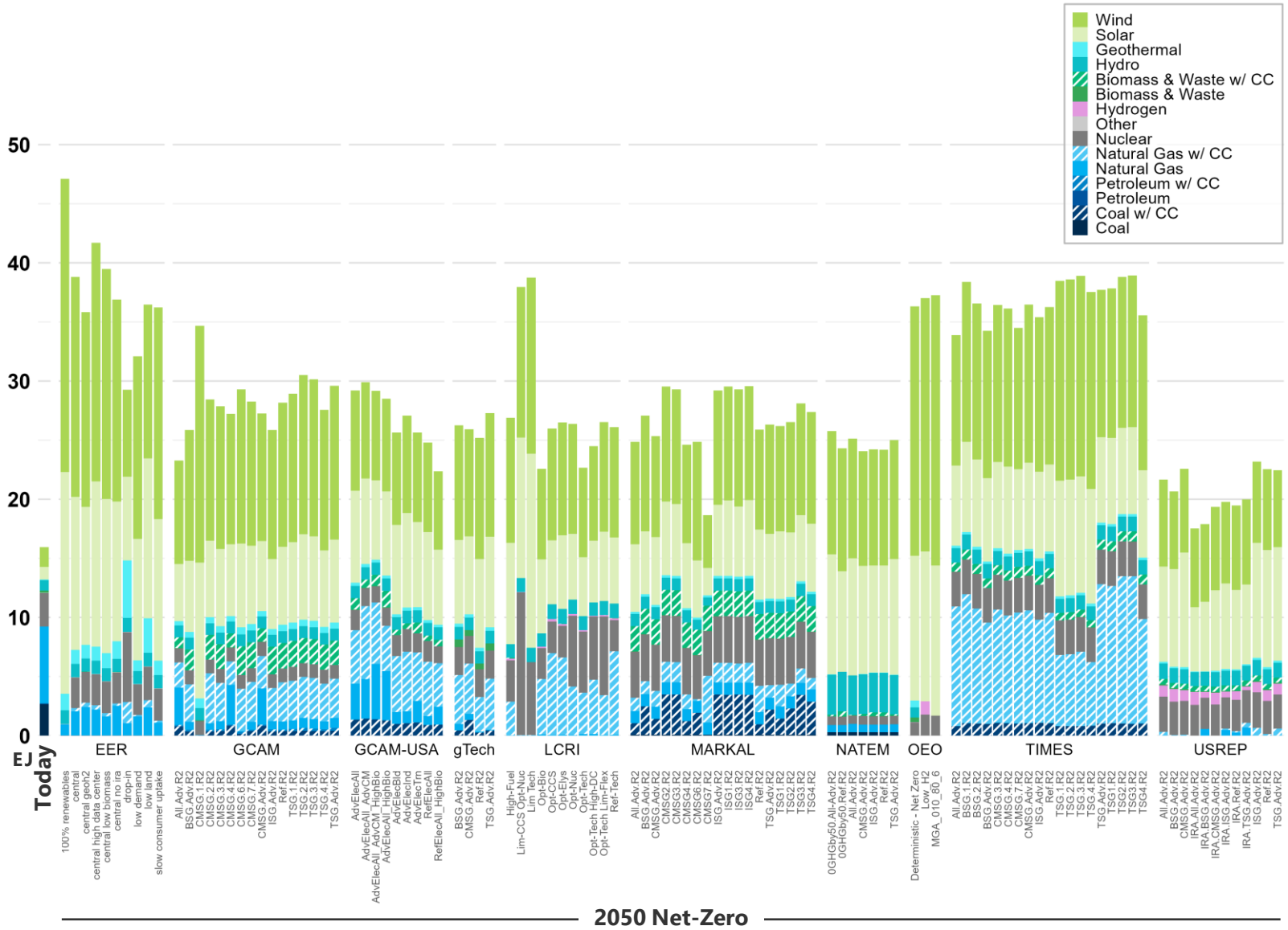
Results | Electricity Capacity by Source [GW]



- **Electricity generation capacity grows relative to today in all NZ scenarios** that report capacity, ranging from approximately 1.5 to four times today's installed capacity across scenarios.
- **Wind and solar dominate new capacity in nearly all NZ scenarios,** with some scenarios leaning more toward wind and others more toward solar. Combined wind and solar capacity ranges from 3.5 to 13 times today's level, with most scenarios between roughly four and seven times today's level.
- **Electricity storage capacity grows relative to today in most NZ scenarios**, balancing short-duration (hourly to daily) differences between when electricity is generated and when it is needed.
- **Fuel-based power provides firm capacity in all NZ scenarios.** Fossil-, nuclear-, bioenergy-, and/or hydrogen-fueled power plants balance longer-duration (multiday to seasonal) differences between electricity supply and demand. Total fuel-based capacity ranges from 7% to 186% of today's level across scenarios. Gas-fired capacity is present in nearly every scenario, ranging from 5% to 284% of today's level. Coal capacity ranges from minimal or absent (e.g., EER, LCRI, USREP) to near or above today's level (e.g., MARKAL, TIMES). Nuclear capacity ranges from well below today's level (e.g., OEO) to more than double today's level (e.g., some LCRI scenarios and one EER scenario). Bioenergy capacity remains small in most scenarios, with the largest deployments in GCAM and MARKAL paired with carbon capture. Hydrogen-fired capacity is largest in USREP, with smaller amounts in LCRI and OEO.
- **Hydro and geothermal play a smaller role in capacity**. Hydro capacity remains similar to today in most scenarios (NATEM is a notable exception, with more hydro capacity than today), while geothermal capacity is substantial in EER but minimal elsewhere.

gTech did not report electricity capacity. "Other" in EER, NATEM, and MARKAL cannot be separated further. "Natural Gas" in EER 100% renewables refers to a biogenic pipeline gas mix. The TIMES dataset did not differentiate electricity capacity from Natural Gas versus Natural Gas w/ CC, whereas such differentiation was reported for annual electricity generation.

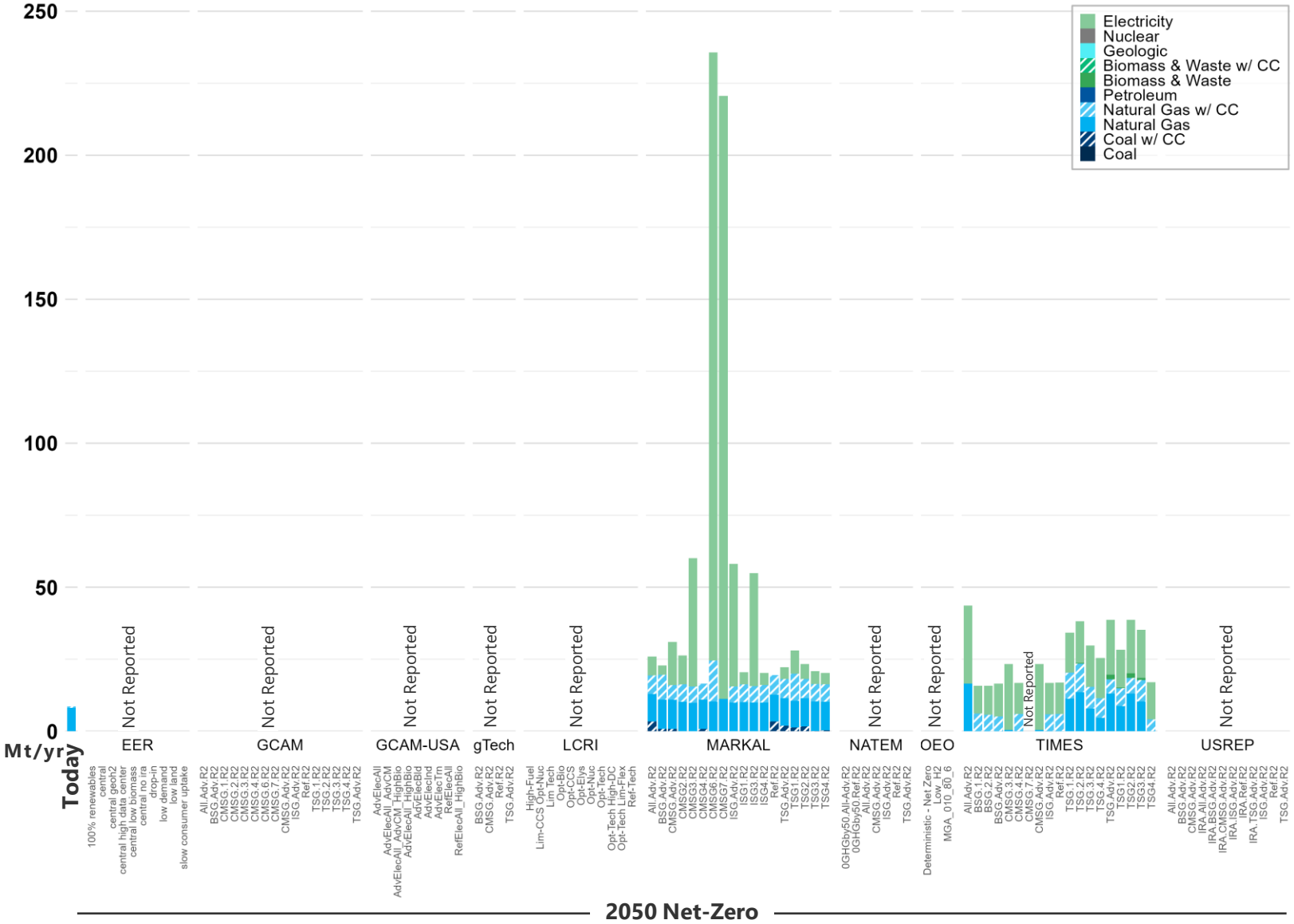
Results | Annual Electricity Generation by Source [EJ]



- **Electricity generation grows substantially relative to today**, with total generation exceeding 1.4 times today's levels in nearly all scenarios, and above twice today's levels in about one-third of scenarios (e.g., most EER and all OEO and TIMES scenarios). Exceptions include most USREP scenarios and one MARKAL scenario, although generation remains above today's level in these scenarios.
- **Wind and solar generation grow significantly to supply the majority of generation in nearly all NZ scenarios.** Combined wind and solar generation ranges from roughly 2.5 to 16 times today's level across scenarios, with most scenarios between five and ten times today's level.
- **Fuel-based generation supplies firm power in all NZ scenarios**, ranging from 30% to 140% of today's levels in most scenarios. Gas-fired generation, with and/or without carbon capture, supplies power in most scenarios (OEO and some USREP and LCRI scenarios are the exceptions). Coal generation is often paired with carbon capture and ranges from minimal or absent (e.g., EER, LCRI, OEO, USREP) to higher than today (e.g., MARKAL). Nuclear generation ranges from below today's level (e.g., OEO) to several times today's level (e.g., some LCRI scenarios). Bioenergy generation, mostly paired with carbon capture, is most prominent in GCAM and MARKAL. Hydrogen-fired generation is small in all scenarios, including in those where hydrogen-fired capacity is appreciable (e.g., USREP).
- **Hydro and geothermal contribute smaller shares of generation**. Hydro generation remains similar to today in most scenarios (NATEM is an exception at several times today's level). Geothermal is substantial in EER but small elsewhere.

Storage is not shown to avoid double counting. "Other" in EER, NATEM, and MARKAL cannot be separated further. Non-biomass, non-hydro renewables in gTech were split among wind (56.9%), solar (41.5%), and geothermal (1.6%) based on their average ratio across the other nine studies per author consultation. "Natural Gas" in EER 100% renewables refers to a biobased pipeline gas mix.

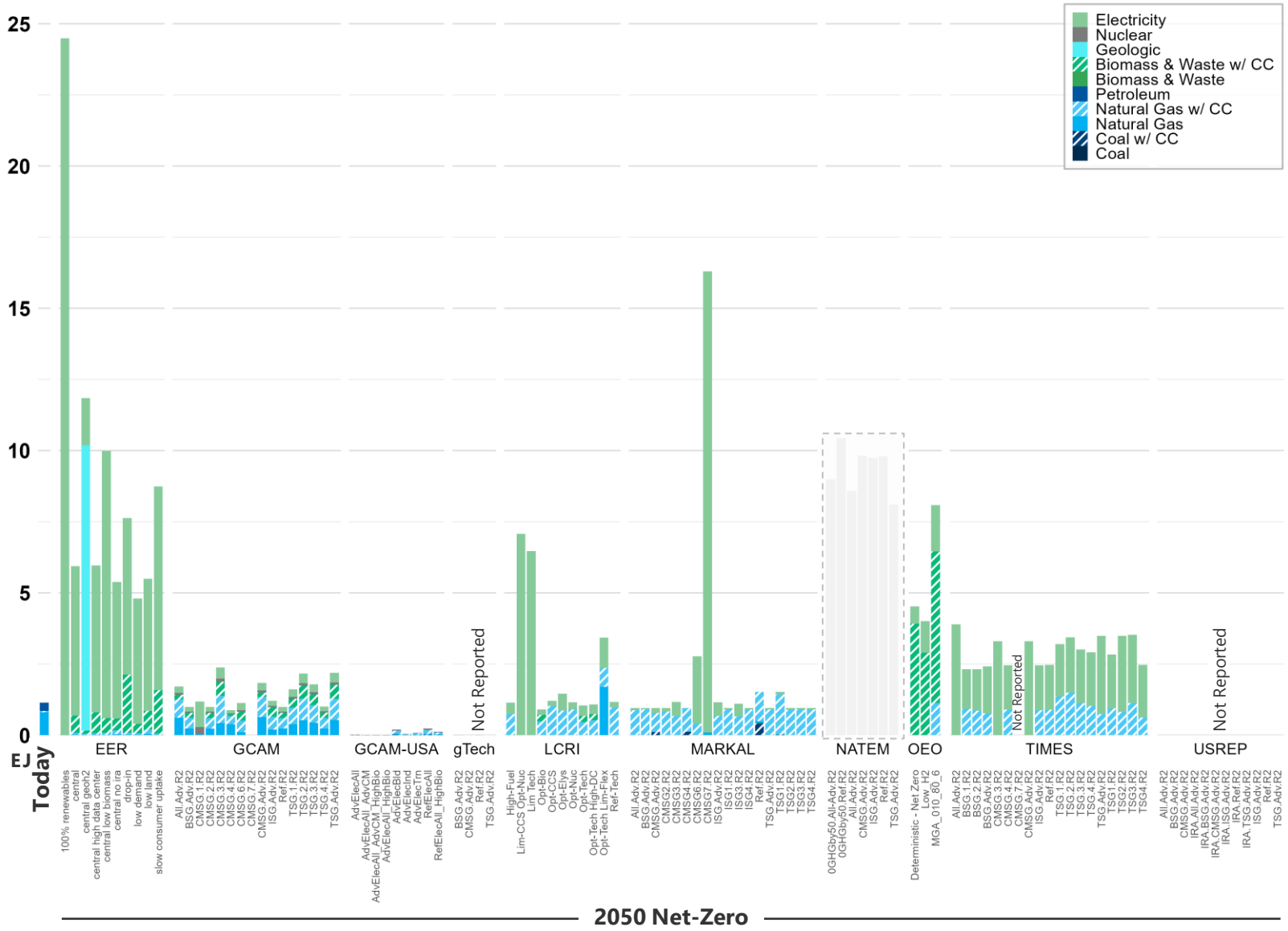
Results | Hydrogen Production Capacity by Pathway [Mt/yr]



- **Hydrogen production capacity is not reported comprehensively across all analyses.** Two of the ten analyses reported hydrogen capacity by production pathway.
- **Hydrogen production capacity increases relative to today for the two analyses that report it.** Capacity is roughly twice today's level or higher across all scenarios, with some scenarios greater than six times that of today.
- **Electrolysis and natural gas-based pathways dominate hydrogen production in nearly every reported scenario**. Coal and biomass-based hydrogen production capacity is deployed at lower levels in MARKAL and TIMES, respectively.

LCRI reported production capacity for electrolysis only.

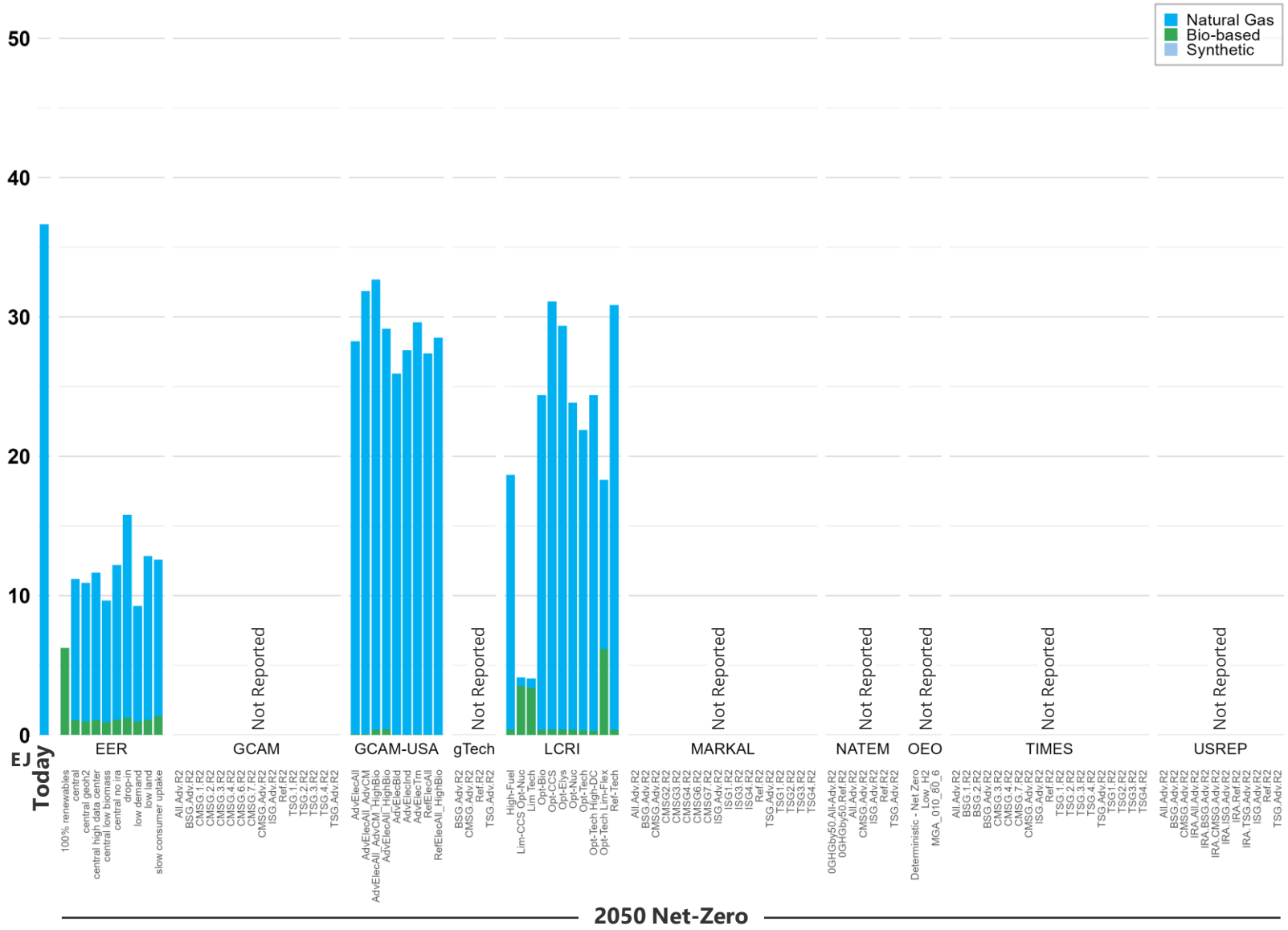
Results | Annual Hydrogen Production by Pathway [EJ]



- **Hydrogen production varies widely across NZ scenarios, in both magnitude and pathway.** Where reported, production ranges from roughly the same to three times today's level in most scenarios, with three scenarios reaching roughly ten times or more . The GCAM-USA scenarios are an exception, with production near zero.
- **Hydrogen production is not reported comprehensively across all analyses.** Eight of the ten analyses reported the annual hydrogen supply mix by production pathway.
- **Electrolysis and natural gas-based pathways dominate hydrogen production in nearly every reported scenario**, with one of the two typically supplying the clear majority. While natural gas-based production leads in more scenarios (e.g., GCAM, MARKAL, and most LCRI scenarios), electrolysis tends to account for relatively higher production levels in the scenarios where it leads. Most natural gas-based production is paired with carbon capture.
- **Bio-based production is the third most prevalent pathway**, appearing in roughly one-third of scenarios with reported data (most EER and GCAM, a few LCRI, and all OEO scenarios), and is the largest pathway in OEO. It is predominantly paired with carbon capture.
- **Other production pathways appear in a few analyses** with reported composition data. Geologic hydrogen appears in one EER scenario. Nuclear-based production appears in some GCAM and GCAM-USA scenarios. Coal-based production appears in some MARKAL scenarios.

All fuels reported on a higher-heating-value basis. The NATEM production level is reported, however, the production type is not shown here due to an unresolved data discrepancy.

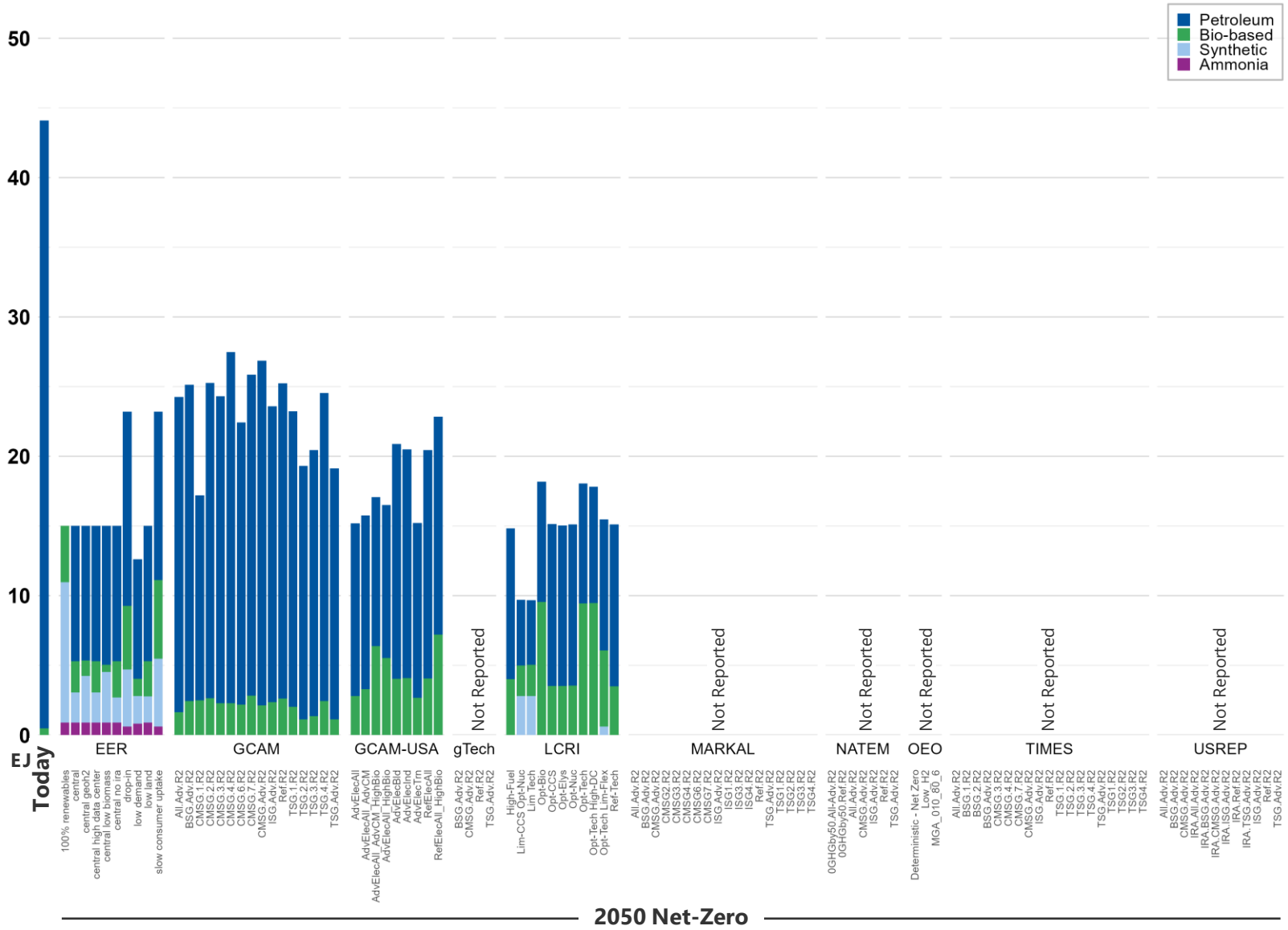
Results | Annual Pipeline Gas Consumption by Source [EJ]



- **Pipeline gas consumption declines relative to today but remains in all NZ scenarios.** Total consumption ranges between roughly 10% and 90% of today's levels in the three analyses that report pipeline gas supply composition.
- **The pipeline gas supply mix is not reported comprehensively across all analyses.** Three of the ten analyses report the annual pipeline gas supply mix by production pathway. None of the ten analyses report peak consumption or throughput capacity.
- **Natural gas remains the largest source of pipeline gas supply in nearly all scenarios**, for analyses that report composition. In the three scenarios with explicit constraints on fossil fuels or carbon sequestration (EER 100% Renewables, LCRI Lim-CCS Opt-Nuc, LCRI Lim Tech), natural gas is minimal or absent.
- **Bio-based gaseous fuels, such as renewable natural gas, are used in the three analyses** that report composition. All EER and LCRI scenarios use bio-based gas, generally at low shares, except where fossil fuels or carbon sequestration are constrained.
- **Synthetic natural gas and hydrogen are not blended into pipeline gas at discernable levels**, for analyses that report composition.

All fuels reported on a higher-heating-value basis.

Results | Annual Liquid Fuel Consumption by Source [EJ]



- **Liquid fuel consumption declines relative to today but remains in all NZ scenarios**. Where reported, total consumption ranges between roughly 30% and 60% of today's levels in most scenarios.
- **The liquid fuel supply mix is not reported comprehensively across all analyses.** Four of the ten analyses report the annual liquid fuel supply mix by production pathway. None of the ten analyses report peak consumption or throughput capacity.
- **Petroleum-based fuels remain the largest source of liquid fuel supply in most scenarios**, for analyses that report composition.
- **Bio-based liquid fuels are used in all NZ scenarios**, for analyses that report composition.
- **Synthetic liquid fuels and ammonia appear in some scenarios**, for analyses that report composition.

Includes non-energy use of fuels. All fuels reported on a higher-heating-value basis.

Results | Cost Information

Different analyses reported costs with different metrics, counterfactuals, and level of detail, making it difficult to generate a harmonized data set for Meta 2.0 from which robust cost comparisons can be made. While there are some indications that more highly constrained scenarios trend towards higher costs, as was found in Meta NZ, the available data do not provide a robust validation of this finding.

Study	Cost metric	Counterfactual	IRA treatment
EER (ADP 2024)	Annualized energy costs including end-use equipment, plus land and non-CO_2 measures.	Current Policy scenario. (cheaper EVs make Current Policy the lower-cost reference).	Included. Tax credits are subtracted from gross cost but added back for the "true" net cost.
USREP-ReEDS (Becker et al.)	Equivalent variation (% change in full consumption) and carbon price.	Reference (no net-zero cap). Separate IRA and IRA + net-zero variants.	Modeled as cost-free subsidies with an uncovered deficit making IRA welfare results incomplete.
gTech (Starke et al.)	GDP in 2050 relative to Reference scenario.	Reference with only legislated policies.	Excluded.
US-REGEN (LCRI 2.0)	Marginal cost ($/t CO_2), plus household energy spending as a share of GDP.	Reference: IRA plus EPA power-plant rules	Included. IRA incentives phase out and replaced by harmonized carbon policy.
TIMES GCAM MARKAL NATEM (Browning et al.)	Carbon price only	Each model's own Reference. Not harmonized, so base years and calibration data differ.	Excluded from core scenarios.
GCAM-USA (O'Keefe et al.)	Marginal cost of the emissions constraint	NT-RefElecAll (no target, default GCAM-USA assumptions)	Excluded for EMF 37 consistency.
Temoa (Sinha et al.)	No transition cost reported	Least-cost net-zero solution, used to set the slack for near-optimal runs	Included.

Varied Perspectives. Shared Patterns.

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Finding #1 – 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.

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.

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.

Varied Perspectives. Shared Patterns.

Finding #2 – The features of "***and***" energy systems endure as the landscape changes.

Meta NZ drew on 5 analyses and 23 net-zero scenarios. Meta 2.0 draws on 10 analyses and 109 net-zero scenarios. Across this expanded dataset, all key findings from Meta NZ endure. 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.

Key Findings from Meta NZ (5 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 10 analyses and 109 net-zero scenarios

Varied Perspectives. Shared Patterns.

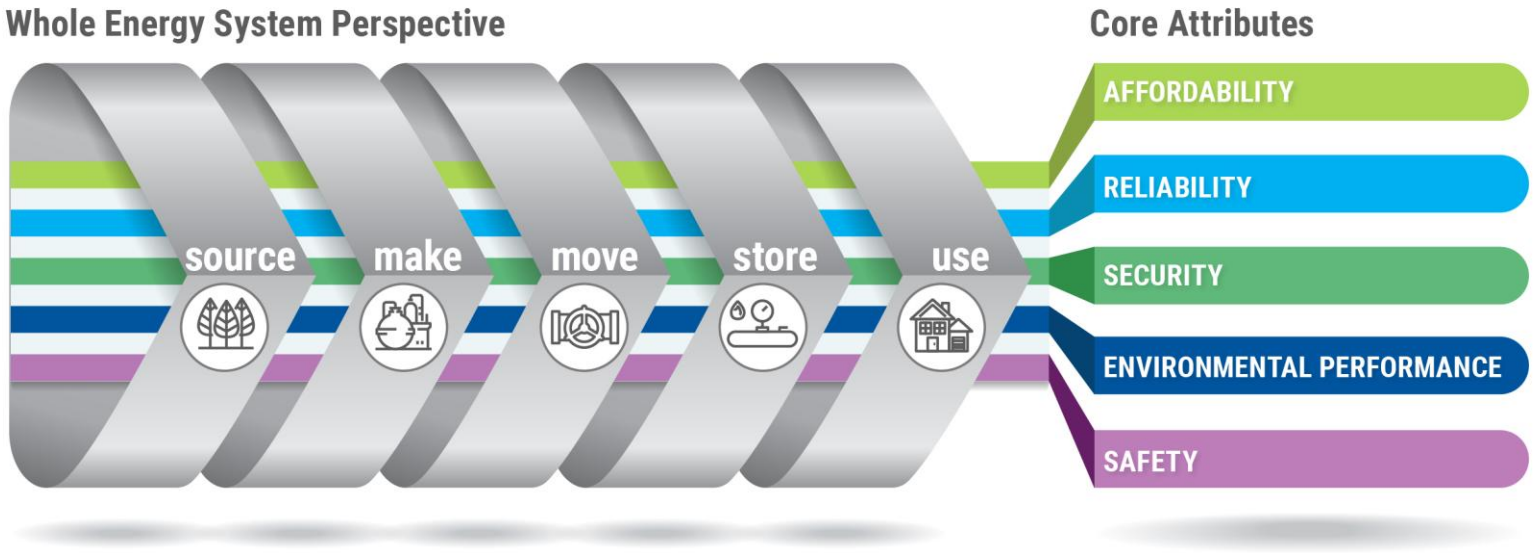
Finding #3 – What "***and***" energy systems look like can vary widely.

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.

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.



Acronyms

AEO	Annual Energy Outlook
BECCS	Bioenergy with Carbon Capture and Sequestration
CC	Carbon Capture
CCS	Carbon Capture and Sequestration
CGE	Computable General Equilibrium
CO_2	Carbon Dioxide
DACCS	Direct Air Capture with Carbon Sequestration
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
GHG	Greenhouse Gas
H_2	Hydrogen
HHV	Higher Heating Value
IRA	Inflation Reduction Act
NCA5	Fifth National Climate Assessment
NZ	Net-Zero
OBBBA	One Big Beautiful Bill Act
OEO	Open Energy Outlook
RNG	Renewable Natural Gas
SNG	Synthetic Natural Gas

Units

EJ	exajoule
$GtCO_2e$	gigatonnes of CO_2 equivalent
GW	gigawatt
Mt/yr	megatonne per year

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GTI Energy is where complex energy challenges meet bold solutions. With expertise in energy research, technology development, and business innovation, partners across every sector trust us to build and demonstrate solutions for better-performing energy systems. Guided by systems thinking, collaboration, and innovation, we are focused on driving progress that matters for people everywhere.

About Operations Technology Development

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

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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