EXECUTIVE SUMMARY

LCRI NET-ZERO 2050: U.S. ECONOMY-WIDE DEEP DECARBONIZATION SCENARIO ANALYSIS

As part of the Low-Carbon Resources Initiative (LCRI), EPRI and GTI Energy led an integrated energy system scenario modeling exercise to evaluate alternative technology strategies for achieving economy-wide net-zero emissions of carbon dioxide (CO_2) in the United States by 2050 (full report here). Building on previous research[1], this study finds that a broad portfolio of clean energy technologies underpins an affordable and reliable clean-energy transition and offers new insights into three hypothetical net-zero scenarios.

Table 1. Hypothetical net-zero scenarios

	All Options	Higher Fuel Cost	Limited Options
Geologic storage of CO_2	Lower costs	Higher costs	Not available
Natural gas supply costs	Lower costs	Higher costs	Lower costs
Bioenergy feedstock supply	Full	Supply limited	Supply limited

1. **All options**. Assumes the full portfolio of clean energy technologies is available, including renewables (solar, wind, and hydropower), nuclear, fossil, and bioenergy with carbon capture and storage (CCS), electricity storage (for example, battery storage and pumped hydro), hydrogen and hydrogen-derived fuels (for example, synthetic jet fuel and synthetic natural gas), and biofuels (for example, renewable natural gas and renewable diesel).
2. **Higher fuel cost**. Assumes all technologies are available, but with higher costs for gas, oil, bioenergy, and CO_2 transport and storage.
3. **Limited options**. Assumes geologic storage of CO_2 is not available and bioenergy supply is limited. All other technologies are available.

This analysis reflects a future snapshot based on recent findings. While these results are specific to the continental United States, insights derived from this study could be applied to markets around the world. Opportunities for costs of emissions reductions and low-carbon technology deployment vary significantly across regions and sectors of the economy. Regional differences in factors such as resource availability and climate, and sectoral differences in relative costs and applicability of alternative technologies can lead to significant differences in the optimal low-carbon technology mix.

The transition to a net-zero energy system could be impacted by many factors. To develop meaningful insights based on a range of potentially viable technology solutions, the modeling in this analysis considered an extensive—but not comprehensive—set of assumptions and interactions. This study does not include a detailed assessment of factors such as supply chain constraints, operational reliability and resiliency, non-CO_2 environmental impacts, and distributional outcomes, such as localized economic and environmental justice impacts. This analysis also does not include the specific incentives in the recently enacted U.S. Inflation Reduction Act.

[1] The analysis builds on extensive, collaborative research, including an inter-model comparison assessment and a separate EPRI study focused on strategies and actions to reduce U.S. energy-related greenhouse gas emissions 50% below 2005 levels by 2030.

While there are many potential low-carbon technology scenarios, there remains significant uncertainty around future cost and performance. This study is a starting point. Future research will explore sensitivity to a broader range of uncertain assumptions, including the potential impacts of the Inflation Reduction Act and other factors on the path to net zero.

Key Findings

- **Optionality enables affordability**. Achieving economy-wide net-zero CO_2 emissions while maintaining reliable delivery of energy and energy services across the economy will require a broad set of low-carbon technologies. An economy-wide, net-zero target with the flexibility to allocate positive and negative CO_2 emissions allows each sector and region to follow their own decarbonization path while minimizing overall costs (Figure ES-1). Imposing greater limitations on resource and technology options could significantly increase the overall cost to achieve net-zero emissions. *More detail here and here in the full report.*

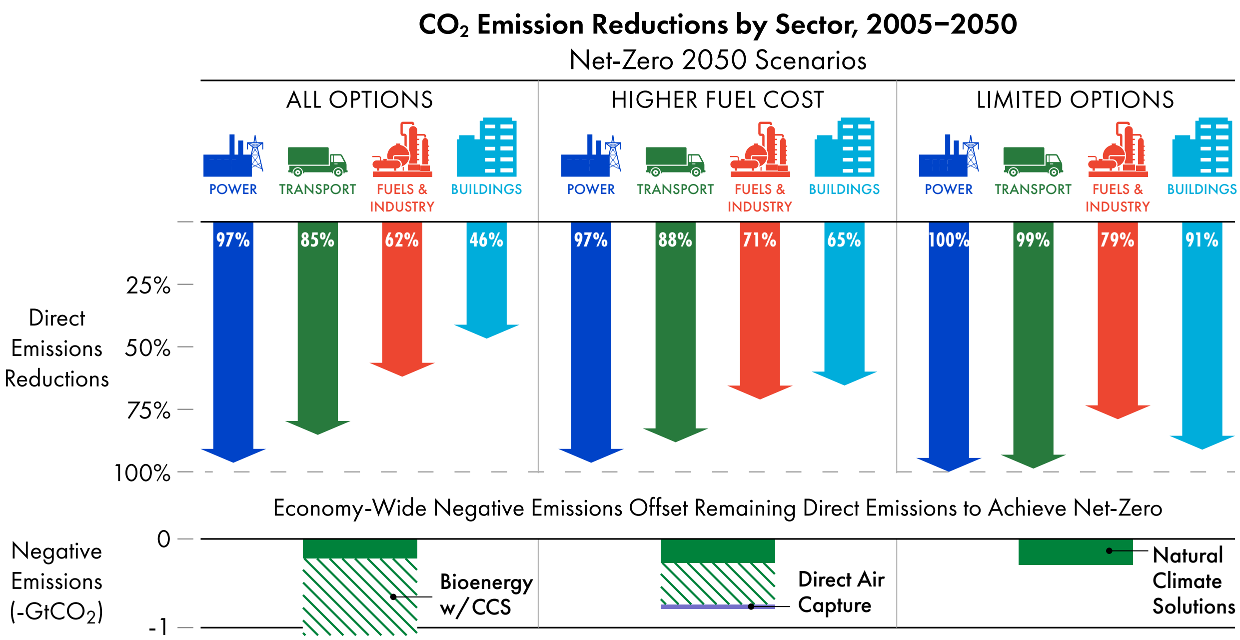
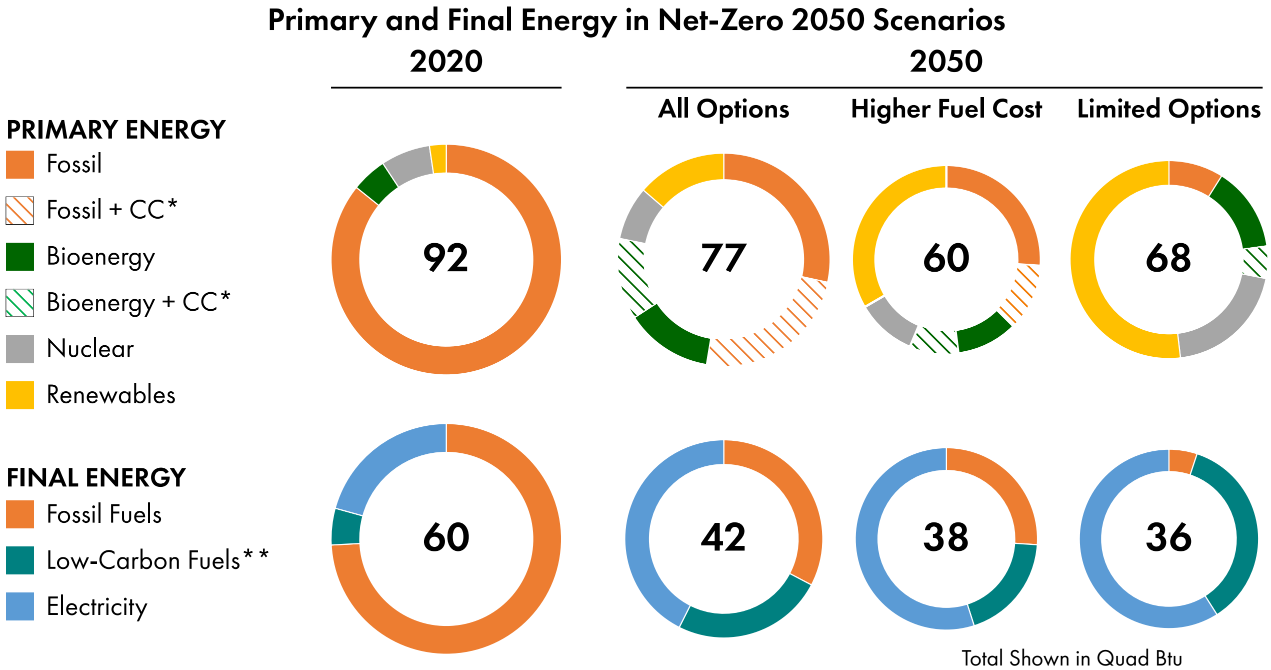


Figure ES-1. CO_2 Emission Reductions by Sector, 2005 to 2050—Net-Zero 2050 Scenarios

- **Primary and final energy transform**. Today the United States derives 86% of its primary energy from fossil fuels. In the net-zero scenarios, between 9% and 53% remains fossil-based by 2050, depending on the availability and deployment of carbon management technologies. At the same time, final energy—energy consumed at the point of end use—shifts to more efficient, low-carbon energy carriers as electricity and hydrogen use grows significantly in a clean energy economy (Figure ES-2). Through this transition, electricity grows from providing 21% of final energy today to 43% to 59% in 2050, while low-carbon fuels increase from 5% today to 19% to 36% in 2050 and fossil fuels decline from 74% today to 5% to 33% in 2050 in the net-zero scenarios. *More detail here in the full report.*



Carbon capture, with storage or utilization

***Low-carbon fuels include hydrogen, hydrogen-derived fuels (e.g., synthetic fuels and ammonia) and bioenergy.*

Figure ES-2. Primary and Final Energy in Net-Zero 2050 Scenarios

- **Energy efficiency and efficient electrification expand**. Improved energy efficiency, increased adoption of efficient electrification technologies, and structural shifts to less energy-intensive activities across the economy combine to reduce final energy 25% to 38% by 2050 relative to today, even with 80% GDP growth compared to 2020. The modeling shows that reductions in energy consumption enable emissions reductions throughout energy value chains and across the transportation, buildings, and industrial sectors through technological improvement and switching to more efficient energy carriers and technologies. Many of these changes are cost-effective and are assumed to occur even in the absence of an explicit decarbonization target. Further adoption of energy-efficient technologies and cleaner fuels occurs in the Higher Fuel Cost and Limited Options cases, in which supply-side decarbonization options are more costly. *More detail here and here in the full report.*

- **Firm and variable electric generating capacity grows substantially**. Decarbonizing electric generation entails increasing shares of intermittent renewables, combined with expanded clean firm capacity (Figure ES-3). Across net-zero scenarios, total wind and solar through 2050 ranged from roughly 600 gigawatts (GW) to 3,500 GW, compared to 273 GW today, with the high end driven by electricity supporting hydrogen production. Total clean firm capacity to balance these intermittent resources ranged from 1,140 GW to 1,446 GW, including a combination of natural gas (conventional or renewable, with or without carbon capture), nuclear, hydrogen, hydro, geothermal, bioenergy (with or without carbon capture), and electricity storage technologies (for example, battery storage, pumped hydro, and compressed air energy storage). By comparison, 767 GW of firm electric generating capacity exists in the United States today. Total new capacity in the electric sector ranged from 1,650 GW to 4,860 GW, a 160% to 480% increase over today's resources. The optimal mix of renewables and clean firm resources varies by region and depends on interactions with decarbonization options outside the electric sector, such as opportunities for negative emissions and demand for electrolytic hydrogen. In all scenarios, new gas- and/or hydrogen-fueled electric generating capacity plays a critical role in providing resource adequacy and flexibility for reliable power generation.

  In these scenarios, both existing and new nuclear capacity contribute to decarbonization. Zero-emission electricity from existing nuclear provides essential firm capacity in a net-zero energy system. In the Limited Options scenario, in which CCS is restricted, new advanced nuclear technologies, such as small modular reactors, provide around 60 GW of generating capacity as a carbon-free baseload option by 2050. Continued expansion and modernization of electric T&D infrastructure are essential to support increased integration of renewables, electrification, and flexible demand-side resources, as well as enhance reliability and resilience during the energy transition. Electric T&D investments increase over time in all scenarios and accelerate in the All Options and Higher Fuel Cost scenarios. Additional investments in intelligent grid systems have the potential to enable benefits of more sophisticated customer interactions. *More detail here in the full report.*

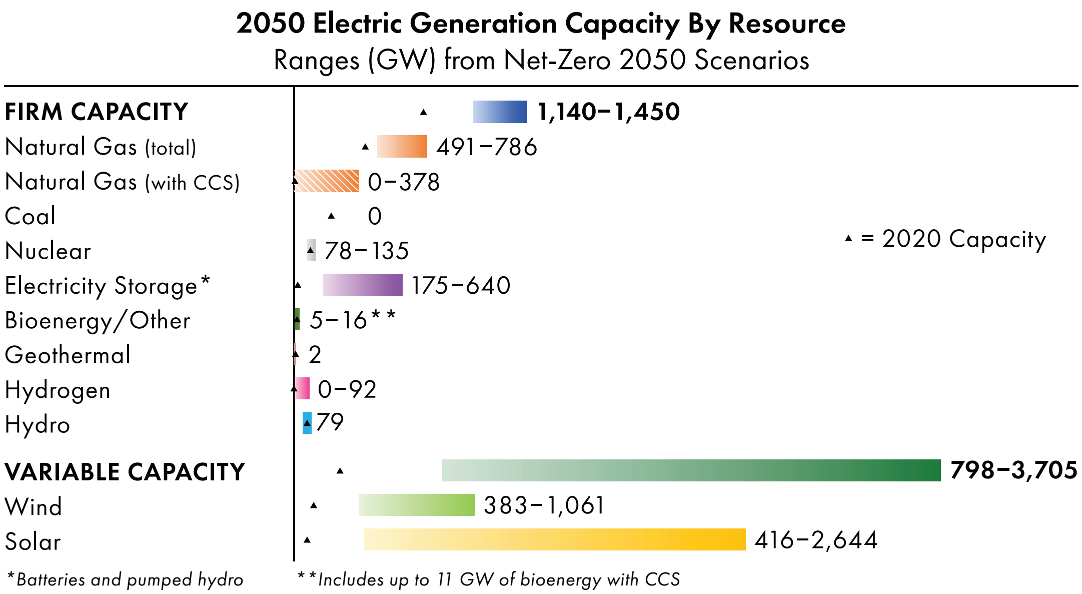


Figure ES-3. 2050 Electric Generation Capacity by Resource—Ranges (GW) from Net-Zero 2050 Scenarios

- **Pipeline gas continues serving multiple markets**. Pipeline gas continues serving multiple markets. Natural gas infrastructure plays a crucial role in all scenarios in providing firm capacity for a transitioning power sector and delivering low-carbon fuel to industry and buildings, particularly in colder climates. The composition of delivered gas varies by scenario and may include a blend of fossil, renewable and synthetic natural gas, and hydrogen. With available options for CCS, negative emissions, and blending, annual U.S. natural gas consumption could remain at levels similar to today, even in a net-zero energy future (Figure ES-4). With higher natural gas prices, as in the Higher Fuel Costs scenario, pipeline gas consumption declines to around 15 quads, about half of today's level. Without CCS, as in the Limited Options scenario, renewable and synthetic natural gas can substitute for fossil supply as the economy-wide emissions target approaches zero; in this case, pipeline gas consumption decreases to around 17% of today's level. Even with lower volumes of delivered gas, pipeline capacity requirements remain to serve peak demands. Evolution of business models to support investment in the maintenance and modernization of gas infrastructure will enable continued reliable delivery of gas for peak energy needs, as well as the expanded use of low-carbon fuels. *More detail here in the full report.*

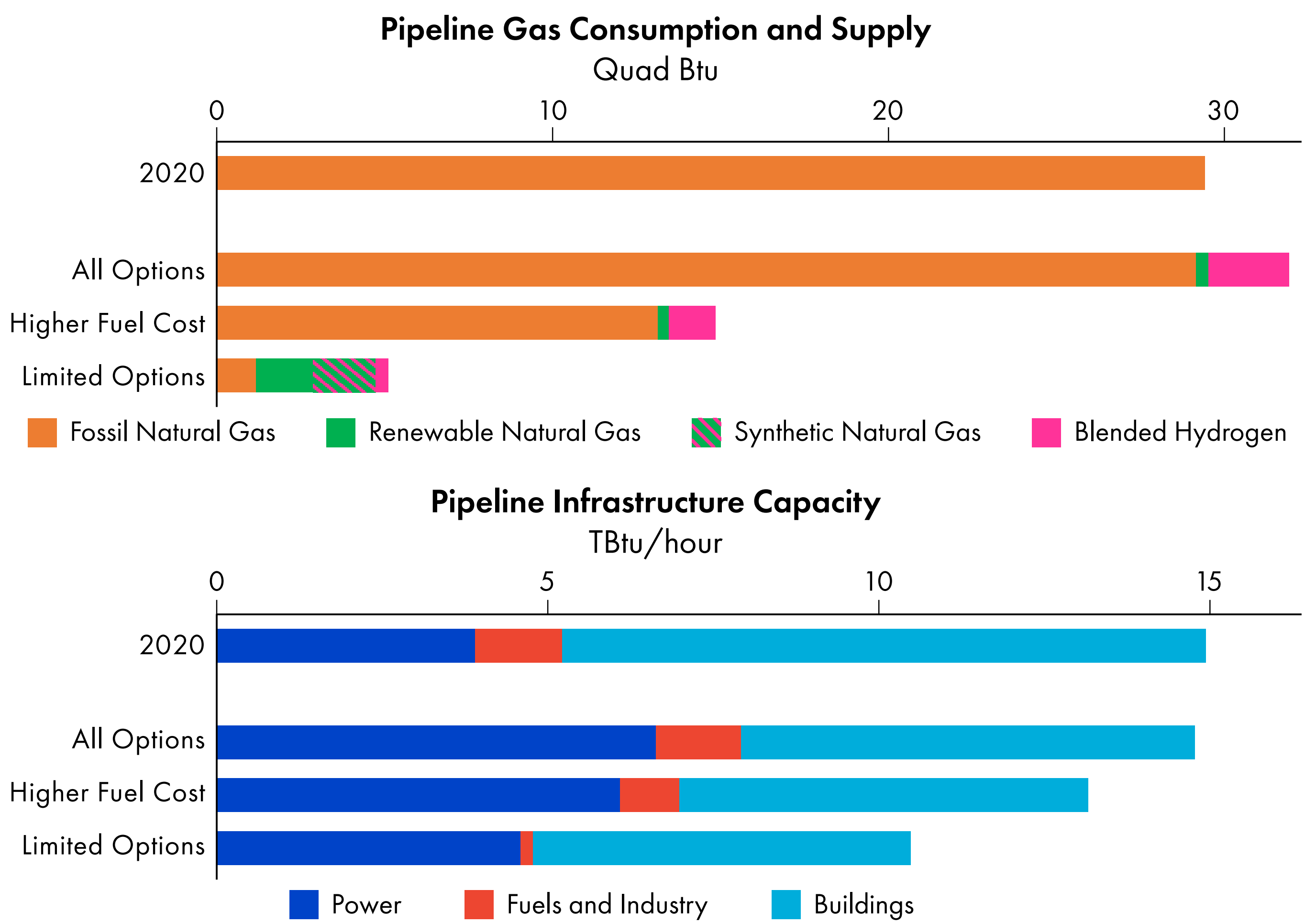


Figure ES-4. Pipeline Gas Supply and Infrastructure Capacity in Net-Zero 2050 Scenarios

- **Carbon capture and storage (CCS) technologies are pivotal**. New natural gas plants with CCS emerge as a key clean firm capacity option for the electric sector, providing up to 33% of generation, and, potentially, a significant portion of hydrogen and ammonia production. Combining bioenergy with CCS, particularly in the production of liquid fuels, could provide a cost-effective pathway to remove CO_2 from the atmosphere. In addition to bioenergy with CCS, direct air capture and storage and natural climate solutions (for example, afforestation) also provide pathways for **atmospheric carbon dioxide removal** (CDR). The ability to introduce negative CO_2 flows via CDR in some portions of the energy system can offset positive emissions in applications with high relative costs of direct abatement. Together, CCS and bioenergy can enable both the continued use of fossil fuels and the production of low-carbon fuels to replace fossil fuel applications. If CCS and bioenergy are limited, hydrogen and electricity could play an even more significant role in a net-zero energy future. *More detail here and here in the full report.*

- **Clean energy carriers expand across sectors**. Hydrogen's use as a low-carbon fuel is projected to increase, whether through fuel cell vehicles, blending with the natural gas supply to support needs in buildings, or through direct use for process heating in industries. The roles of hydrogen and hydrogen-derived fuels expand significantly if CCS and CDR are limited, increasing clean electricity generation by around 4,000 TWh to support production from electrolysis—as much as the total U.S. electricity generation today. Bioenergy emerges as another key decarbonization resource; advanced cellulosic biofuels provide low-carbon alternatives to petroleum-based fuels and, when combined with CCS, provide CDR to offset other positive emissions sources elsewhere. The value of synthesizing net-zero fuels from hydrogen and biogenic carbon increases substantially when CCS and bioenergy are limited. Similarly, ammonia produced from hydrogen as a fuel pathway is deployed only in scenarios with limited alternatives.
  - **Transportation**. While electrification plays a key role in decarbonizing on-road transportation, biofuels and hydrogen provide important options for specific applications, especially in medium- and heavy-duty and non-road segments.
  - **Industry**. Clean energy carriers are a crucial low-carbon solution for high-temperature process heat (in certain industries) and as fuel for non-road vehicles.
  - **Buildings**. Hydrogen blended with natural gas supports space heating and other residential and commercial needs in climates where gas remains part of the end-use energy mix.

  More detail here, here, and here in the full report.

Discussion

Achieving net-zero energy across the United States by 2050 would involve an energy transformation that is unprecedented in scope, scale, and timeframe. A customer-focused approach to building, connecting, and operating this future energy system rests on dramatically increasing optionality, innovation, and collaboration across the energy sector:

- **Optionality**. Leveraging the full portfolio of existing and emerging energy resources while accounting for regional differences.
- **Innovation**. Developing and deploying new and creative technology solutions across the clean energy economy.
- **Collaboration**. Reaching across industry and government to align technology development and deployment with customer and community needs.

While this analysis assesses technology pathways to 2050, the clean energy technology transition is expected to continue beyond that time frame.

The path to net-zero energy requires innovation in many forms—from technology to market and regulatory structures to customer behavior and business models. As technology advances, so must the workforce needed to support development and deployment, as well as public education aiming to better inform consumer decision-making. Robust research, development, and demonstration are essential to advance the technologies poised to make a net-zero energy future possible.

The future energy mix is projected to consist of an increasingly complex and integrated blend of existing and emerging resources and infrastructure. Changes in resource options, technology readiness, and constraints on electricity transmission or gas pipeline development could significantly impact the path forward. Logistical challenges must be addressed for new and emerging technologies, including a major scale-up of renewable generation and clean hydrogen production. From establishing a reliable supply chain to siting large-scale installations to adapting market structures to shifting utilization rates of infrastructure assets to mitigating environmental impacts to decommissioning facilities responsibly, stakeholders will need clear solutions spanning the entire technology life cycle.

Making a net-zero energy economy a reality will require all stakeholders to consider energy use differently, as decisions by hundreds of millions of consumers will impact the carbon reduction trajectory. While decarbonization will likely increase delivered fuel prices, projected structural changes in the economy leading to lower energy intensity—combined with increased energy efficiency and electrification—will potentially mitigate economic impacts on customers by lowering energy's share in overall household budgets. Customers must think in terms of total energy footprint and overall economic benefits. Shifting the energy mindset will be central to building support and achieving cleaner end-use technology adoption.

Near-term decisions by stakeholders across industry and government will ultimately affect transition costs. As energy companies, energy producers, and energy consumers examine technology pathways, constructive regulation and energy policy that encourage the full complement of clean energy resources today can help preserve affordability and accelerate market adoption of clean energy technologies tomorrow. Balancing reliability, resiliency, and affordability on the path to a net-zero 2050 entails building on progress in energy efficiency; preserving existing clean electricity generation sources; continuing investments in electric and gas infrastructure; achieving advances in clean energy resources such as CCS, advanced nuclear, bioenergy, and hydrogen; and realizing the economic adoption of electrification and low-carbon fuel switching in transportation, buildings, and industry. Additionally, leading a just transition requires deliberately examining and minimizing impacts while providing economic growth opportunities to customers and communities at each step of the clean energy journey.

Today's decisions shaping the future energy system will directly impact equity and environmental justice in the decades ahead. Public and private sector determinations of when, where, and how to deploy clean energy technologies and programs will directly impact customers and communities across the United States. This presents a significant opportunity to advance disadvantaged communities through targeted infrastructure investments, job creation, and other economic development measures. Environmental justice aligns affordable and accessible clean energy deployment with societal needs to improve public health, reduce pollution, and revitalize communities that have been historically marginalized, underserved, and overburdened by pollution. Environmentally burdened communities—as well as developers of projects that advance environmental justice—will see benefits through inclusive engagement, collaboration, and consideration of the economic, environmental, and societal benefits of deploying clean energy thoughtfully and equitably.

Harnessing the value of clean energy technologies and approaches through the transition depends on close collaboration across all stakeholders, from technology development to deployment to commercial operation. Many technologies key to achieving net-zero are not yet commercially available at scale, and their potential cost and performance characteristics remain uncertain. As new solutions approach deployment, the total system costs of achieving net-zero will largely depend on costs and availability of key energy production and end-use technologies, combined with a flexible policy design.

Delivering insights with direct applications to regions and markets across the United States and around the world will require the type of continued coordination and engagement at the core of the LCRI. Key characteristics of the United States vary greatly across regions—particularly its large resource base for renewable, fossil, nuclear, and bioenergy, significant potential for geologic storage of CO_2, and climate and economic structure. Over the next several years, the LCRI will continue global collaboration to improve the understanding of these technologies and refine the scenario analysis with updated assumptions and sensitivities to better inform the clean energy transition.

The Low-Carbon Resources Initiative

This report was published under the Low-Carbon Resources Initiative (LCRI), a joint effort of EPRI and GTI Energy addressing the need to accelerate development and deployment of low- and zero-carbon energy technologies. The LCRI is targeting advances in the production, distribution, and application of low-carbon energy carriers and the cross-cutting technologies that enable their integration at scale. These energy carriers, which include hydrogen, ammonia, synthetic fuels, and biofuels, are needed to enable affordable pathways to economy-wide decarbonization by mid-century. For more information, visit www.LowCarbonLCRI.com.

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Founded in 1972, EPRI is the world's preeminent independent, non-profit energy research and development organization, with offices around the world. EPRI's trusted experts collaborate with more than 450 companies in 45 countries, driving innovation to ensure the public has clean, safe, reliable, affordable, and equitable access to electricity across the globe. Together, we are shaping the future of energy.

Note
For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

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