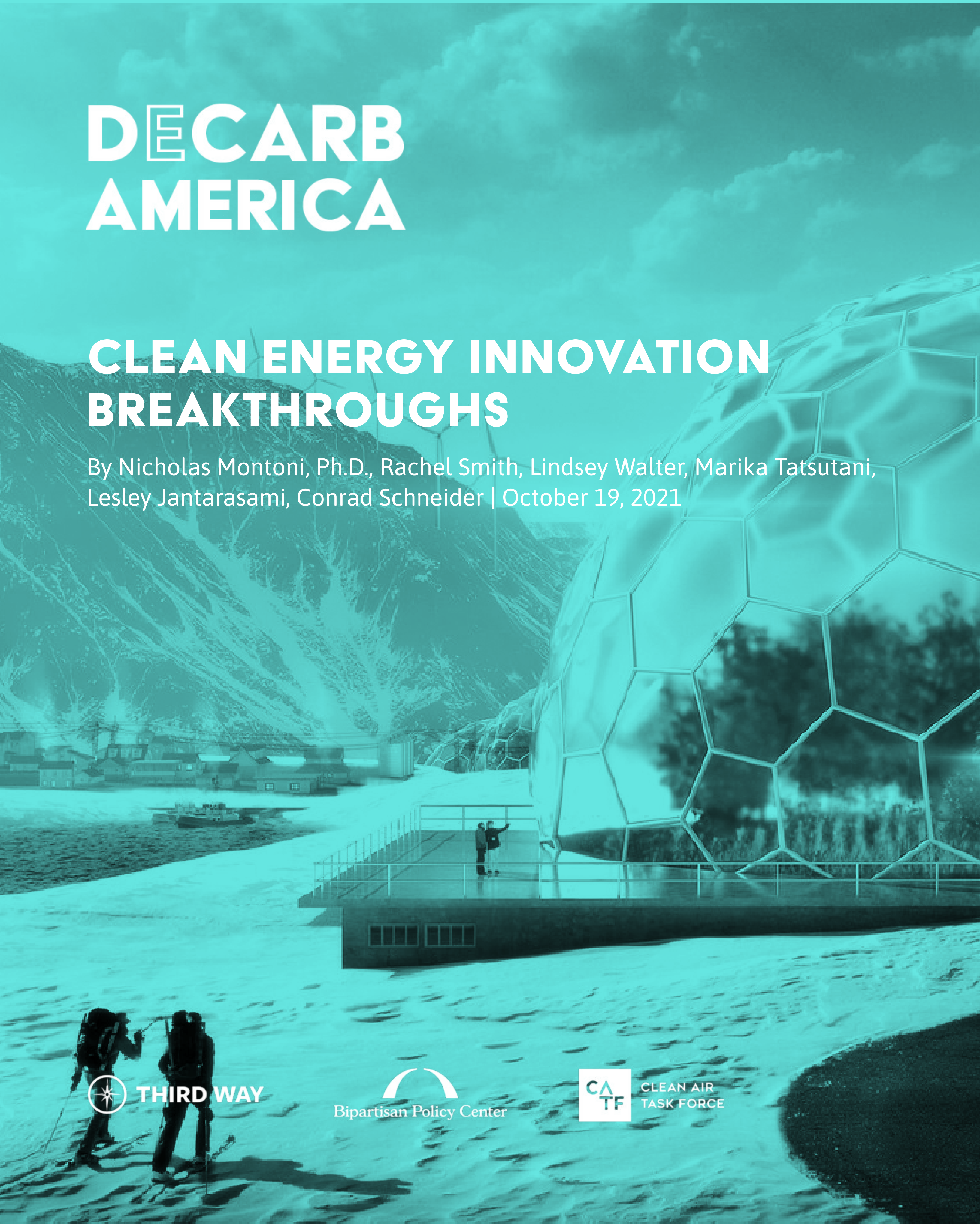

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CLEAN ENERGY INNOVATION BREAKTHROUGHS

By Nicholas Montoni, Ph.D., Rachel Smith, Lindsey Walter, Marika Tatsutani, Lesley Jantarasami, Conrad Schneider | October 19, 2021

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OVERVIEW

The Decarb America Research Initiative analyzes policy and technology pathways for the United States to reach net-zero greenhouse gas emissions by 2050. Our work aims to advance understanding of the tradeoffs between different proposed strategies for achieving net-zero and to identify the national, regional, and state-level economic opportunities that a new clean energy economy will generate. Our analytical results are intended to inform policymakers as they consider options for addressing climate change and modernizing America's energy systems.

To develop these results, Decarb America commissioned Evolved Energy Research and Industrial Economics, Inc. to undertake a rigorous, multi-part modeling analysis (more information is available at About the Initiative). The analysis explores five main research topics: (1) Pathways to Net-Zero Emissions, (2) Energy Infrastructure Needs for a Net-Zero Economy, (3) Power Sector Deep Dive, (4) Clean Energy Innovation Breakthroughs, and (5) Impacts on Jobs and the Economy.

This report presents key takeaways on topic (4) from the modeling analysis and responds to a critical, policy-relevant question:

> How might technology breakthroughs affect the cost and feasibility of reaching net-zero emissions? *(Here, we define a "technology breakthrough" as an innovation that dramatically reduces the cost and/or increases the efficacy of an advanced energy technology.)*

KEY TAKEAWAYS

1. Innovation reduces the cost of reaching net-zero emissions and enables greater policy ambition.
2. Breakthroughs across multiple technologies lead to a more balanced deployment of technologies; by contrast, a breakthrough in a single technology can result in market dominance for that technology.
3. A breakthrough in one technology doesn't preclude the need for a diverse portfolio of clean energy options.
4. Hydrogen production benefits from cost reductions in each innovation scenario.

MODELING APPROACH

Evolved Energy Research modeled four scenarios that incorporate different assumptions about the types of technology innovation needed to achieve net-zero U.S. greenhouse gas emissions by 2050, for both electricity and fuels. Each of the four scenarios assume some number of breakthroughs in energy technologies that significantly reduce energy-system costs, based on existing research and projections, and conversations with experts in specific technology areas. We then compared these technology breakthrough scenarios to our previously modeled high renewables/high electrification (HRHE) net-zero scenario, which effectively serves as our base scenario for modeling the benefits of innovation. To assess cost impacts, we compare modeled energy-system costs for each of the innovation scenarios and the HRHE net-zero scenario to costs for a "business-as-usual" reference scenario that does not achieve net-zero emissions by 2050—in fact, in the business-as-usual reference scenario, emissions in 2050 are only 17% lower than current (2020) emissions.

Key assumptions for each scenario are summarized in **Tables 1** and **2** and in the paragraphs below. It should be noted that the 2050 HRHE net-zero innovation base case also assumes cost declines over the next three decades for key low-carbon technologies relative to current (2020) costs. These declines reflect performance improvements and cost reductions that could be expected to flow from mass deployment, as low-carbon technologies benefit from economies of scale and "learning-by-doing," and from baseline levels of investment in research, development, and demonstration. The innovation scenarios, by contrast, assume breakthroughs that produce additional, large "step changes" in technology cost, availability, and performance.

Our first innovation scenario, labeled "Carbon Capture Innovation" (CCI), assumes technology breakthroughs that substantially reduce both the cost of producing hydrogen from natural gas and the cost of capturing and sequestering carbon dioxide (CO2). Cost assumptions for the CCI scenario, and for the other innovation scenarios, relative to 2020 costs and 2050 costs from the HRHE base case, are summarized in **Table 2**.

In the CCI scenario, hydrogen production from natural gas is accomplished by autothermal reformation, so the per-kilowatt (kW) cost shown in Table 2 is based on the generating capacity and capital costs of the hydrogen production plants themselves. (The model uses these costs to derive the economy-wide cost of hydrogen based on a variety of scenario parameters and other technology assumptions; modeled costs per unit of hydrogen in different innovation scenarios are discussed later in this paper, under Key Takeaway 4.) The sequestration costs shown in Table 2 are given as a range because they vary as a function of annual storage potential (in the CCI case, the 2050 cost of CO2 sequestration ranges from negative $1 per ton, implying cost savings, to $47/ton).

Our second modeling scenario, the "Nuclear Innovation" (NI) scenario, assumes breakthroughs in reactor technology that result in a more than six-fold reduction in the 2050 cost for advanced nuclear generating capacity, relative to the HRHE base case. Our third scenario, the "Renewables Innovation" (RI) scenario, assumes breakthroughs that reduce the cost of solar generating capacity by nearly 50%, onshore and offshore wind capacity by 13%, and lithium-ion (short-term) energy storage by more than 20%. The RI scenario also includes long-duration energy storage at a cost of $3.60/kWh. Our fourth scenario, "Universal Innovation" (UI) applies the cost assumptions from all three technology-specific innovation scenarios.

Table 1. Scenario descriptions

SCENARIO	DESCRIPTION
Reference	Business-as-usual (BAU) scenario that assumes no additional policy changes. Uses the Energy Information Administration's Annual Energy Outlook (AEO) 2019 with updated fuel prices and clean energy policies from AEO 2020. The U.S. economy does not achieve net-zero emissions in this scenario: modeled CO2 emissions in 2050 still total nearly 4.1 billion metric tons.
High Renewables/ High Electrification (HRHE)	Achieves net-zero greenhouse gas emissions across the U.S. economy by 2050 assuming cost reductions typical of wide scale adoption without significant technological breakthroughs. This scenario applies sectoral policies analyzed in Decarb America's Pathways to Net-Zero Emissions: Key Takeaways report and then allows the model to choose the optimal path to net-zero. This scenario includes assumptions common to other net-zero analyses in terms of achieving high levels of electrification and renewable energy deployment.
Carbon Capture and Sequestration Innovation (CCI)	Assumes technology breakthroughs that reduce the cost for hydrogen production from natural gas by $660/kW and geological sequestration costs by $25/ton CO2 (with geological sequestration, coal and gas can continue to be used in the power sector as net-zero power sources).
Nuclear Energy Innovation (NI)	Achieves net-zero by allowing new advanced nuclear reactors to be built and by converting coal plants into advanced nuclear reactors. Innovations are assumed to reduce the cost of new nuclear generating capacity by an order of magnitude relative to current (2020) costs, from $7000/kW to $700/kW.
Renewables Innovation (RI)	Assumes breakthroughs that reduce the cost of solar generating capacity to $430/KW, onshore and offshore wind energy to $872/kW and $1070/kW respectively, and costs for energy storage—specifically for short-duration (lithium-ion) and long-duration storage technologies—of $47/kWh and $3.60/kWh respectively.
Universal Innovation (UI)	Reflects all cost benefits from innovation in the CCI, NI, and RI scenarios simultaneously.

Table 2. Costs of low-carbon energy technologies in 2020, in 2050 under the HRHE scenario, and in 2050 with technology breakthroughs.

TECHNOLOGY	2020 COST	2050 COST (as modeled in the net-zero HRHE scenario assuming base-case tech improvement)	2050 COST (as modeled in innovation scenarios that assume technology breakthroughs in key areas)
Blue Hydrogen	$1444/kW thermal	$1127/kW thermal	$660/kW thermal
Carbon Sequestration	$24–$72/ton	$24–$72/ton	$-1–$47/ton
Advanced Nuclear	$7000/kW	$4716/kW	$700/kW
Solar	$1012/kW	$802/kW	$430/kW
Onshore Wind	$1496/kW	$1007/kW	$872/kW
Offshore Wind (OSW)	$3604/kW	$1235/kW	$1070/kW
Green Hydrogen	$922/kW thermal	$461/kW thermal	$199/kW thermal
Lithium-Ion (Li-ion) Batteries	$146/kWh	$60/kWh	$47/kWh
Long Duration Energy Storage (LDS)	N/A	N/A	$3.60/kWh

How might technology breakthroughs affect the cost and feasibility of reaching net-zero emissions?

KEY TAKEAWAY 1

Innovation reduces the overall cost of reaching net-zero emissions and enables greater policy ambition.

Our analysis shows that relative to the high renewables/high electrification case from a previous Decarb America analysis (the HRHE scenario is our base case for reaching net-zero by 2050 with no major innovations), any breakthrough in carbon capture and storage, hydrogen production, nuclear energy, renewable energy, and energy storage reduces the cost of achieving net-zero emissions by 2050. To be clear: achieving net-zero emissions increases energy-system costs in all scenarios, relative to a "business-as-usual" reference case that does not achieve net-zero emissions. However, costs for all modeled pathways to net-zero in Decarb America's analysis are well below historic levels of spending on the U.S. energy system as a percent of GDP, as explained in our Pathways to Net-Zero Emissions: Key Takeaways report. Not surprisingly, innovation across multiple key technologies produces the largest cost savings. Our UI scenario, which assumes across-the-board innovation, cuts the cost of getting to net-zero by more than 60%, saving the United States an estimated $250 billion per year in 2050 compared to a net-zero scenario with more incremental technology improvements.

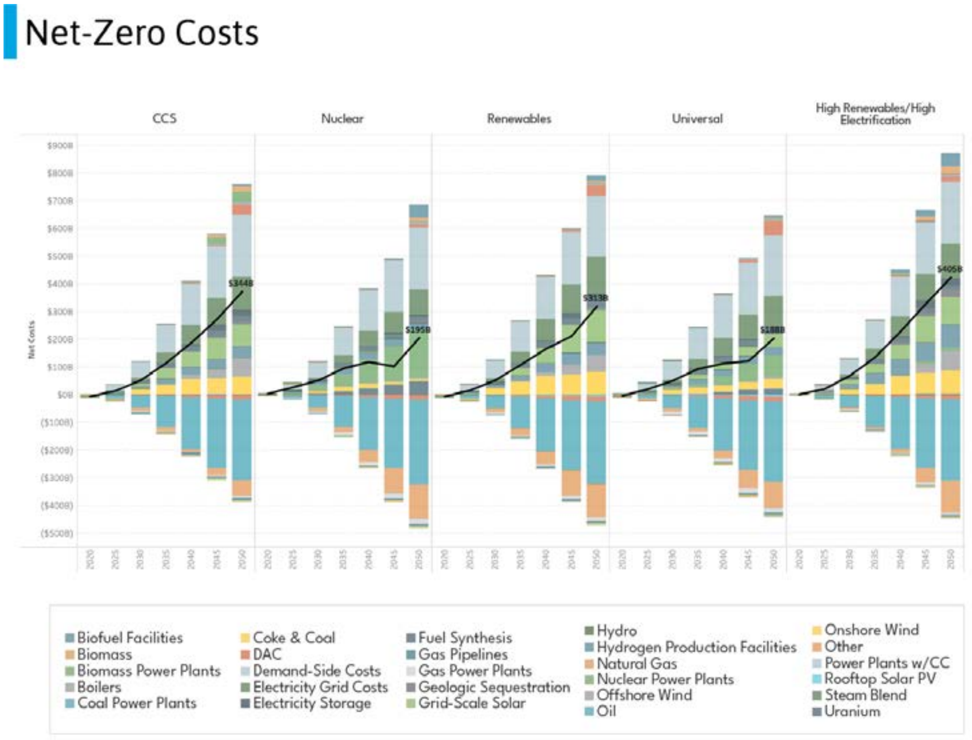

Figure 1: Breakdown of net costs and costs per energy source across net-zero scenarios.

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A detailed picture of cost impacts from changes in the energy mix over time under different scenarios is provided in **Figure 1**. The costs shown are relative to a business-as-usual scenario that does not achieve net-zero emissions by 2050. **Figure 1** shows how added costs for new, zero-carbon resources in each of our scenarios are offset by negative costs (savings) from the reduced use of conventional fossil fuels. The net cost impact is indicated by the black line. The figure shows, for example, that reduced oil use accounts for the largest cost savings—approximately $300 billion per year—in all our scenarios. **Figure 1** also shows that, in several scenarios, the need to add direct air capture (DAC) of CO2 from the atmosphere to reach the net-zero goal leads to a distinct cost bump in the years leading up to 2050.

Table 3 summarizes net energy-system cost differences in the year 2050, relative to both the business-as-usual scenario that does not achieve net zero emissions and the net-zero HRHE base innovation scenario. The third column of the table highlights the specific impacts of our innovation scenarios, showing how each reduces the modeled energy-system costs of reaching net-zero by 2050 relative to the HRHE scenario. These cost savings range from $92 billion in 2050 for the CCI scenario to a maximum, as noted previously, of $251 billion in 2050 for the UI scenario, which incorporates breakthroughs in all three technology areas. Notably, the cost reductions from breakthroughs across scenarios are not additive. This is because the model calculates the most cost-effective deployment and utilization of all the available technologies, taking into account their individual costs. As costs fall dramatically for all of the technologies in the UI scenario, overall patterns of deployment shift. For instance, in the NI scenario, advanced nuclear energy provides roughly 70% of electricity, whereas in UI the electricity mix consists of 40% nuclear and 60% renewable energy. Thus, the cost savings attributable to nuclear breakthroughs only in the UI scenario are less than in the NI scenario. These technology interactions are discussed further in the next key takeaway.

Table 3: Summary of net energy-system costs in 2050 across net-zero scenarios

SCENARIO	COST ABOVE REFERENCE BAU SCENARIO IN 2050 (BILLIONS)	SAVINGS DUE TO	DRIVERS OF SAVINGS (RELATIVE TO HRHE CASE)
High Renewables/High Electrification	$1444/kW thermal	$1127/kW thermal	$660/kW thermal
CCS Innovation	$24–$72/ton	$24–$72/ton	$-1–$47/ton
Nuclear Innovation	$7000/kW	$4716/kW	$700/kW
Renewables Innovation	$1012/kW	$802/kW	$430/kW
Universal Innovation	$1496/kW	$1007/kW	$872/kW

Overall, however, **Table 3** shows that technology breakthroughs reduce the cost of achieving net-zero, relative to the HRHE case, in all our innovation scenarios. The specific drivers of these cost differences vary by scenario, as illustrated by **Figure 1**. For instance, most of the cost difference between the CCI scenario and the other innovation scenarios can be explained by lower avoided costs from the phase out of natural gas, which results in relatively modest savings of $57 billion in 2050. In the NI scenario, savings come from reduced spending on the electricity grid ($93 billion cost reduction in 2050) and on renewables ($7 billion cost reduction in 2050) compared to the other scenarios. The RI scenario is interesting because it results in significantly higher costs for renewables ($225 billion more in 2050), grid expenses ($133 billion more in 2050), and hydrogen production ($47 billion more in 2050) relative to the HRHE case, but still results in substantial net savings overall. This is because innovations in renewable energy and energy storage in this scenario produce large reductions in fossil-fuel costs (net savings of $446 billion in 2050).

The central message here is simple: Robust investments in technology innovation are warranted by the large cost savings that innovation delivers in the transition to a net-zero economy. These cost savings, it bears noting, are in addition to the benefits realized by achieving the net-zero target in terms of avoiding or mitigating climate damages, including damages from extreme weather and related catastrophes such as floods, droughts, heat waves, and wildfires. Investments in clean energy technology innovation, from basic research to large-scale demonstration projects, should be considered a down payment on reducing the long-term cost of building a net-zero economy.

KEY TAKEAWAY 2

Breakthroughs across multiple technologies lead to a more balanced deployment of technologies; by contrast, a breakthrough in a single technology can result in market dominance for that technology.

This takeaway is illustrated by **Figure 2**, which shows how the mix of technologies used to supply electricity and CO2 reductions changes across the different innovation scenarios. The figure shows, for example, that breakthroughs in carbon capture technology in the CCI scenario result in increased deployment of carbon capture relative to the other scenarios. This enables continued use of natural gas and biofuels in the power sector, such that these fuels account for around 5% of power sector generation in 2050. Carbon capture and sequestration is also used to decarbonize more than 92% of the hydrogen produced for use across all sectors.

Similarly, in the scenario that assumes breakthroughs exclusively in nuclear technology, nuclear energy is widely deployed across all sectors, providing more than 70% of the energy needed in the power sector and more than 90% of the energy needed for hydrogen production (via high-temperature steam electrolysis).

Every net-zero scenario modeled by Decarb America shows the widespread deployment of renewable energy technologies, which generally dominate the power sector in all our modeling scenarios because their cost curves have already fallen further relative to the cost curves for advanced nuclear and carbon capture. However, in the RI scenario, we see renewable technology deployment to the point where renewables account for nearly 90% of power generation and 90% of hydrogen production.

Total electricity generation, annual load, & negative-CO_2 supply across net-zero scenarios

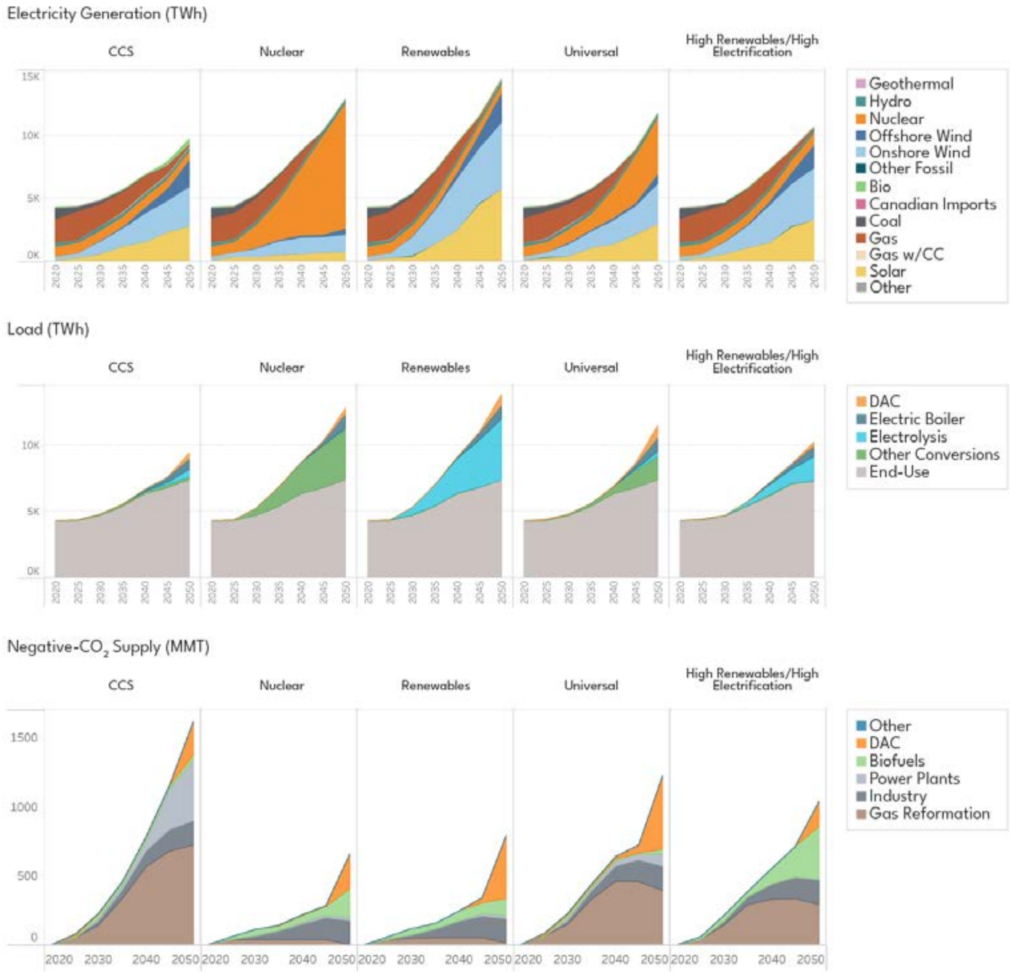

Figure 2: Total electricity generation, annual load, and negative-CO_2 supply across net-zero scenarios. The negative-CO_2 supply curves indicate the rate at which DAC needs to be deployed in each scenario, and show how technologies that remove CO_2 from the atmosphere can contribute to the net-zero goal.

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In a scenario that assumes breakthroughs in multiple technologies, such as carbon capture, nuclear, and renewables, all at once, no single technology dominates the future energy system. This is evident from the results for our UI scenario, which indicate a more balanced deployment of climate-friendly technologies because all of them are cost competitive. Specifically, this scenario shows a mix of roughly 40% nuclear and 60% renewables to meet power sector needs in 2050, with carbon capture playing a bigger role (greater than 50%) in hydrogen production compared to high-temperature steam electrolysis or water electrolysis (**Figure** 3). The role of hydrogen is discussed at greater length under Key Takeaway 4.

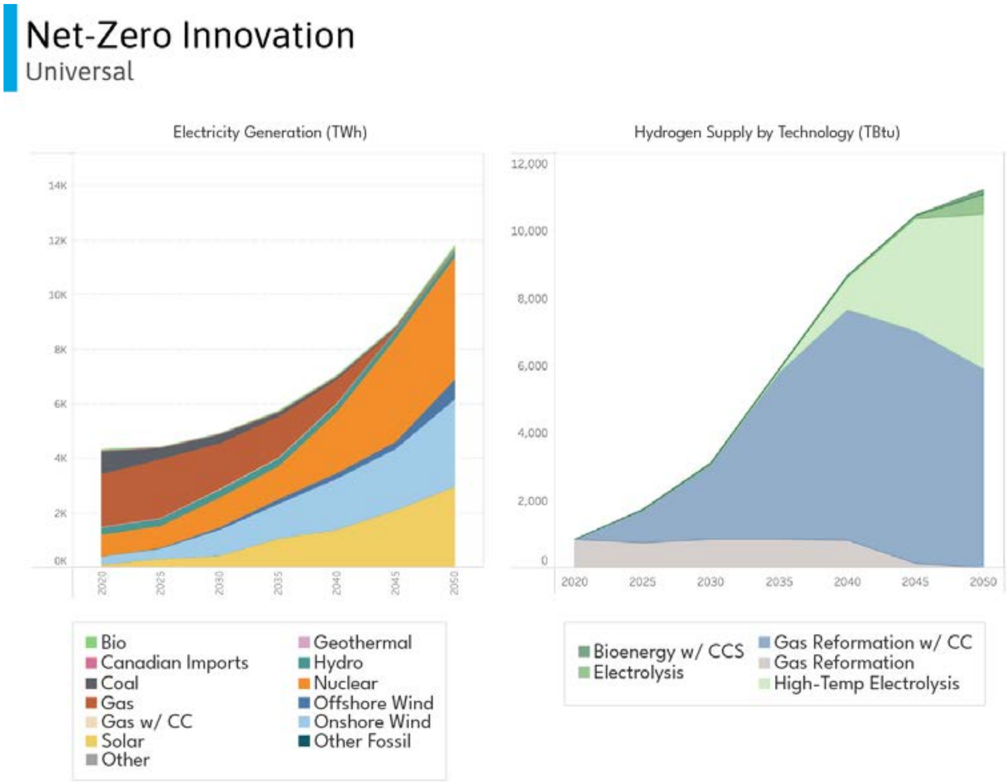

Figure 3: Total electricity generation and hydrogen supply in the UI scenario.

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Innovation across multiple different technologies has benefits that go beyond cost savings alone. Building out any of the technologies we model at the scale and pace needed to reach net-zero emissions by 2050 will be extremely challenging. In fact, every net-zero scenario we model demands clean-energy deployment at a rate that is twice the rate ever achieved historically. If the burden of rapid deployment falls solely on one or two technologies, additional issues with siting, supply chains, and workforce development are far more likely to arise. With a greater number of cost-competitive options on the table, technologies can be deployed where they can contribute most to a reliable, affordable zero-carbon system.

KEY TAKEAWAY 3

A breakthrough in one technology doesn't preclude the need for a diverse portfolio of clean energy options.

Though a breakthrough in a single technology can result in a dominant role for that technology, as discussed in the previous section, each of the key zero-carbon technologies we modeled—carbon capture, nuclear, and renewables—plays some role in the future energy mix in all the scenarios. This general result also holds for the HRHE scenario, which assumes gradual improvement but no major breakthrough innovations in any of the key technology areas.

For instance, in the renewables innovation scenario, most of the existing nuclear fleet must be maintained for power supply—in 2050, existing nuclear still accounts for about 690 terawatt-hours (TWh) of electricity production (nationally, nuclear generating capacity falls from 99 gigawatts (GW) in 2020 to 85 GW in 2050 in the RI scenario). Similarly, carbon capture and storage is still needed to enable continued use of small amounts of natural gas—sequestration, in particular, is especially important for the deployment of DAC technologies, which capture CO2 from the atmosphere. In the RI scenario, DAC consumes 821 TWh of electricity and offsets more than 450 million metric tons of CO2 annually by 2050 (**Figure 2**). Each individual innovation scenario has similar results: in the carbon capture innovation scenario, renewables and nuclear are still needed to meet the energy needs of the power sector, and in the nuclear innovation scenario, renewables are utilized in the power sector while carbon capture and storage is needed to offset the emissions associated with remaining uses of fossil fuels.

Figure 4, which shows the modeled trajectory of positive and negative CO2 emissions from different energy and industrial sources over the next three decades, provides further evidence of the complementarity of technologies across our innovation scenarios. While net emissions (indicated by the black line in **Figure 4**) decline at roughly the same rate in all scenarios (largely as a function of the model's assumptions) the balance of contributions from different sources—and the deployment of negative emissions technologies such as DAC, in particular—shifts. For example, to provide enough negative emissions to hit the net-zero target in the RI and NI scenarios, the model predicts an abrupt increase in geologic sequestration of CO2—supplied mainly by DAC—between 2045 and 2050. In the CCI and UI scenarios, by contrast, lower costs for carbon capture mean that geologic sequestration is deployed much earlier and ramps up gradually over the entire period.

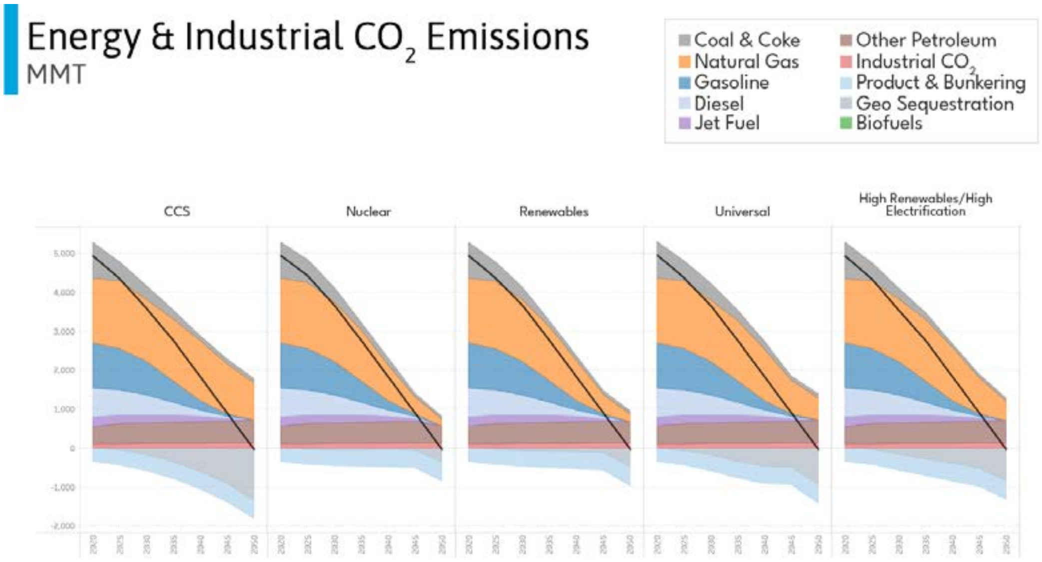

Figure 4: CO_2 emissions (positive and negative) from different sources over the 2020–2050 period, across the four innovation scenarios and the HRHE scenario.

It is worth emphasizing that technologies for actively capturing or removing and sequestering carbon (shown as negative emissions in **Figure 4**) are needed to reach the net-zero goal in all our scenarios. But it is also the case that negative emissions technologies alone aren't adequate. Even when sequestration costs are relatively lower, as in the CCI and UI scenarios, renewable and nuclear energy are still needed to reduce (positive) emissions from fossil fuel consumption.

Two additional points about **Figure 4** bear noting. First, the primary contributors to negative energy and industrial emissions in the figure are geologic sequestration and a category called "product and bunkering." Here, "product" refers to hydrocarbons that, because they are embodied in durable products instead of being combusted, do not generate CO2 emissions and "bunkering" refers to fuels that are stored in the United States but will be used elsewhere, and thus do not count toward U.S. emissions. A second important point is that **Figure 4** does not include important sources of negative emissions outside the energy and industrial sectors, including terrestrial forms of carbon sequestration (such as in forests and soils); in addition, **Figure 4** does not include positive and negative emissions of greenhouse gases other than CO2, such as methane. All these sources—i.e., positive and negative sources of CO2 outside the energy and industrial sectors and non-CO2 greenhouse gases—are captured in the modeling analysis, however, and do factor into the overall achievement of the net-zero target in each of our scenarios.

In sum, **Figure 4** further underscores the point that there is no single path to net-zero carbon emissions and no technology "silver bullet" to decarbonize the entire economy. While renewable energy is sometimes put forward as a solution that could meet 100% of the nation's energy needs, our modeling results indicate that even with large cost reductions in solar, wind, and energy storage, some nuclear and fossil fuel generation with carbon capture is still necessary to firm up the intermittent resources and support the transition to hydrogen fuels. This observation highlights the distinction between what is technically feasible and what is practical, both politically and technologically. Nonetheless, solar and wind play an integral role in all modeled pathways to net-zero by 2050—across all our innovation scenarios. Even in the nuclear innovation scenario, where nuclear energy supplies more than three-fourths of overall electricity demand, solar, wind, and carbon capture are needed to achieve the net-zero goal.

KEY TAKEAWAY 4

Hydrogen production benefits from cost reductions in each innovation scenario.

Previous Decarb America modeling analyses found that hydrogen fuel will need to play a significant role in decarbonizing multiple sectors of the economy, including medium- and heavy- duty truck transport, shipping, freight rail, bulk chemicals production, and other parts of the industrial sector. Demand for hydrogen in a net-zero economy is projected to reach 9–22 times current levels of demand. In all our innovation scenarios, breakthroughs in a particular type of technology lead to higher use of that technology for hydrogen production and a reduction in the cost of producing hydrogen, as shown in **Figures 5** and **6**. We also see that innovation in autothermal reformation, high-temperature steam electrolysis , and water electrolysis using renewably generated electricity leads to reduced dependence on bioenergy with carbon capture and sequestration (CCS). In the base HRHE net-zero scenario, the model projects hydrogen cost at $14 per million British thermal units (MMBtu) in 2050. Each of our innovation scenarios has the effect of reducing the cost of hydrogen (**Figure 6**): to $11/MMBtu in the CCI scenario, $10/MMBtu in the RI scenario, $9/MMBtu in the NI scenario, and $8/MMBtu in the UI scenario.

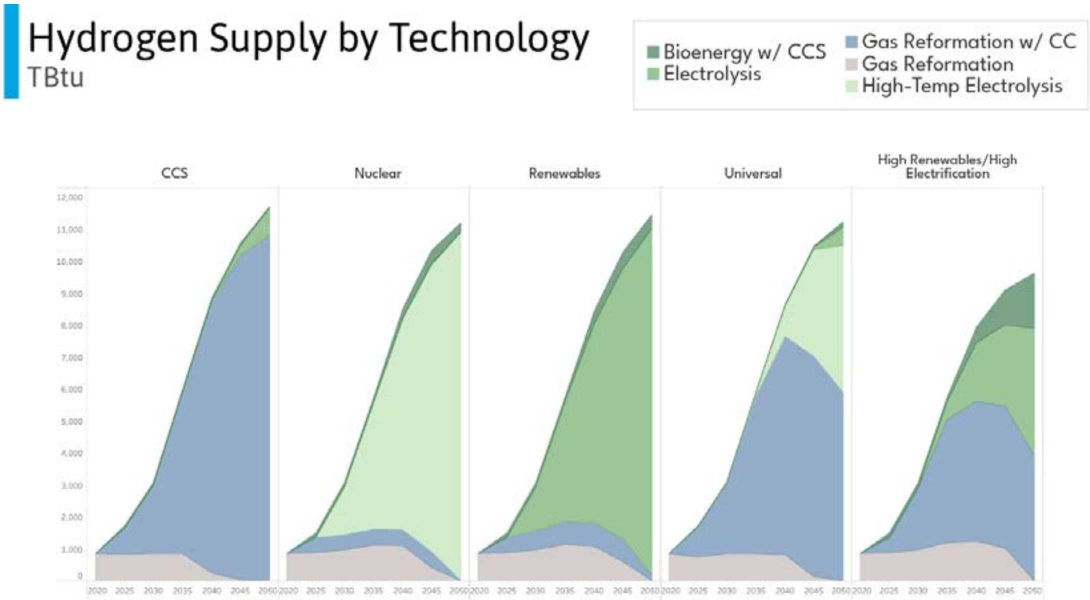

Figure 5: Hydrogen supply across net-zero scenarios.

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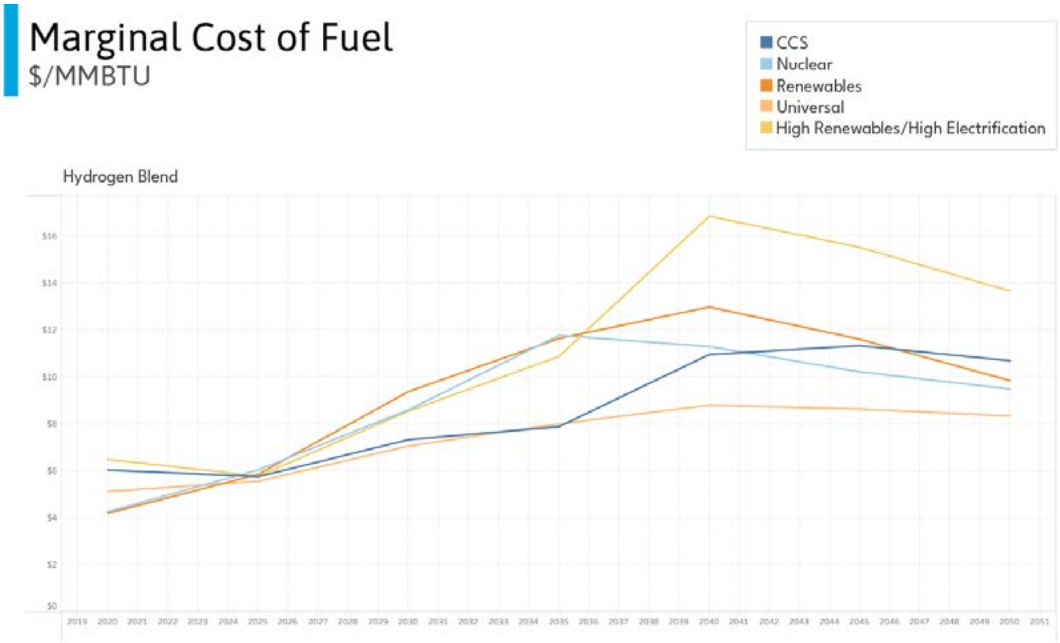

Figure 6: Cost of hydrogen across net-zero scenarios.

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Relative to the base HRHE net-zero scenario, the CCI scenario results in a 10% reduction in overall electricity demand in 2050 (**Figure 7**). This is because carbon capture innovations eliminate the need to use solar and wind power to produce hydrogen from water via electrolysis. Instead, lower-cost carbon capture and storage allows for the use of autothermal reformation, which turns natural gas into hydrogen and carbon dioxide—the CO2 can then be captured and stored or converted back into a hydrocarbon that can be used as a fuel or for some other purpose. If the natural gas used in this process is from a geological rather than biological source, it will add CO2 to the atmosphere and must be offset with DAC. Notably, the hydrogen supply in the CCI scenario increases relative to the other innovation scenarios as well (though only slightly). This is because it becomes more economical to use carbon capture and storage to produce hydrogen using energy sources other than electricity and to use that hydrogen to meet other end-use energy demands.

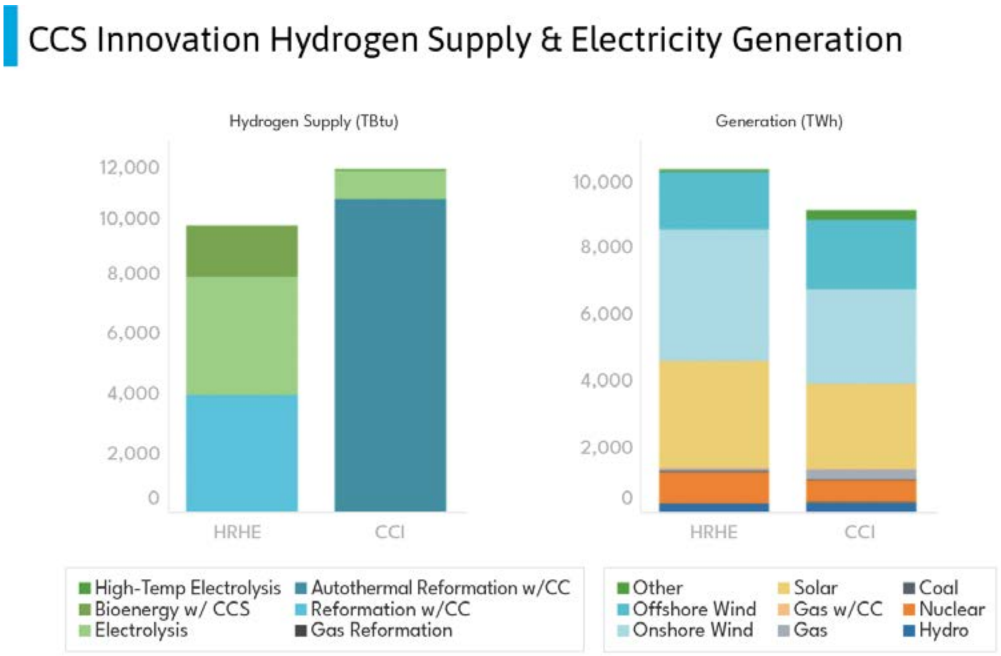
CCS Innovation Hydrogen Supply & Electricity Generation

Figure 7: Breakdown of hydrogen supply and electricity generation in the CCI scenario.

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In our NI scenario, the high temperatures produced by advanced reactors are used to produce hydrogen via steam electrolysis (instead of producing hydrogen from natural gas). Higher temperatures reduce the electricity required to break water molecules into hydrogen and oxygen. Thus, technology breakthroughs that make nuclear energy more affordable make it economical to supply most hydrogen using nuclear reactors.

Similarly, in the RI case, solar and wind become so cost effective that they are utilized to produce hydrogen by water electrolysis. Normally, water electrolysis is more expensive than natural gas reformation as a method for producing hydrogen because it requires more energy. But in this scenario, water electrolysis using low-cost wind and solar is more cost-effective than either autothermal reformation or building new nuclear reactors. In fact, hydrogen production is so important for the net-zero economy that it becomes a major source of electricity demand that drives solar deployment—even with cost reductions in energy storage technologies. Indeed, electrolysis is so much more important than energy storage from an economic standpoint, that we predict cost reductions for energy storage do not substantially affect the deployment of this technology between now and 2050 (**Figure 8**). Similarly, our scenarios show no major increase in pumped hydroelectric storage (PHS) over the next several decades, despite its dominant role in energy storage at present. The central role of hydrogen is also reflected in our calculations for annual electricity load in 2050 (**Figure 3**, second panel).

Finally, our UI scenario produces the largest cost reductions for hydrogen production because each of the breakthrough technologies can be deployed where it is most economical. As we have already noted, more than half of hydrogen production in this scenario comes from reformers equipped with carbon capture and sequestration, while high-temperature steam electrolysis using nuclear reactors supplies most of the remainder. Electrolysis from renewables accounts for just a small fraction of hydrogen production; instead, most renewables deployment is needed to meet power sector demand.

Given hydrogen's usefulness and the marginal reductions in hydrogen production cost that can be achieved with different technology innovations, it is reasonable to say that hydrogen benefits drive the overall cost reductions seen in all our innovation scenarios. That is, no matter where innovation is focused or how successful it is, hydrogen becomes cheaper. This further underscores our first key takeaway: innovation has large benefits—benefits that warrant substantial investment.

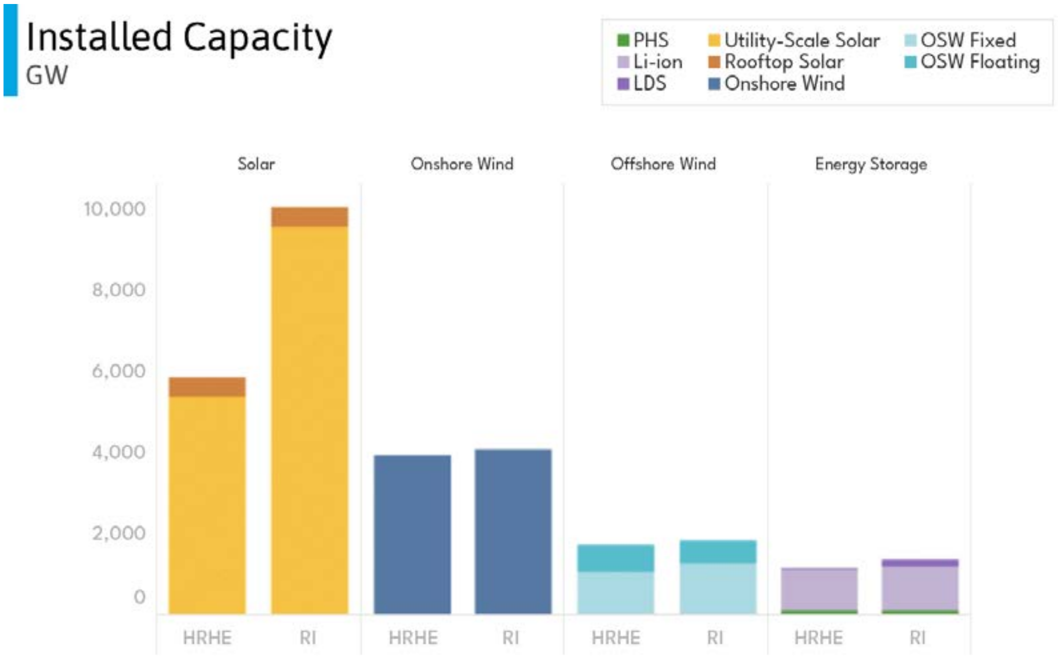

Figure 8: Installed generating capacity in 2050 compared between the HRHE scenario and the RI scenario.

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CONCLUSION

Our modeling analysis shows that any innovation in clean energy technology helps reduce the cost of reaching net-zero emissions by 2050—and more innovation leads to greater cost reductions. We did not, in this analysis, explore how breakthrough innovations could affect the speed of decarbonization—that is, we did not model scenarios that reach net-zero emissions before 2050. But it is worth noting, as a general point, that breakthrough technology innovations—by accelerating cost reductions and enabling faster deployment—can also make it possible to achieve a given mitigation target more quickly. Since there is usually a tradeoff between cost and speed, innovation, roughly speaking, can make it possible to achieve a given target in a shorter timeframe for the same cost, or to achieve that target in the same timeframe for a lower cost.

Technology breakthroughs do not happen in a vacuum, however, and historically they haven't been brought about by the private sector alone. The track record in energy-system innovation suggests that massive public investments in research, development, and demonstration will be needed to commercialize advanced energy technologies and deploy them at scale.

Decarb America's modeling shows that innovation reduces the cost of decarbonization, that more innovation is better, that there is no silver bullet to climate mitigation, and that a key benefit of innovation in carbon capture and storage, nuclear energy, and renewables is to reduce the future cost of producing hydrogen. More broadly, our findings underscore the point that innovation in one or multiple clean energy technologies increases flexibility and complementarity in the whole energy system, making the task of achieving net-zero much more feasible. All these results raise the stakes for accelerating the pace of energy innovation over the next several decades and create a compelling argument for robust public investment to spur the technology breakthroughs that will be critical—practically, economically, and politically—to achieving a net-zero economy by 2050.

LIST OF ACRONYMS

BAU	business-as-usual
CC	carbon capture
CCI	Carbon Capture Innovation (scenario for this modeling analysis)
CCS	carbon capture and sequestration
CO_2	carbon dioxide
DAC	direct air capture
HRHE	High Renewables/High Electrification (one net-zero scenario from previous Decarb America analysis)
kW	kilowatt
kWh	kilowatt-hour
LDS	long-duration storage
Li-ion	lithium-ion (type of battery used for energy storage)
MMBTU	million British thermal units
NI	Nuclear Innovation (scenario for this modeling analysis)
OSW	offshore wind
PHS	pumped hydroelectric storage
RI	Renewable Innovation (scenario for this modeling analysis)
UI	Universal Innovation (scenario for this modeling analysis)