EVOLVED ENERGY RESEARCH

Unlocking Deep Decarbonization: An Innovation Impact Assessment

PREPARED FOR

Environmental Defense Fund

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About this Study

Environmental Defense Fund commissioned Evolved Energy Research to develop an analytical framework for assessing and prioritizing research and development funding in the energy space to support deep decarbonization of the economy. We are grateful to the Bernard and Anne Spitzer Charitable Trust for its generous support of this project.

About Evolved Energy Research

Evolved Energy Research (EER) is a research and consulting firm focused on questions posed by transformation of the energy economy. Their consulting work and insight, supported by complex technical analyses of energy systems, are designed to support strategic decision-making for policymakers, stakeholders, utilities, investors, and technology companies. They have developed models to simulate and optimize economy-wide energy systems, bulk power systems operations, and utility distribution systems.

About Environmental Defense Fund

Environmental Defense Fund (EDF) is one of the world's leading environmental nonprofit organizations. Guided by science and economics, EDF finds practical and lasting solutions to the most serious environmental problems.

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Executive Summary

To avoid the worst effects of climate change, the United States will need to achieve net-zero greenhouse gas (GHG) emissions by mid-century. Meeting this goal requires a shift to low-carbon technologies throughout our energy system, many of which are not yet at significant commercial scale. This suggests that research and development (R&D) has a critical role to play in enabling the technologies that are necessary to rapidly reduce emissions. Recognizing this, many have called for a doubling or tripling of federal clean energy innovation funding within the decade.

Against this backdrop, we posit the question: **How should federal decision-makers prioritize innovation efforts to best contribute to climate goals?** To inform the U.S. energy innovation strategy, we developed an analytical framework for assessing and prioritizing funding to support deep decarbonization of the economy. Our modeling approach enables us to understand how technologies interact within the energy system under various technology innovation scenarios and policy paradigms. We evaluated fifteen promising technology areas, identified three innovation trajectories for each (no progress, baseline and breakthrough), and determined their uptake under two levels of climate policy ambition (modest and aggressive).

By comparing deployment and emissions outcomes, we can ascertain the relative importance of targeted innovation efforts. Regardless of policy ambition, we find that continued progress on renewable electricity generation technologies is of foremost importance, given the dual role as a power sector decarbonizer and an enabler of zero-emissions technologies in other sectors. This is less of a consensus finding than it may seem at face value; while it is well-understood that continued deployment of renewables is important for deep decarbonization, there may be a sense that the cost parity of renewables today makes continued R&D less critical. In contrast, we find that renewable breakthroughs have immense upside, even in comparison to a baseline trajectory that has costs declining rapidly. Since a large portion of energy services are ultimately provided by renewable electricity generation either through end-use electrification or electric fuel production, even modest cost reductions have a large impact on total costs.

Alongside renewables, the second cluster of technologies that rise to the top across all levels of policy ambition are those that use clean electricity at scale. This includes technologies adopted by consumers (e.g., heat pumps and lithium-ion batteries in electric vehicles) and technologies deployed at an industrial scale (e.g., hydrogen electrolysis).

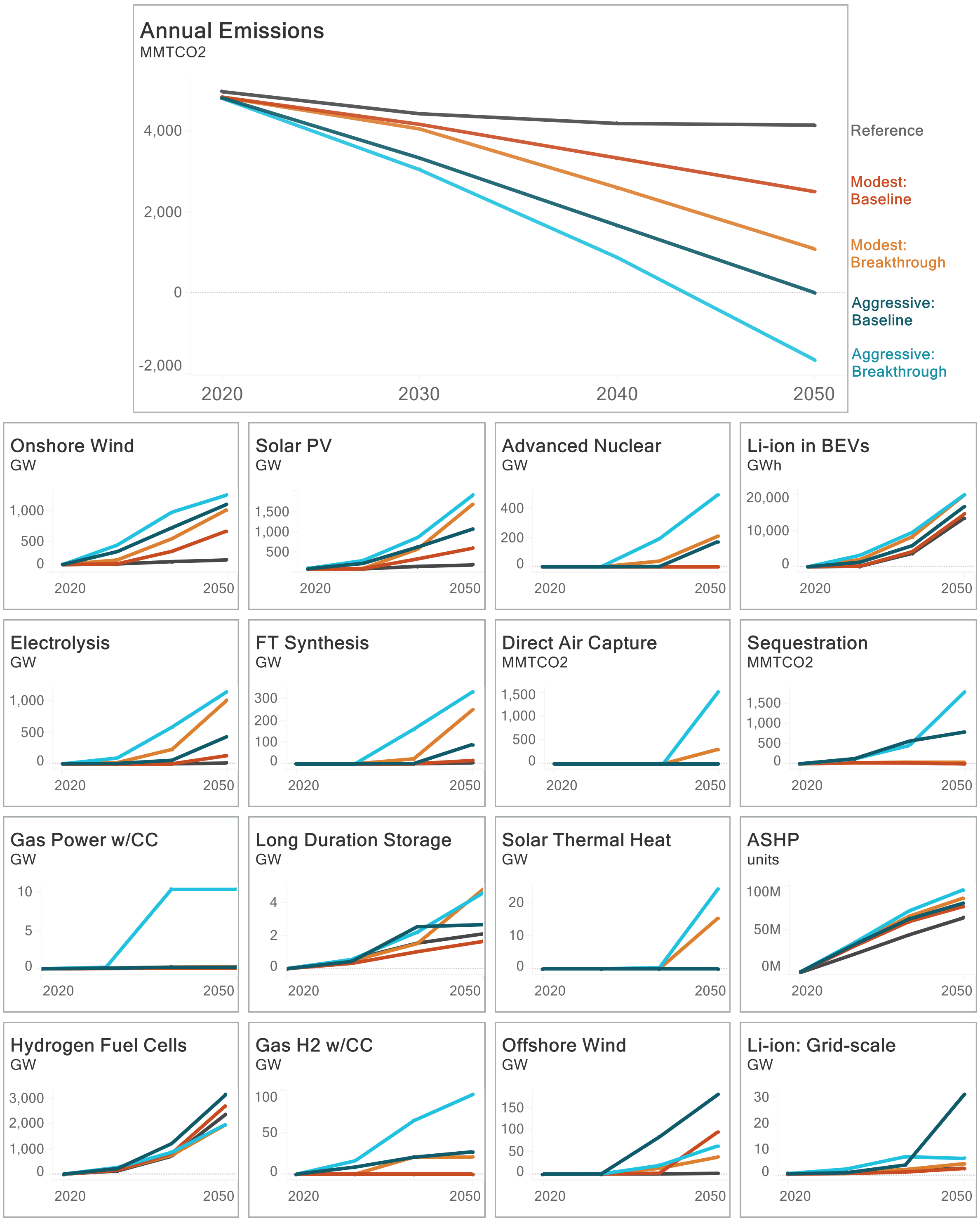
For many of the remaining technologies surveyed in this study, we find breakthroughs can accelerate decarbonization, but only under certain circumstances. Understanding these circumstances can enable decision-makers to make judgement calls about prioritization. For instance, a breakthrough in geologic sequestration costs has major implications when pursuing aggressive climate action, but it is not necessary in the modest policy context. Other technologies only proliferate when they achieve a breakthrough and competing technologies do not, while some technologies demonstrate limited complementarity with other technology areas.

One of the principal values of R&D is driving forward emissions reductions at a faster rate than policy alone, as well as lowering the cost of achieving a binding emissions policy.[1] Since GHGs accumulate over time in the atmosphere, faster mitigation generates cumulative climate benefits. As shown in the figure below, an aggressive policy ambition combined with baseline technology trajectories results in achievement of net-zero emissions in 2050 via a straight-line path from today with substantial deployment for many of the technologies considered in this study. A universal breakthrough enabled by R&D results in sharper emissions reductions driven by the accelerated deployment of key technology areas. Net-zero emissions are achieved in the mid-2040s primarily due to an uptake in technologies across the synthetic fuel supply chain: (a) clean electricity generation in the form of wind, solar and advanced nuclear; (b) hydrogen from electrolysis; (c) captured carbon; and (d) Fischer-Tropsch facilities for fuel synthesis. Adoption of electric end-use equipment such as battery electric vehicles and air-source heat pumps also accelerates due to lower input electricity costs. Other areas see modest growth in deployment

[1] The approach applied in this study explores the impact of technology progress on emissions (e.g., breakthroughs may lead to deeper emissions targets than the emissions constraint), while an alternative approach could hold emissions constant and focus on the reduced costs enabled by innovation.

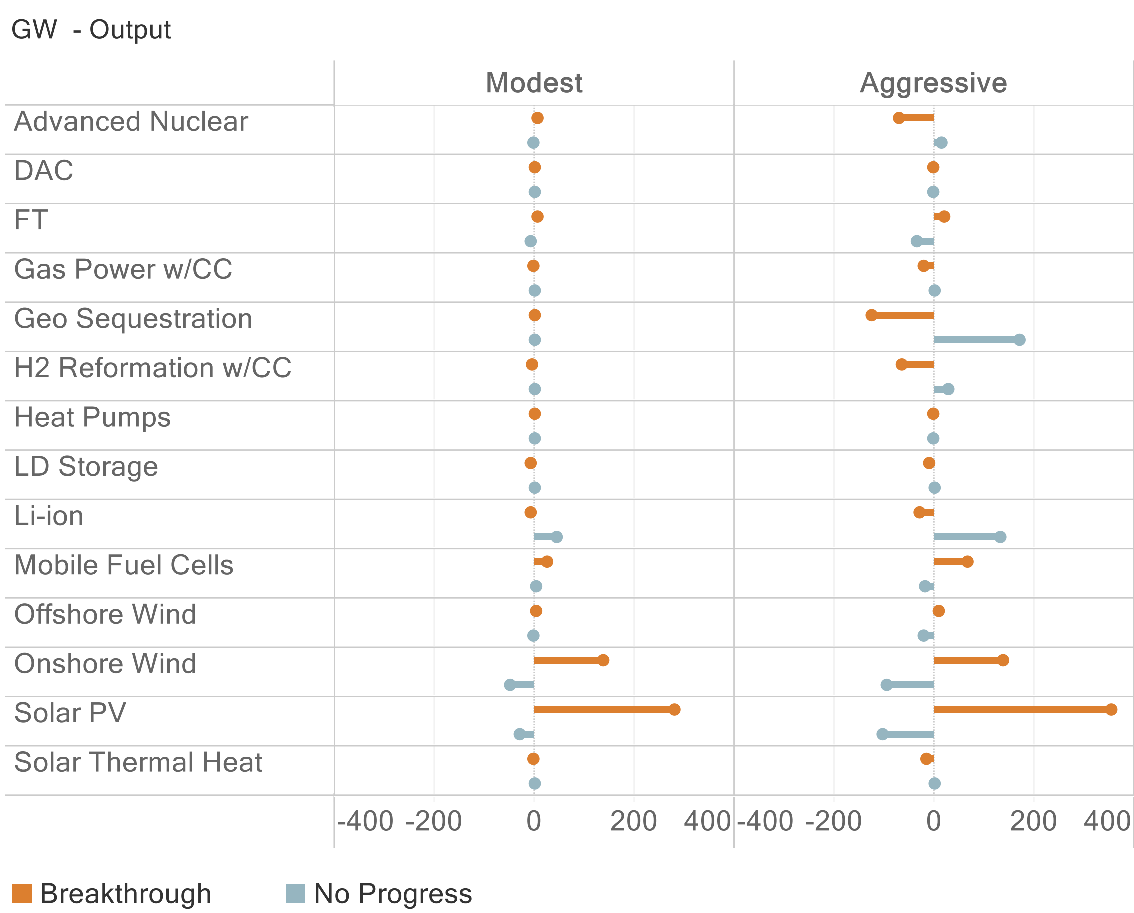
or declines due to competition with other technologies. Faster emissions reductions also occur under modest policy ambition, but annual emissions fall short of net-zero.

Emissions and Deployment by Technology Area



A primary finding of our study is that there are significant interactions between technologies, with a breakthrough for one technology having positive or negative deployment impacts on others. For example, the figure below presents the change in electrolysis deployment due to alternative trajectories for other technologies, where the difference is measured from the scenario where all technology areas realize their baseline trajectory. Electrolysis is a technology that has a high level of complementarity with breakthroughs in other areas, specifically onshore wind and solar PV, because lower renewable costs reduce the cost of electrolytic hydrogen production. In contrast, geologic sequestration competes with electrolysis for the same captured CO_2 resources. Hydrogen from electrolysis can be used for carbon capture and utilization (to produce synthetic hydrocarbons), while geologic sequestration is the alternative, with the sequestered CO_2 offsetting continued fossil hydrocarbon use.

Electrolysis Deployment Relative to the Baseline Trajectory: 2050



An important qualification to these results is that they depend on the assumed cost and performance trajectories, including each technology's baseline trajectory and the extent of progress enabled by a breakthrough. For example, the baseline capital cost assumption for advanced nuclear reflects a 45% reduction below today's level by 2050 and a further 45% reduction if a breakthrough is achieved (approximately $2,050/kW). On the other hand, cost trajectories for renewable electricity generation technologies demonstrate a smaller range (e.g., a breakthrough for onshore wind results in capital costs approximately 15% below baseline levels in 2050). Results may be highly sensitive to these assumptions, particularly for nascent technologies where expectations may be significantly more optimistic or pessimistic than the values considered in this study.

We identify six factors to consider for innovation decision-making:

1. **The level of carbon policy ambition has implications for how technology breakthroughs permeate the energy system**. Establishing the relevant decarbonization policy context is fundamental to evaluating and prioritizng R&D and should be accounted for when prioritizing R&D. Relevant price and deployment potentials for many of the technologies investigated in this study are reflective of society's value of reducing emissions. Without this, there is no guiding principle to prioritize R&D.
2. **Sustained technological progress must not be taken for granted**. Our baseline technology trajectories assume cost and performance improvements from sustained R&D funding and deployment, but there is no guarantee this will materialize based on business-as-usual conditions.
3. **Innovation policy should take a systems approach**. Our analysis reveals how changes in one technology area influence another, suggesting that the best R&D efforts will coordinate clusters of technologies and consider interactions within the energy system.
4. **Competitive landscapes matter for innovation**. R&D progress may lead some technologies that are not competitive in some regions and under certain circumstances to be more broadly competitive. For instance, improvements for onshore wind

technology can allow it to reach regions with lower-quality resources that may not be competitive today.

5. **The value of R&D should be compared against its cost**. This analysis evaluated the value of R&D in terms of impacts on deployment and emissions, but the cost (i.e., R&D expenditures) to realize technology progress from today needs to be considered. For example, the R&D expenditures needed to realize advanced nuclear capital costs of $2,000/kW may be significantly higher than those needed to reduce lithium-ion battery pack costs to $50/kWh.
6. **Non-economic factors have big implications for adoption, but are not easily captured in analysis**. An innovation strategy that targets cost alone is unlikely to maximize uptake. Market barriers, consumer demand and enabling policies, among other considerations, all play significant roles in determining technology deployment trajectories. The impacts of R&D can also extend to global energy markets, which were not evaluated in our U.S. energy system modeling.

In a forthcoming policy brief from EDF, the above findings – using both our analytical findings about the most important areas of technological progress for deep decarbonization and some of these other key considerations for decision-makers – will be utilized to make specific recommendations for innovation priorities and funding at the U.S. Department of Energy.

1. Introduction

Environmental Defense Fund (EDF) commissioned Evolved Energy Research to develop an analytical framework for assessing and prioritizing research and development (R&D) funding in the energy space to support deep decarbonization of the economy. Meeting decarbonization goals involves a complex mix of technology choices across different sectors that have implications for the wider energy system. Our approach addresses this complexity in a holistic manner by considering all technology options to reduce energy system emissions within the same least-cost optimization. By doing so, this study contributes to the existing understanding of the importance of R&D in a variety of ways.

First, our approach allows for an improved understanding of the potential scale of impact a technology breakthrough might make in terms of reducing overall energy costs and emissions, something that has not always been well communicated in R&D funding prioritization. Second, we can comprehensively assess the role that technologies play within decarbonizing energy systems. For example, electrolysis provides a feedstock for zero-carbon synthetic fuel production (e.g., carbon-free hydrogen) and is typically compared with other methods of zero-carbon fuel production such as biofuels. However, electrolysis plays an additional role in the electric sector as a balancing resource to enable higher renewable penetrations and should also be assessed against alternatives such as electric energy storage. Finally, wider energy system interactions provide an understanding of: (a) technology competitiveness (e.g., offshore wind versus advanced nuclear); (b) technology complementarity (e.g., solar PV and hydrogen electrolysis); (c) sectoral competitiveness (e.g., transportation versus industry); and (d) sectoral complementarity (e.g., transportation electrification and decarbonized electricity).

We studied fifteen technology areas that encompass the spectrum of a low-carbon energy system, ranging from renewable electricity generation technologies to negative emissions technologies. For each of these, we considered a range of technology progress through 2050 and evaluated their deployment across two levels of greenhouse gas policy ambition.

The remainder of this report is organized as follows. Section 2 discusses the analytical framework and assumptions used in the study. Section 3 summarizes the deployment of each technology area and impacts on energy CO_2 emissions. Section 4 discusses key observations and potential areas for further study.

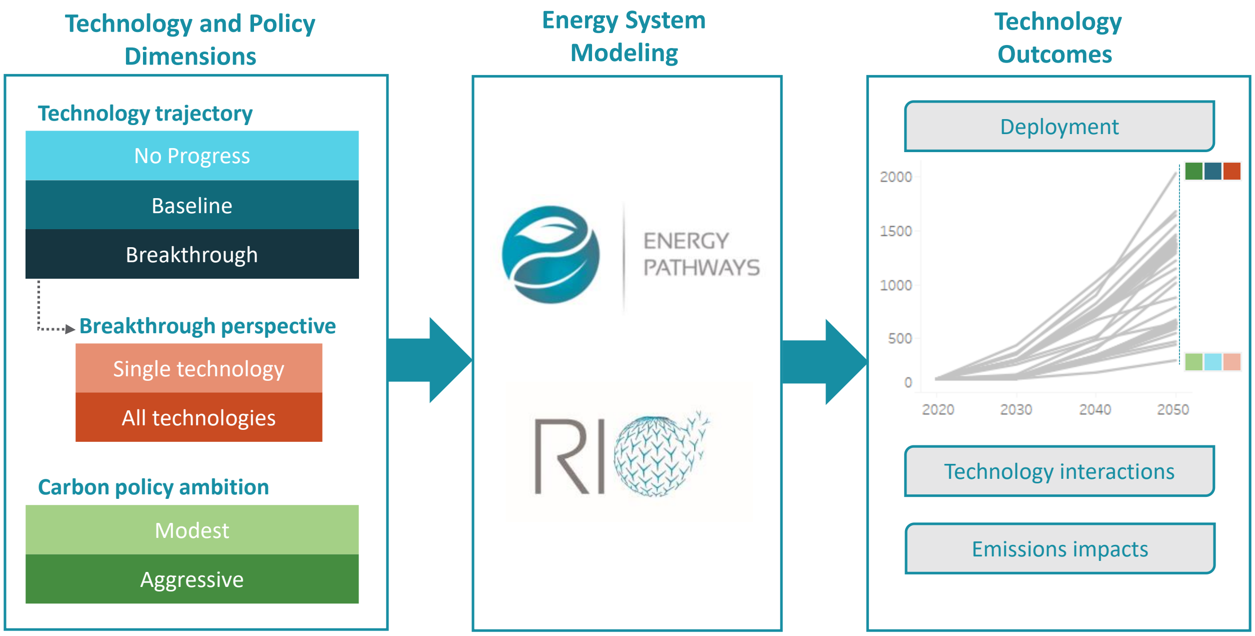
2. Study Design

In this section, we describe the approach for assessing and prioritizing R&D funding in the energy sector to support deep decarbonization of the economy. This includes a description of: (a) the analytical framework employed; (b) Technology areas and technologies considered; (c) carbon policy and technology cost and performance trajectories assumptions; and (d) energy system modeling methods used.

2.1. Analytical Framework

We evaluated fifteen technology areas using the analytical framework shown in Figure 1. For each technology area, we considered: (a) three cost and performance trajectories reflecting alternative levels of technology progress; (b) two perspectives on technology breakthrough (e.g., breakthrough for a single technology versus a universal breakthrough across all studied technologies); and (c) two levels of carbon policy ambition in the United States. Each of the possible technology and carbon policy dimensions is simulated in our energy system modeling toolkit, which allows for a holistic consideration of all technologies that affect decarbonizing the energy system. Outputs from each simulation include technology deployment over time and energy-related CO_2 emissions. These results allow us to compare the competitiveness and complementarity of individual technologies and sectors of the economy.

Figure 1
Analytical Framework

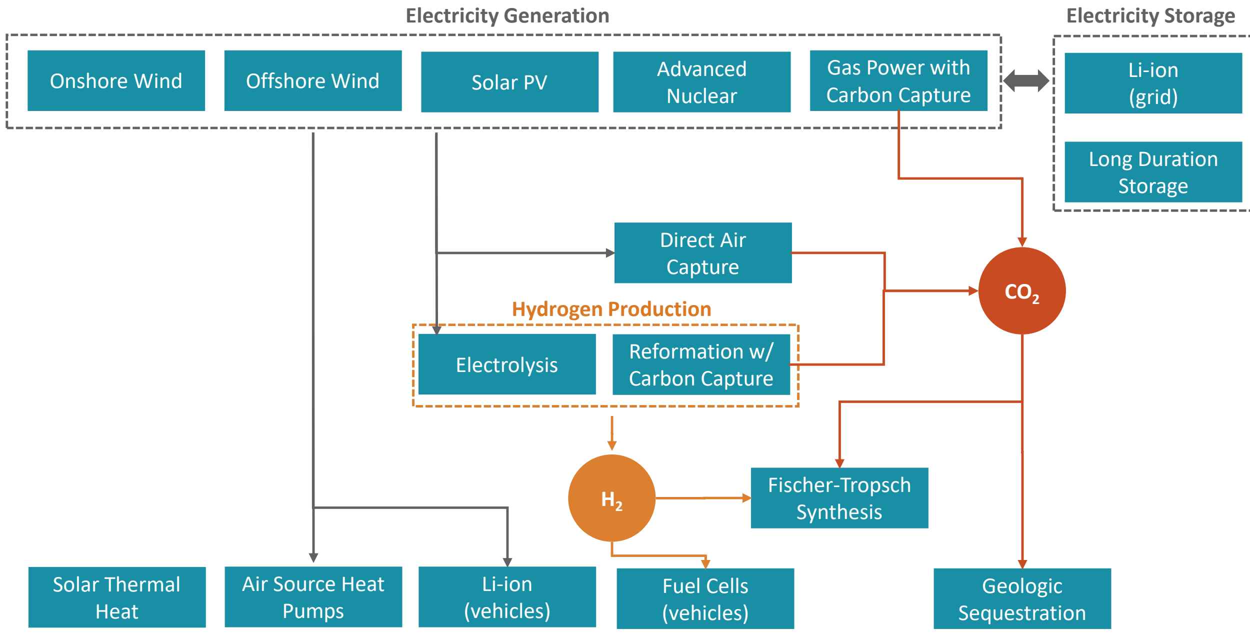


2.2. Technology Areas

We chose fifteen technology areas based on our expert judgment of technologies likely to have a material impact on decarbonization outcomes. However, it is important to note that this is a starting point for our R&D impact framework and is not a comprehensive view of all technology areas that may play important roles in deep decarbonization.

As shown in Figure 2, the selected technology areas encompass the spectrum of a low-carbon energy system, ranging from electricity generation technologies to negative emissions technologies. Many of the technologies interact with one another, where the output from one technology is used as an input in another. For example, electrolysis uses electricity generated by wind and solar technologies to produce hydrogen that can be used directly in a fuel cell or as an input into Fischer-Tropsch synthesis (e.g., power-to-liquids). This dynamic is important when considering one or multiple breakthroughs across the considered technologies.

Figure 2
Technology Areas in a Low-Carbon Energy System



Note: figure does not show all possible technologies or interactions in an energy system.

Table 1 summarizes the technology areas and our implementation method in the analysis, which typically involved adjustments to projected capital cost and efficiencies. Our selection of technology areas considered: (1) the origin of current energy CO_2 emissions; and (2) areas of synergy where breakthroughs in one industry could accelerate the transformation of other sectors. We consider this list to be representative of many of the high priority R&D funding opportunities in energy, but it is not exhaustive. Focus was placed on energy supply and conversion pathways since those tend to result in systemic energy system impacts that our modeling approach was uniquely suited to capture. Notable areas for R&D that were not explored include end-use efficiency, demand response, industrial process changes, electric boilers, bio-energy, advanced geothermal, alternative construction materials, non-CO_2

emissions, and institutional changes that may unlock energy system change (e.g., new business models, financing structures, or market devices).[2]

Table 1
Technology Areas and Implementation

Technology Area	Sector(s)	Implementation Description
Residential Air-Source Heat Pumps	Buildings	Cost and performance of residential air-source heat pumps to provide space heating
Onshore Wind	Electricity	Cost and performance of onshore wind power plants
Offshore Wind	Electricity	Cost and performance of offshore wind power plants
Solar PV	Electricity	Cost of solar PV power plants
Advanced Nuclear	Electricity	Cost of new nuclear power plants
Long-Duration Storage	Electricity	Cost of new long-duration electricity storage with discharge durations greater than 50 hours
Gas Power Plants with CCUS	Electricity	Cost and performance (capture rate and efficiency) of gas power plants with carbon capture
Li-ion	Electricity Transportation	Cost of new Li-ion batteries for mobile and stationary applications
Fuel Cells	Transportation	Cost of fuel cells for mobile applications
Hydrogen Electrolysis	Fuels Carbon Management	Cost and performance (efficiency) of hydrogen electrolysis
Fischer-Tropsch Synthesis	Fuels Carbon Management	Cost of new Fischer-Tropsch (FT) facilities to synthesize liquid fuels from syngas ($CO + H_2$)
Gas Reformation with CCUS	Fuels Carbon Management	Cost and performance (efficiency and capture rate) of natural gas hydrogen production with carbon capture
Geologic Sequestration	Fuels Carbon Management	Cost and availability of annual geologic CO_2 sequestration
Direct Air Capture	Fuels Carbon Management	Cost and performance of direct air capture (DAC) of CO_2
Industrial Solar Thermal Heat	Industry	Cost of solar thermal industrial heat production to replace natural gas process heat and boilers in steam production

[2] Many of these were included in the energy system modeling, but their cost and performance were not varied.

2.3. Technology and Carbon Policy Trajectories

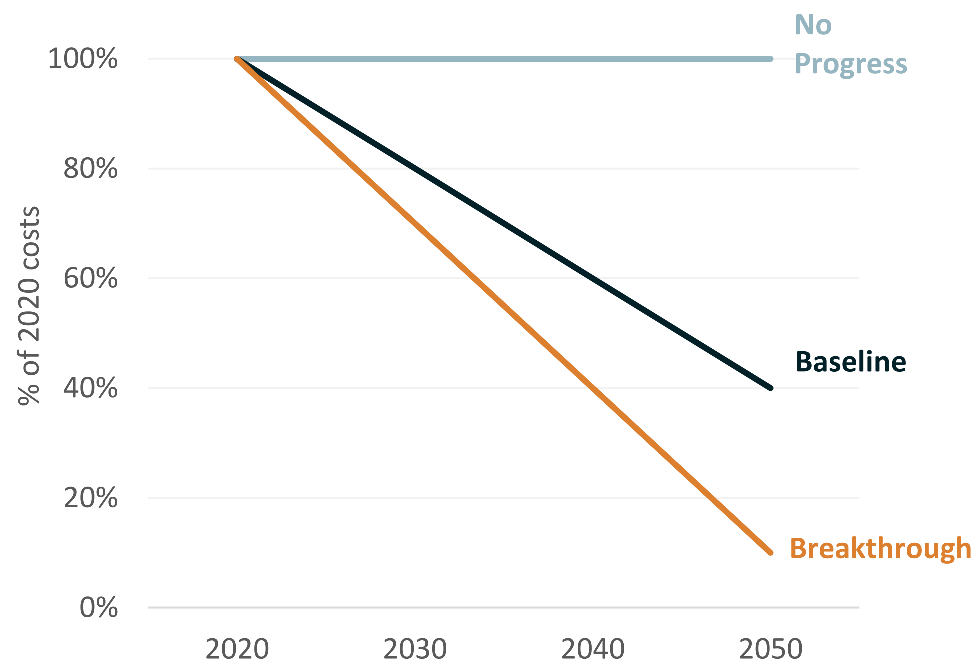
2.3.1. Technology trajectories

We modeled three trajectories for all technology areas under investigation:

1. **Baseline**: represents a likely scenario based on sustained R&D funding and deployment;
2. **No Progress**: represents a "worst case" where continued technology development is not prioritized and we see no technology progress from today; and
3. **Breakthrough**: represents a future where R&D funding is accelerated, and technology progress accelerates towards optimitic cost and performance estimates

Figure 3 illustrates potential capital cost trajectories for a low-carbon energy technology through 2050. The trajectories assumed in this study are intended to be illustrative and represent plausible sensitivity ranges for technology cost and performance. Ultimately, the cost and performance in these areas will be determined by some combination of R&D funding, early-stage deployment support and sustained policy support both domestically and internationally. Nevertheless, accelerated R&D investment makes achieving performance along the Breakthrough trajectories significantly more likely and this analysis provides insight into the value that breakthroughs might ultimately provide to the challenge of rapid energy system decarbonization.

Figure 3
Illustrative Technology Cost Trajectory



Cost and performance trajectories were informed by a literature review of publicly available studies, as summarized in Table 2. Projections are primarily derived from academic studies or national energy laboratory reports, and our application of the trajectories is explained further in Section 3. For the *No Progress* trajectory, most technology areas assume no improvements (i.e., cost and performance in 2050 is the same as today). For a select group of nascent technology areas, we assume commercialization is not realized. This includes: (a) gas power plants with carbon capture; (b) long-duration storage; (c) gas reformation with carbon capture; and (d) direct air capture.

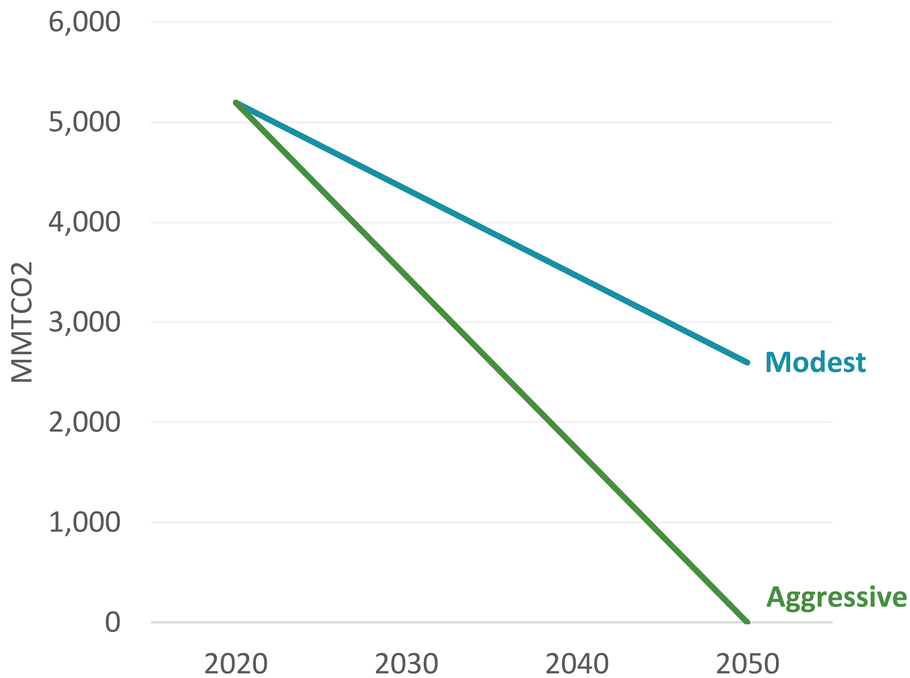
Table 2
Sources Used for Cost and Performance Trajectories

Technology Area	Source
Residential Air-Source Heat Pumps	Jadun et al. (2017)
Onshore Wind	NREL (2019)
Offshore Wind	NREL (2019)
Solar PV	NREL (2019)
Advanced Nuclear	EON (2018)
Long-Duration Storage	Form Energy (2020)
Gas Power Plants with CCUS	IEA (2015)
Li-ion	Cole and Frazier (2019)
Fuel Cells	ICCT (2017): present-day costs Whiston et al. (2019): cost projections
Hydrogen Electrolysis	IRENA (2019): Baseline trajectory BNEF (2019): Breakthrough trajectory
Fischer-Tropsch Synthesis	Agora (2018)
Gas Reformation with CCUS	IEA (2019): Baseline HyNet (2019): Breakthrough trajectories
Geologic Sequestration	NETL (2017)
Direct Air Capture	Larsen et al. (2019)
Industrial Solar Thermal Heat	IRENA (2015)

2.3.2. Carbon policy trajectories

Figure 4 shows the two carbon policy environments considered in this study that are implemented with emissions caps for U.S. energy and industry CO_2 emissions. Non-CO_2 GHG emissions and the land CO_2 sink are not considered in the analysis. Modest policy ambition assumes emissions are one-half of today's levels by 2050, while Aggressive policy ambition assumes net-zero emissions by 2050.

Figure 4
U.S. Energy and Industrial CO_2 Emissions Caps



2.4. Energy System Modeling

2.4.1. Paired Modeling Approach

We use two models developed by EER to simulate the U.S. energy system, as described in Table 3. Both models have been used extensively to evaluate low-carbon energy systems at the national and sub-national level. For the purposes of this study, **EnergyPATHWAYS (EP)** is used to simulate user-defined energy system decisions that are not the focus of this study's technology areas. However, these decisions are necessary to achieve the study's ambitious policy targets at reasonable cost. Examples include commercial water heating electrification and aviation efficiency improvements.

In contrast, the **Regional Investment and Operations (RIO**) platform operates by finding the set of energy system decisions that are least cost. This includes detailed capacity expansion functionality for the electricity, fuels, carbon management, and industrial heat sectors of the economy. Consumer decisions are optimized for vehicle choice in light-duty autos, light-duty trucks, medium-duty vehicles, heavy-duty vehicles (short and long-haul), and space heating. These consumer decisions incorporate customer payback curves and therefore reflect plausible customer constraints on adoption of demand-side technologies.

Table 3
Models Used to Evaluate Technology Areas

	Description	Use in this Study
EP	• Bottom-up energy sector planning tool • Represents all producing, converting, storing, delivering and consuming energy infrastructure • Energy system decisions are scenario-based and not a result of an optimization	• Simulate energy system decisions that are not the focus of R&D efforts • Establishes boundary conditions for optimization within RIO
RIO	• Capacity expansion tool used to produce cost-optimal resource portfolios across the electric and fuels sectors • Simulates hourly electricity operations and annual investment decisions • Energy system decisions are a result of a least-cost optimization	• Optimize the deployment of demand- and supply-side technologies considered in the study's technology areas • Results vary depending on policy ambition and technology trajectories

This paired modeling approach, depicted in Figure 5 below, allows for parameterization of energy sector boundary conditions and allows for economy-wide emissions accounting while isolating many of the key decarbonization approaches of interest in an R&D context. Table 4 shows the broad categorization of the energy system decisions that are: (a) user-defined in EnergyPATHWAYS and used to establish boundary conditions; and (b) selected for optimization in RIO. RIO optimizes build and operations for the fifteen technology areas that are the focus of this study, as well as other supply-side technologies that are not the focus of R&D (e.g., gas-fired combined cycle power plants).

Figure 5
Paired Modeling Approach

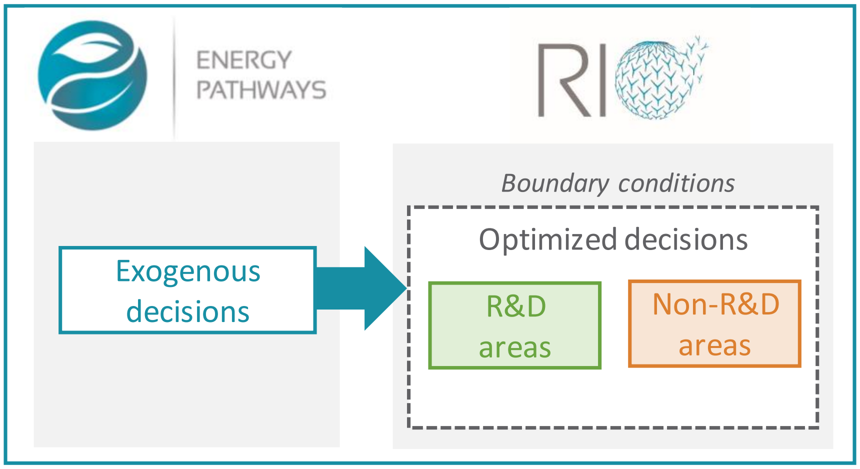
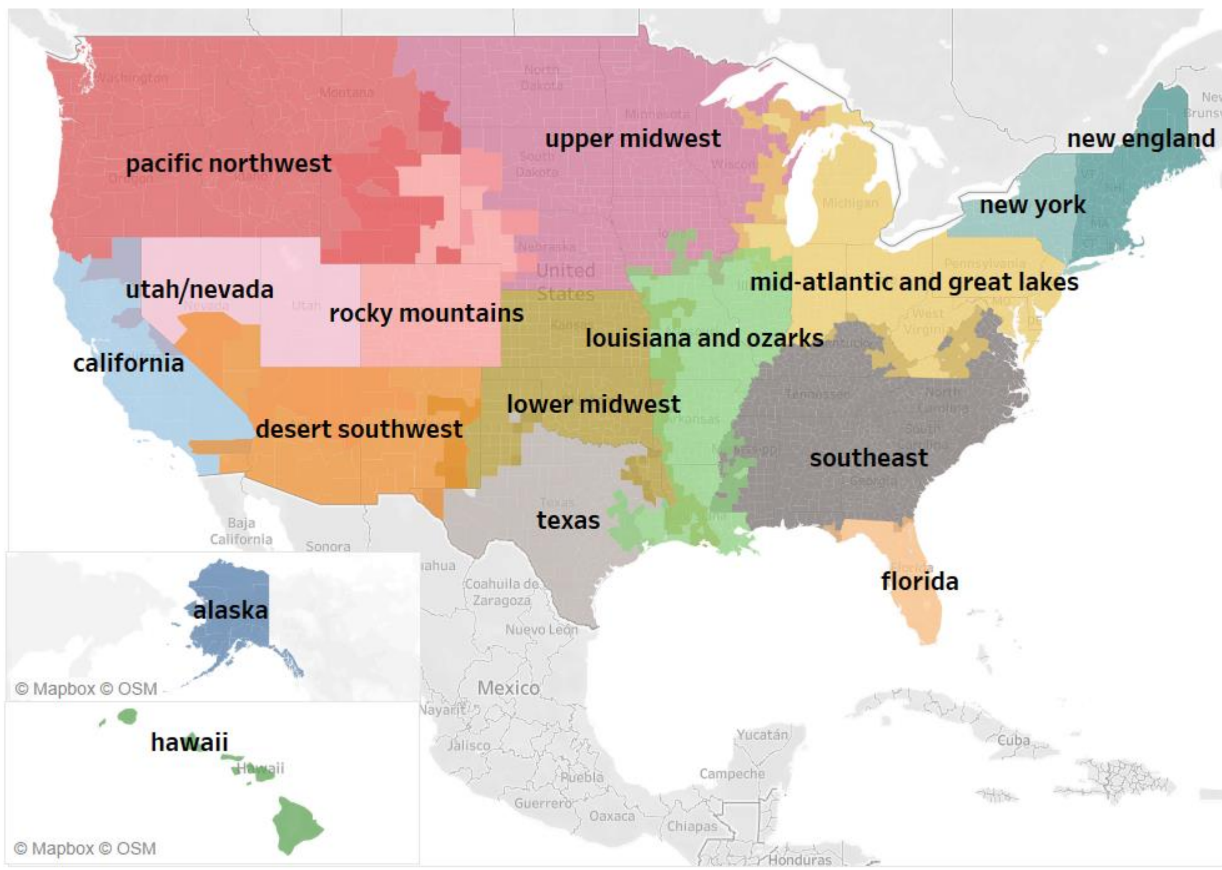


Table 4
Energy System Decisions by Sector

	EP: user-defined	RIO: optimized
Buildings		
Energy Efficiency and Electrification (excl. Space Heating)	✓	✗
Space Heating Electrification	✗	✓
Industry		
Energy Efficiency	✓	✗
Process Electrification	✓	✗
Carbon Capture	✓	✗
Steam Production Electrification	✗	✓
Transportation		
Non-road Efficiency and Fuel Switching	✓	✗
On-road Efficiency, Fuel Switching and Electrification	✗	✓
Supply-side		
Electricity Decarbonization	✗	✓
Fuels Decarbonization	✗	✓
Carbon Management	✗	✓

For the purposes of this study, the U.S. energy system is characterized using a customized geography based on an aggregation of the U.S. Environmental Protection Agency's eGRID geographies, as shown in Figure 6. The aggregation was done for computational purposes to reduce the total number of zones to a manageable number but characterizes important regional differences that affect energy system transformation, including: (a) resource endowments such as renewable resource potential and quality, bioenergy feedstock supply and geologic sequestration availability; (b) climate, which drives space heating electrification impacts; and (c) electric transmission constraints.

Figure 6
Model Regions



2.4.2. Scenario Implementation

To evaluate each technology area, we simulate the U.S. energy system across a wide range of potential technology trajectories for both emissions targets. This study incorporates 32 alternative technology trajectories and 2 emissions targets for a total of 64 model runs. Table 5 summarizes our approach for evaluating technology areas for a single carbon policy (e.g., 32 model runs).

First, we simulate achievement of the emissions target assuming the *Baseline* technology trajectories (run #1). This provides an initial reference point for the cost of achieving emissions through 2050. Next, we perturb our anticipated technology trajectories, simulating individually the *No Progress* (runs 2 through 16) and *Breakthrough* (runs 17 through 31) trajectories. Both trajectories are considered, because technology competitiveness and importance are not necessarily symmetric. Failure to achieve *Baseline* technology performance may be much more impactful than a failure to achieve a *Breakthrough*. In addition, this allows us to assess the impact in terms of emissions reductions for equivalent policy support (determined with run #1). Technology progress and policy ambition are symbiotic, with policy ambition driving technology progress and technology progress allowing for accelerated policy ambition.

Finally, we simulate achievement of the emissions target using the *Breakthrough* technology trajectories for all technologies at once (run #32). This reflects a more comprehensive value of R&D when gains are achieved in all areas simultaneously, and it provides an additional lens on competitiveness and complementarity that may be missed when assessing breakthroughs individually.

The approach described here explores the impact of technology progress on emissions (e.g., breakthroughs may lead to deeper emissions targets than the emissions constraint). An alternative approach could hold emissions constant and focus on the reduced costs enabled by innovation to comply with a specific emissions policy.

Table 5

Scenario Matrix for One Level of Carbon Policy Ambition

	All	Single: No Progress							Single: Breakthrough							All
R&D Area	1	2	3	4	5	..	15	16	17	18	19	20	..	30	31	32
Residential Air-Source Heat Pumps	Baseline	No progress	Baseline	Baseline	Baseline		Baseline	Baseline	Breakthrough	Baseline	Baseline	Baseline		Baseline	Baseline	Breakthrough
Onshore Wind	Baseline	Baseline	No progress	Baseline	Baseline		Baseline	Baseline	Baseline	Breakthrough	Baseline	Baseline		Baseline	Baseline	Breakthrough
Offshore Wind	Baseline	Baseline	Baseline	No progress	Baseline		Baseline	Baseline	Baseline	Baseline	Breakthrough	Baseline		Baseline	Baseline	Breakthrough
Solar PV	Baseline	Baseline	Baseline	Baseline	No progress		Baseline	Baseline	Baseline	Baseline	Baseline	Breakthrough		Baseline	Baseline	Breakthrough
Advanced Nuclear	Baseline	Baseline	Baseline	Baseline	Baseline		Baseline	Baseline	Baseline	Baseline	Baseline	Baseline		Baseline	Baseline	Breakthrough
Long-Duration Storage	Baseline	Baseline	Baseline	Baseline	Baseline		Baseline	Baseline	Baseline	Baseline	Baseline	Baseline		Baseline	Baseline	Breakthrough
Gas Power Plants with CCUS	Baseline	Baseline	Baseline	Baseline	Baseline		Baseline	Baseline	Baseline	Baseline	Baseline	Baseline		Baseline	Baseline	Breakthrough
Li-ion	Baseline	Baseline	Baseline	Baseline	Baseline		Baseline	Baseline	Baseline	Baseline	Baseline	Baseline		Baseline	Baseline	Breakthrough
Fuel Cells	Baseline	Baseline	Baseline	Baseline	Baseline		Baseline	Baseline	Baseline	Baseline	Baseline	Baseline		Baseline	Baseline	Breakthrough
Hydrogen Electrolysis	Baseline	Baseline	Baseline	Baseline	Baseline		Baseline	Baseline	Baseline	Baseline	Baseline	Baseline		Baseline	Baseline	Breakthrough
Fischer-Tropsch Synthesis	Baseline	Baseline	Baseline	Baseline	Baseline		Baseline	Baseline	Baseline	Baseline	Baseline	Baseline		Baseline	Baseline	Breakthrough
Gas Reformation with CCUS	Baseline	Baseline	Baseline	Baseline	Baseline		Baseline	Baseline	Baseline	Baseline	Baseline	Baseline		Baseline	Baseline	Breakthrough
Geologic Sequestration	Baseline	Baseline	Baseline	Baseline	Baseline		Baseline	Baseline	Baseline	Baseline	Baseline	Baseline		Baseline	Baseline	Breakthrough
Direct Air Capture	Baseline	Baseline	Baseline	Baseline	Baseline		No progress	Baseline	Baseline	Baseline	Baseline	Baseline		Breakthrough	Baseline	Breakthrough
Industrial Solar Thermal Heat	Baseline	Baseline	Baseline	Baseline	Baseline		Baseline	No progress	Baseline	Baseline	Baseline	Baseline		Baseline	Breakthrough	Breakthrough

Baseline
No progress
Breakthrough

2.4.3. Key Inputs and Sources

Table 6 summarizes key inputs applied across the modeling and values in 2050 for context.

Table 6

Key Modeling Inputs

Input	Source/Notes	2050 Value
Natural Gas Prices	Annual Energy Outlook 2020 - High Oil & Gas Supply	Henry Hub: $2.54/MMBTU
Oil Prices	Annual Energy Outlook 2020 - High Oil & Gas Supply	Brent Spot Price: $91/Barrel
Biomass Availability	Princeton Net Zero America	1.0 BDT
Annual Sequestration Injection Potential	Princeton Net Zero America	1.9 Gt CO2
Onshore Wind Potential	NREL REEDS (2019); 25% of available technical potential	2.0 TW
Offshore Wind Potential	NREL Reeds (2019); 25% of available technical potential	1.0 TW
Utility-Scale Solar Potential	NREL REEDS (2019); 25% of available technical potential[3]	12.8 TW
Rooftop Solar Potential	NREL Rooftop Solar Photovoltaic Technical Potential in the United States: A Detailed Assessment	1.1 TW

[3] Further constrained to 1% of available land area in every region.

3. Results

In this section, we present the following information for each technology area: (a) an overview of cost and performance assumptions for the *Baseline*, *No Progress* and *Breakthrough* trajectories; (b) deployment over time; and (c) interactions between complementary and competitive technologies. A summary of emissions impacts is provided at the end of the section.

The results in this section should be interpreted as a demonstration of a novel analytical exercise to assess and prioritize R&D, and not as a recommended deep decarbonization pathway for the U.S. Furthermore, there are additional sensitivities not included in the analysis that affect technology area deployment, such as fossil fuel prices, biomass feedstock availability, geologic sequestration injection potential, and assumptions about regional coordination and coupling between the electric power and fuels sectors.

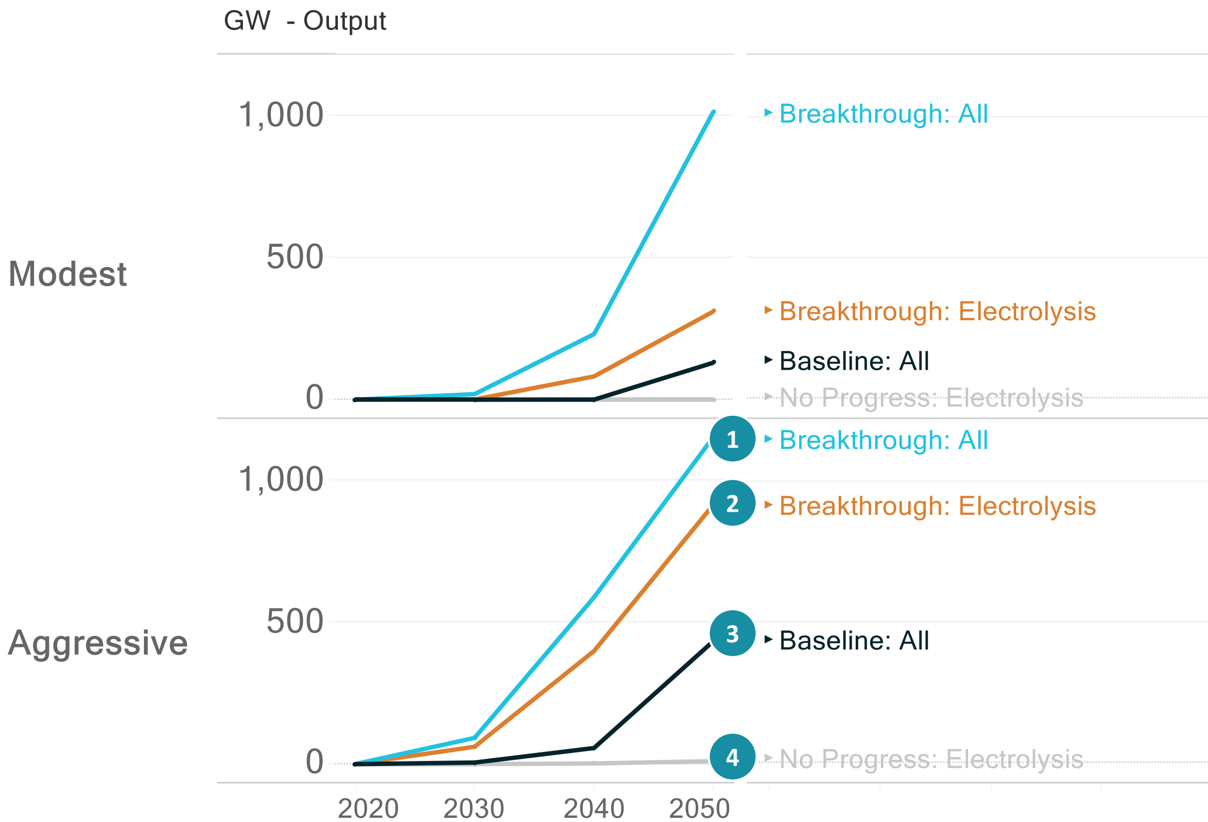
Below we provide a guide to interpreting the deployment and technology interaction figures presented below for each technology area, using electrolysis as the example.

Deployment

Figure 7 depicts electrolysis deployment for each level of policy ambition across four technology trajectories:

1. Breakthrough trajectory for all technologies
2. Breakthrough trajectory for electrolysis only; all other technologies assume Baseline
3. Baseline trajectory for all technologies
4. No Progress trajectory for electrolysis only; all other technologies assume Baseline

Figure 7
Illustrative Electrolysis Deployment



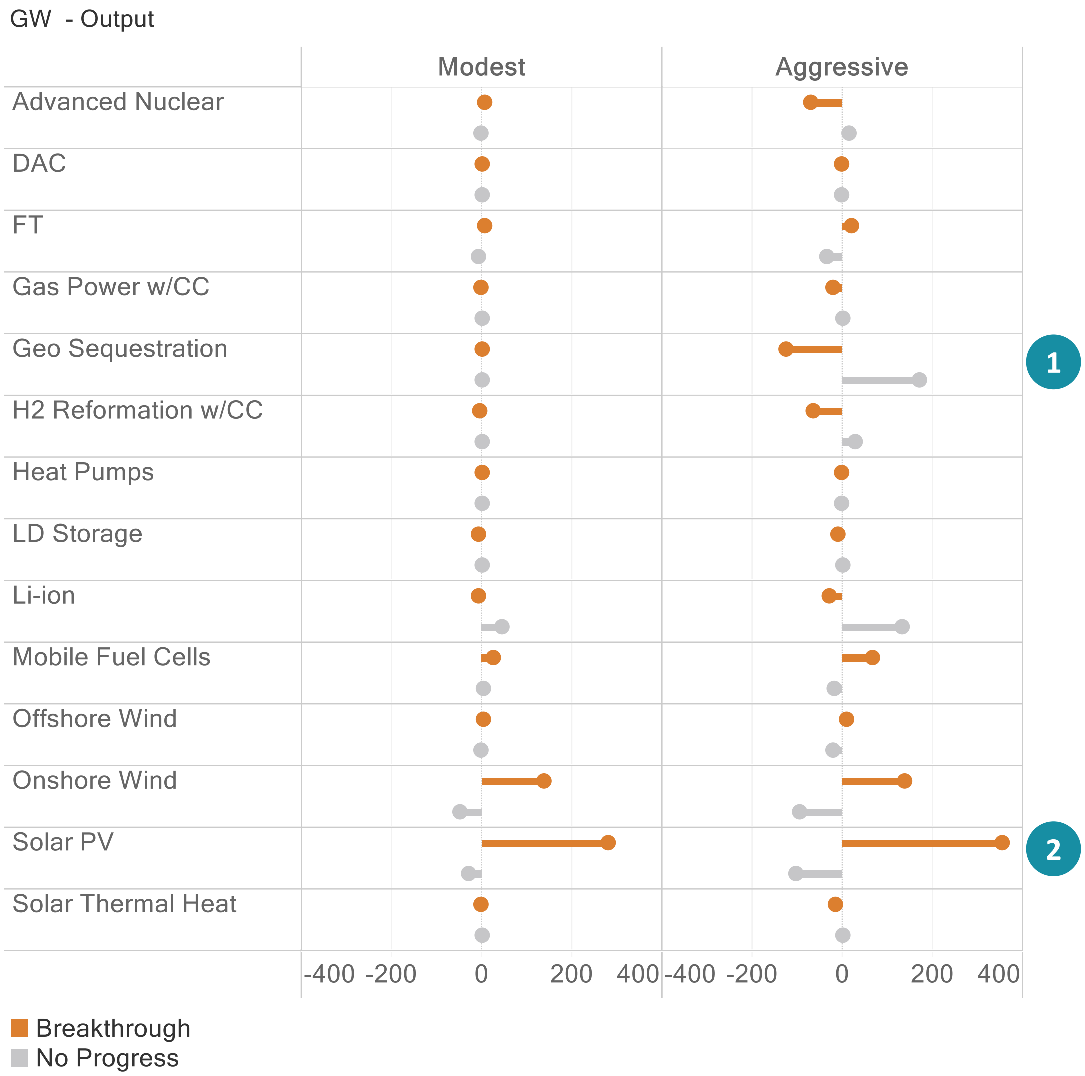
<u>Technology Interactions</u>

The interactions between electrolysis and other technology areas are presented in Figure 8 as the difference in electrolysis deployment in 2050 for each level of policy ambition (Modest and Aggressive) and alternative trajectories (No Progress and Breakthrough) for other technology areas. The difference is measured from the scenario where all technologies realize the Baseline trajectory. Two interactions are highlighted:

1. If geologic sequestration realizes its Breakthrough trajectory, then electrolysis deployment is 125 GW lower. Alternatively, No Progress for geologic sequestration increases electrolysis deployment by 170 GW. Geologic sequestration is a competitor to electrolysis under an Aggressive policy scenario.

2. If solar realizes its Breakthrough trajectory, then electrolysis deployment is 350 GW higher. Alternatively, No Progress for solar reduces electrolysis deployment by 100 GW. Solar and electrolysis have a high level of complementarity.

Figure 8
Illustrative Electrolysis Technology Interactions



3.1. Solar PV

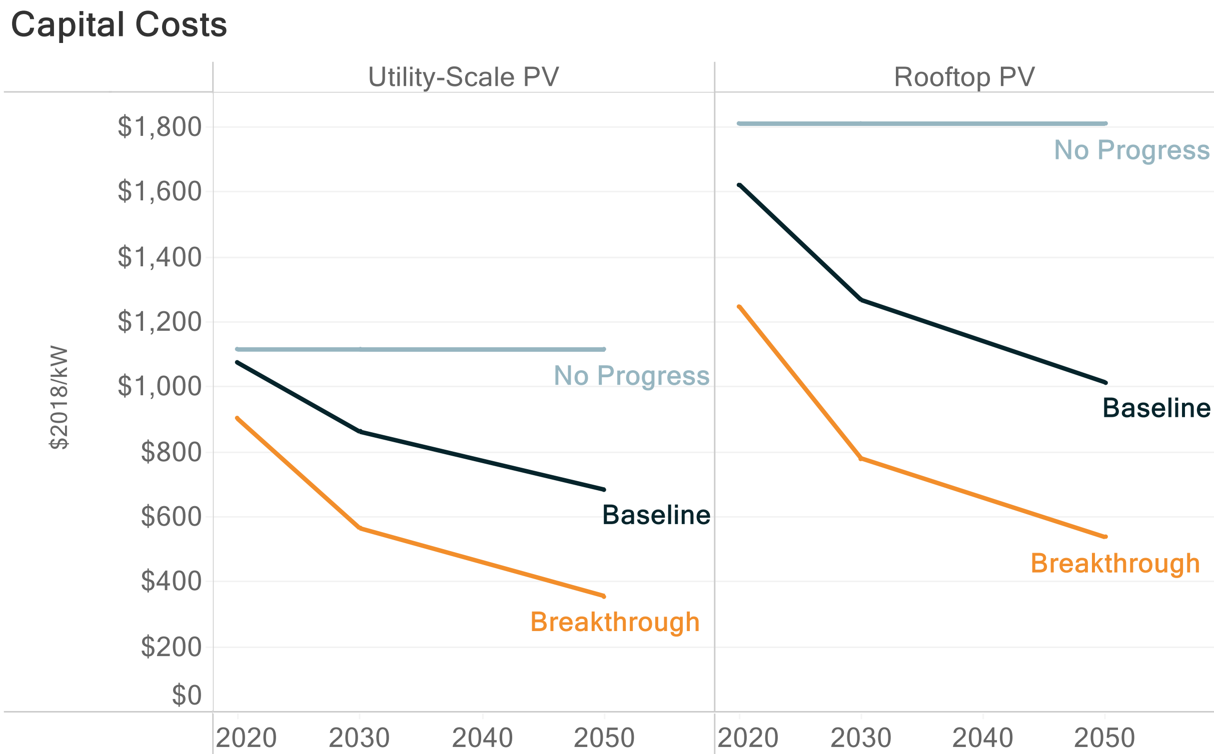
3.1.1. Overview

The U.S. has high-quality solar resources located across the country and has witnessed significant deployment during the past decade for both utility-scale and distributed resources. Historical deployment has been led by state-level renewable policies and falling costs, which in many regions have already reached levels low enough to warrant economic deployment without significant policy support (e.g., Texas).

For this study, we use cost trajectories from NREL's 2019 Annual Technology Baseline (ATB).[4] Technology progress in the Breakthrough case sees rapid reductions in capital costs through 2030 with a more modest decline through 2050. We model these reductions for both utility-scale and rooftop PV. The ultimate adoption of rooftop PV will be moderated by consumer behavior and rates and some of the value, including avoided distribution system costs, are not modeled here. Regardless, we assess its competitiveness against other zero-carbon energy options to understand whether it might be deployed in areas where utility-scale PV potential is constrained.

[4] See NREL (2019).

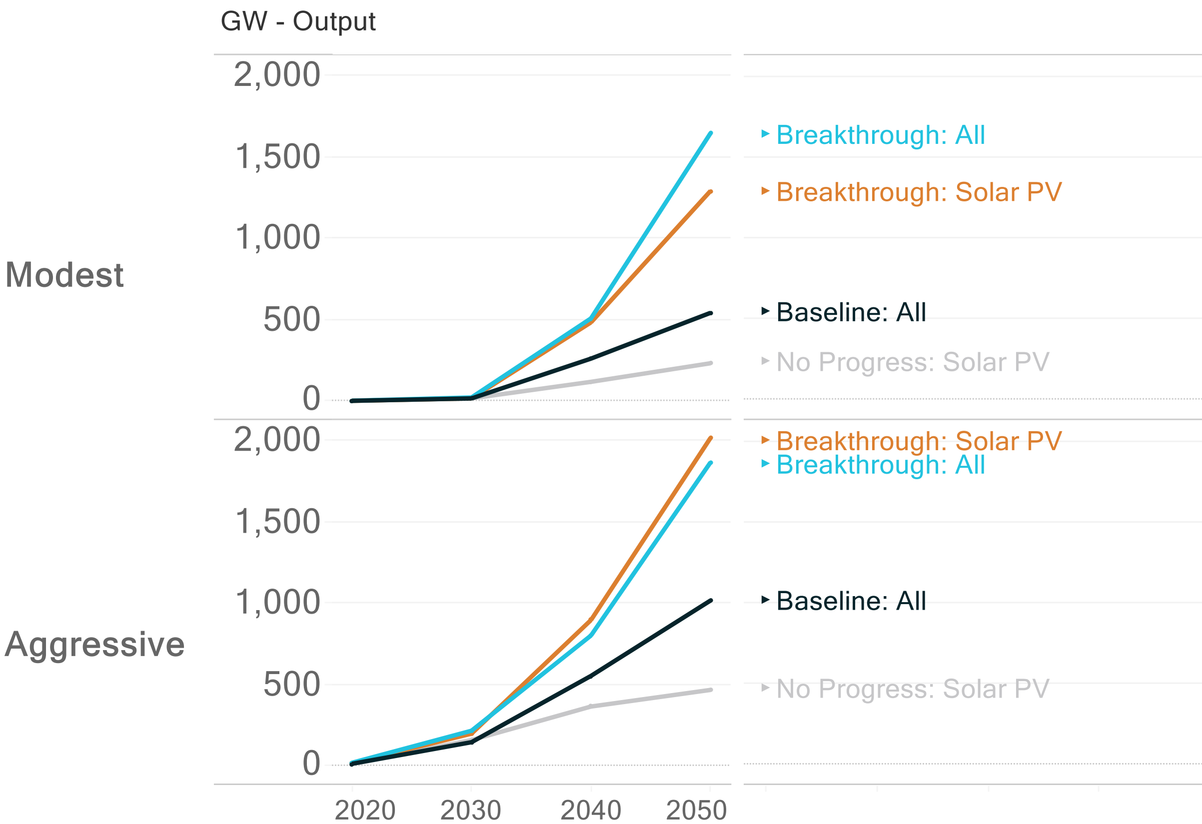
Figure 9
Solar PV Capital Cost Assumptions



3.1.2. Deployment

Solar is naturally constrained by its generation profile, with a relatively modest level of penetration resulting in overgeneration conditions in the middle of the day. We can therefore assess its competitiveness as a technology into two regimes: before overgeneration is reached and afterwards. Before, it is extremely competitive even at today's prices. After the saturation point, costs must continue to decline to overcome lower realized capacity factors due to increasing marginal curtailment, or this energy needs to be low-cost enough such that complementary technologies are deployed in order to access it economically. In the Baseline case, at both levels of policy ambition, we see the deployment of solar PV representing approximately 20% of generation by 2050, but it requires a breakthrough to create a situation where higher levels can be sustained economically. Solar reaches approximately 40% of total generation in 2050 when the technology alone makes a breakthrough with aggressive carbon policy, and this high penetration is realized with significant load growth from electrification.

Figure 10
Solar PV Deployment

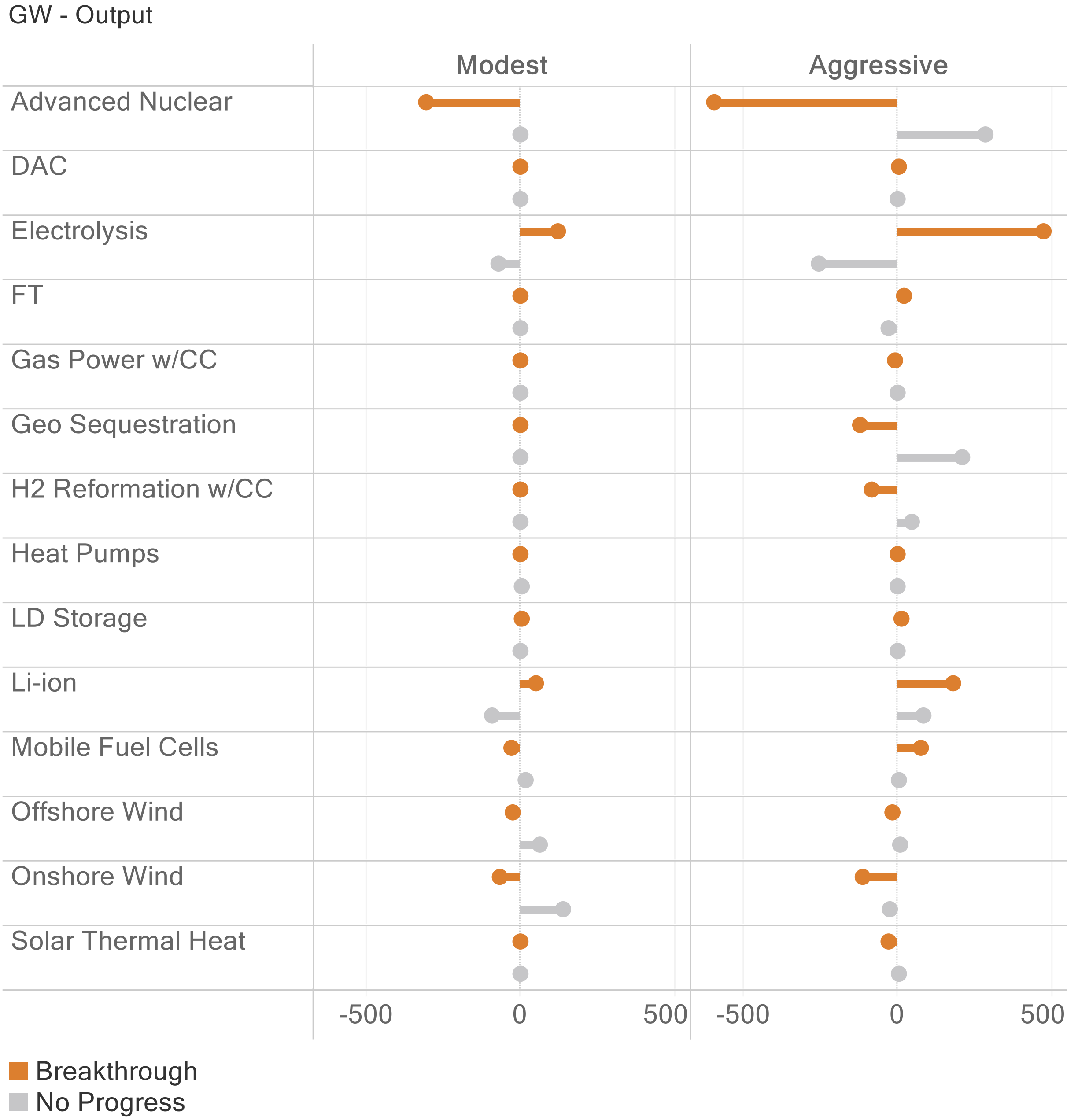


3.1.3. Technology Interactions

Solar's primary technology competitors include other zero-carbon electricity generation sources, such as advanced nuclear and low-quality onshore wind (e.g., plants located in areas with low wind speeds and capacity factors using today's turbines). Any technologies that drive the need for more direct electricity use are complementary with the deployment of solar PV due to the natural limit to the share of this electricity that can be satisfied with solar.

The key complementary technologies for solar are Li-ion batteries and electrolyzers. The complementarity with Li-ion is twofold: (1) vehicle electrification drives additional electricity demand; and (2) Li-ion on the grid allows for management of daily overgeneration conditions. The same dynamics apply to electrolysis as well, with deployment of electrolyzers resulting in more overall consumption of electricity, as well as more flexible demand that can utilize overgeneration in the middle of the day. If geologic sequestration is unable to achieve its Baseline trajectory (e.g., No Progress), then additional solar is deployed to support increased levels of synthetic electric fuel production.

Figure 11
Solar PV Deployment Relative to the Baseline Trajectory



3.2. Onshore Wind

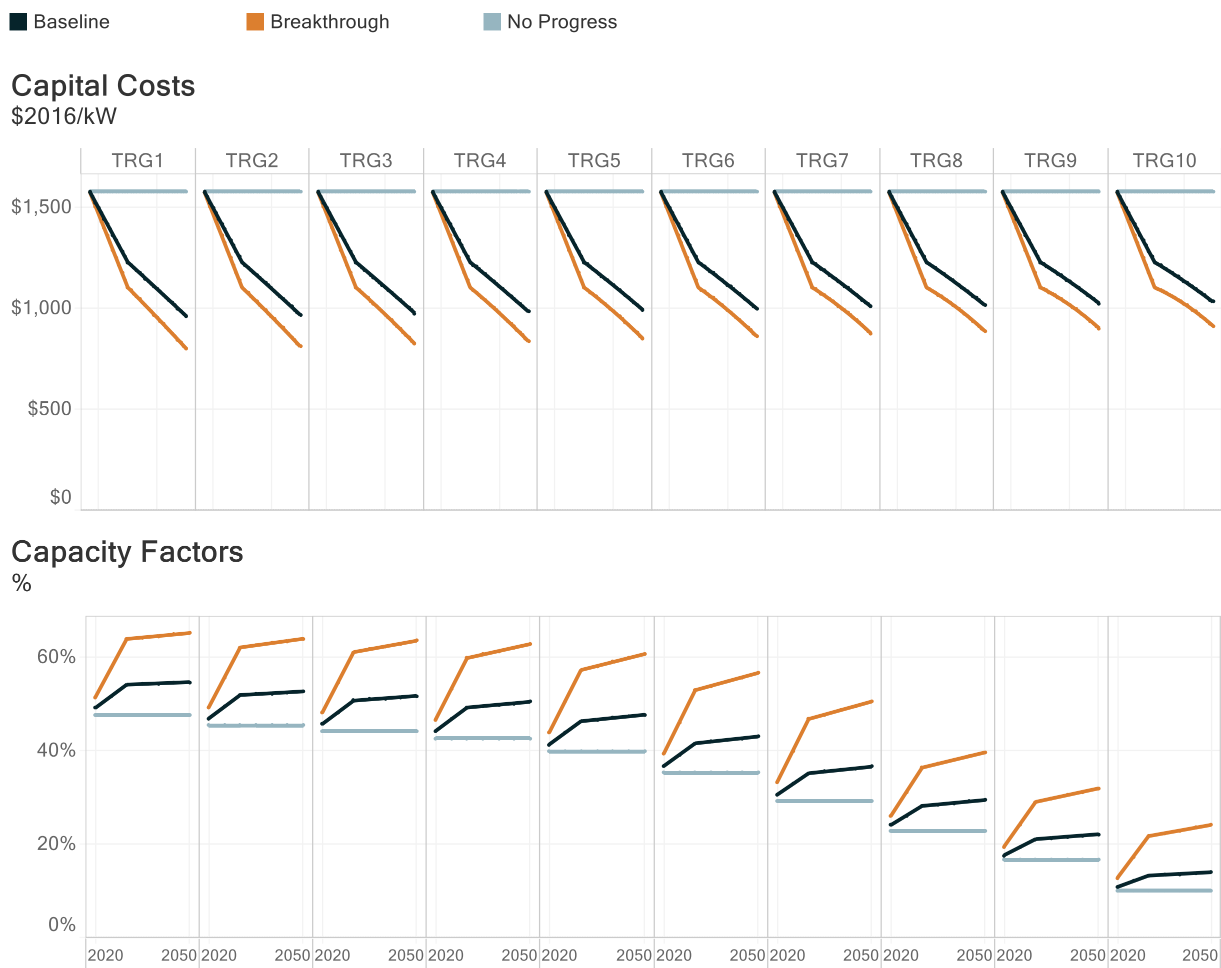
3.2.1. Overview

Onshore wind is a mature technology and already represents more than 7% of the U.S. electricity generation mix. Resource potential is vast, but high-quality potential is concentrated in central states (e.g., Great Plains). Capital costs have continued to decrease during the past decade, while the technology continues to evolve with increased turbine sizes, hub heights and rotor diameter.

To characterize onshore wind cost and performance trajectories, we use projections from NREL's 2019 ATB, as shown in Figure 12.[5] NREL provides alternative projections for 10 techno-resource groups (TRGs), which characterize alternative levels of wind resource quality (e.g., wind speed). TRG1 represents the highest quality wind resources, while TRG10 represents the lowest quality. Technology progress in the Breakthrough case sees some reduction in capital costs, but the principal impact is the improvement in capacity factors, specifically for low-quality wind regimes.

[5] See NREL (2019).

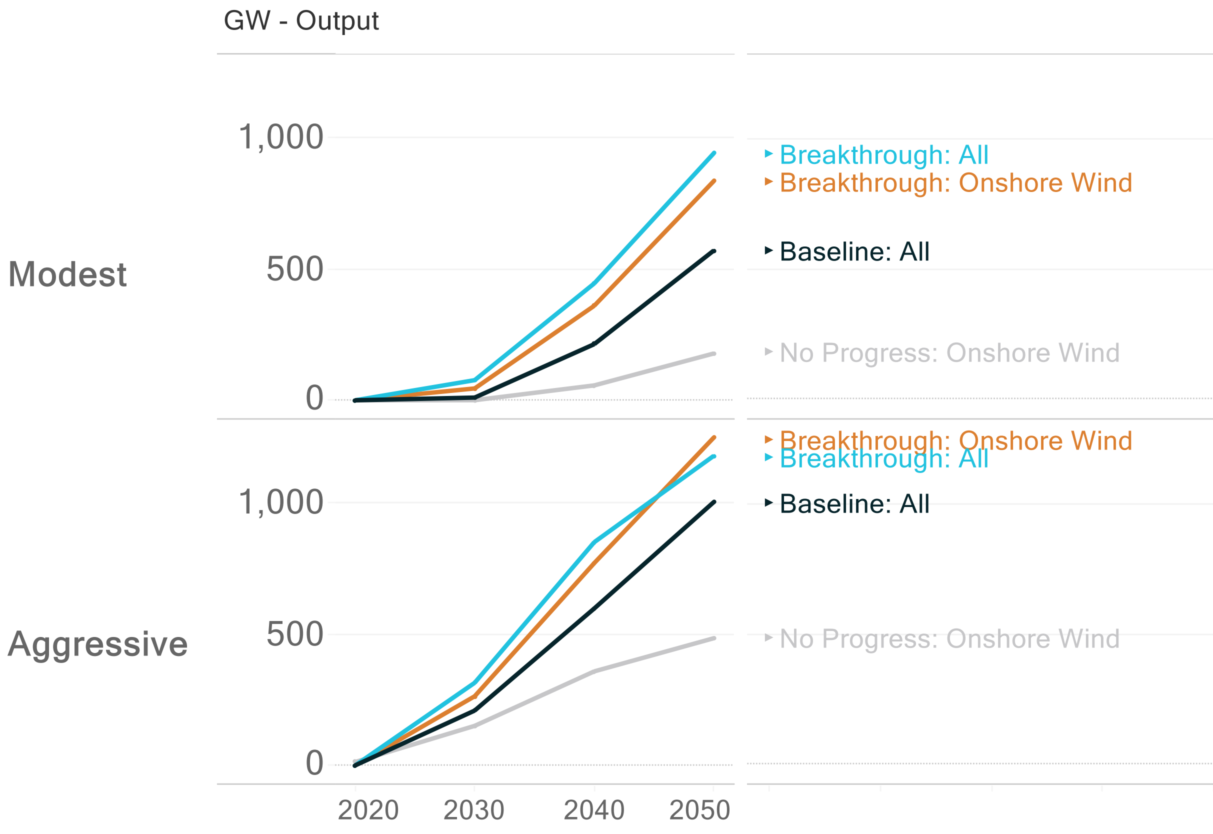
Figure 12
Onshore Wind Capital Cost and Performance Assumptions



3.2.2. Deployment

Onshore wind is a mature technology relative to other technologies considered in this study, with anticipated deployment even with no additional technology progress from today. Under Baseline assumptions of technology progress, it provides more energy than any other low-carbon generation alternative.

Figure 13
Onshore Wind Deployment

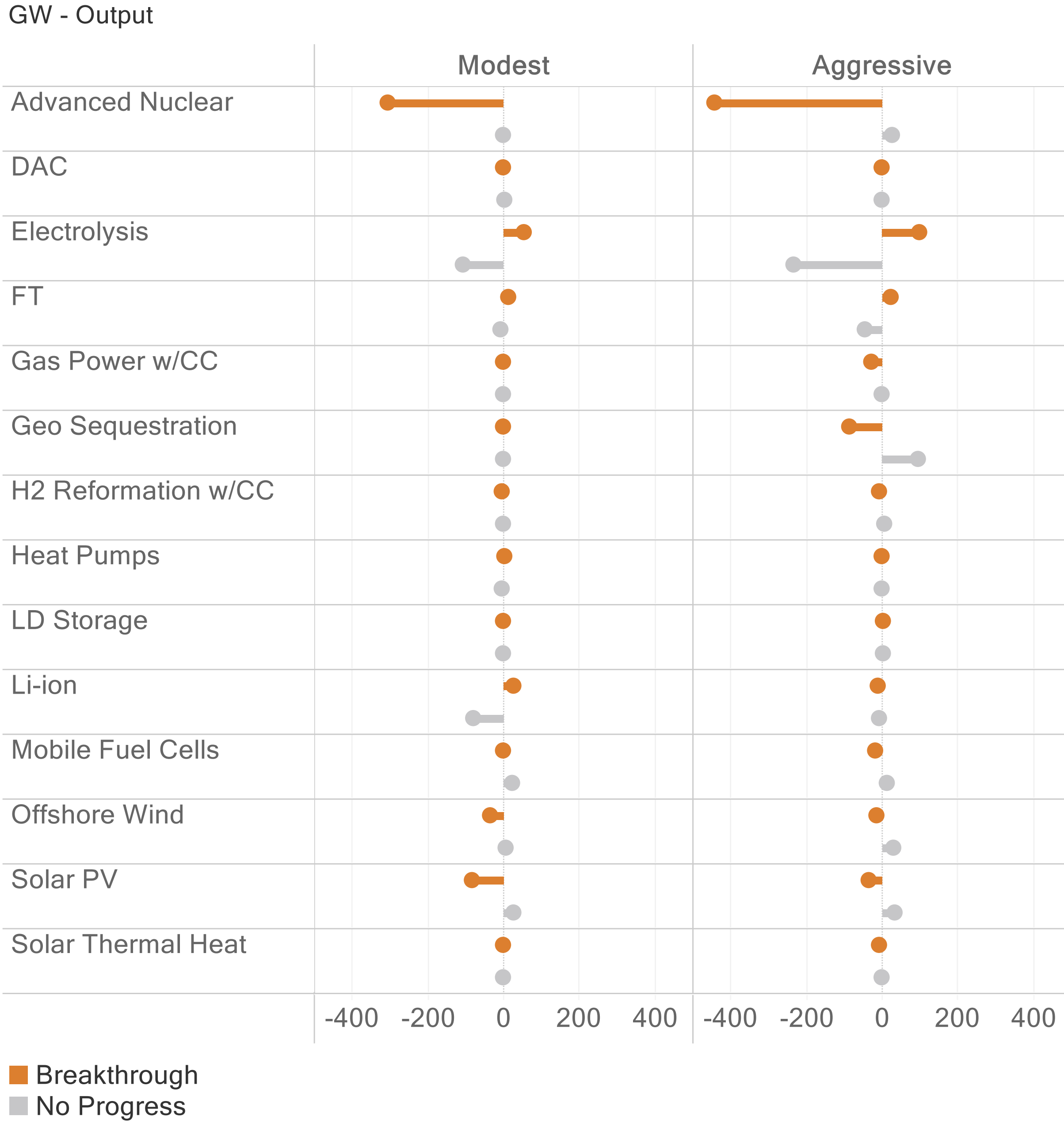


In regions where onshore wind potential is abundant and the resource quality is high (e.g., Great Plains), it is peerless. A breakthrough in onshore wind technology alone ("Breakthrough: Onshore Wind") results in the proliferation in three other areas. First, in regions with lower-quality wind resources or resource availability constraints, technology breakthroughs can make these areas competitive. Wind is likely to face siting constraints that would be alleviated if lower-quality wind regimes were economic. Second, regions with high-quality wind resources are now able to export additional generation with the addition of long-distance transmission (i.e., remote wind with transmission becomes competitive). Third, wind can be deployed as a principal contributor to the production of zero-carbon fuels with electrolysis.

3.2.3. Technology Interactions

Breakthroughs in advanced nuclear compete with marginal onshore wind resources, but high-quality onshore wind is broadly consistent across technology trajectories. Electrolysis is a key complementary technology, with breakthroughs unlocking additional avenues for accessing high-quality wind resources in the Midwest. Breakthroughs in sequestration have the opposite effect, lowering the need for electrolysis as a feedstock for synthetic hydrocarbons and lowering demand for wind.

Figure 14
Onshore Wind Deployment Relative to the Baseline Trajectory



3.3. Offshore Wind

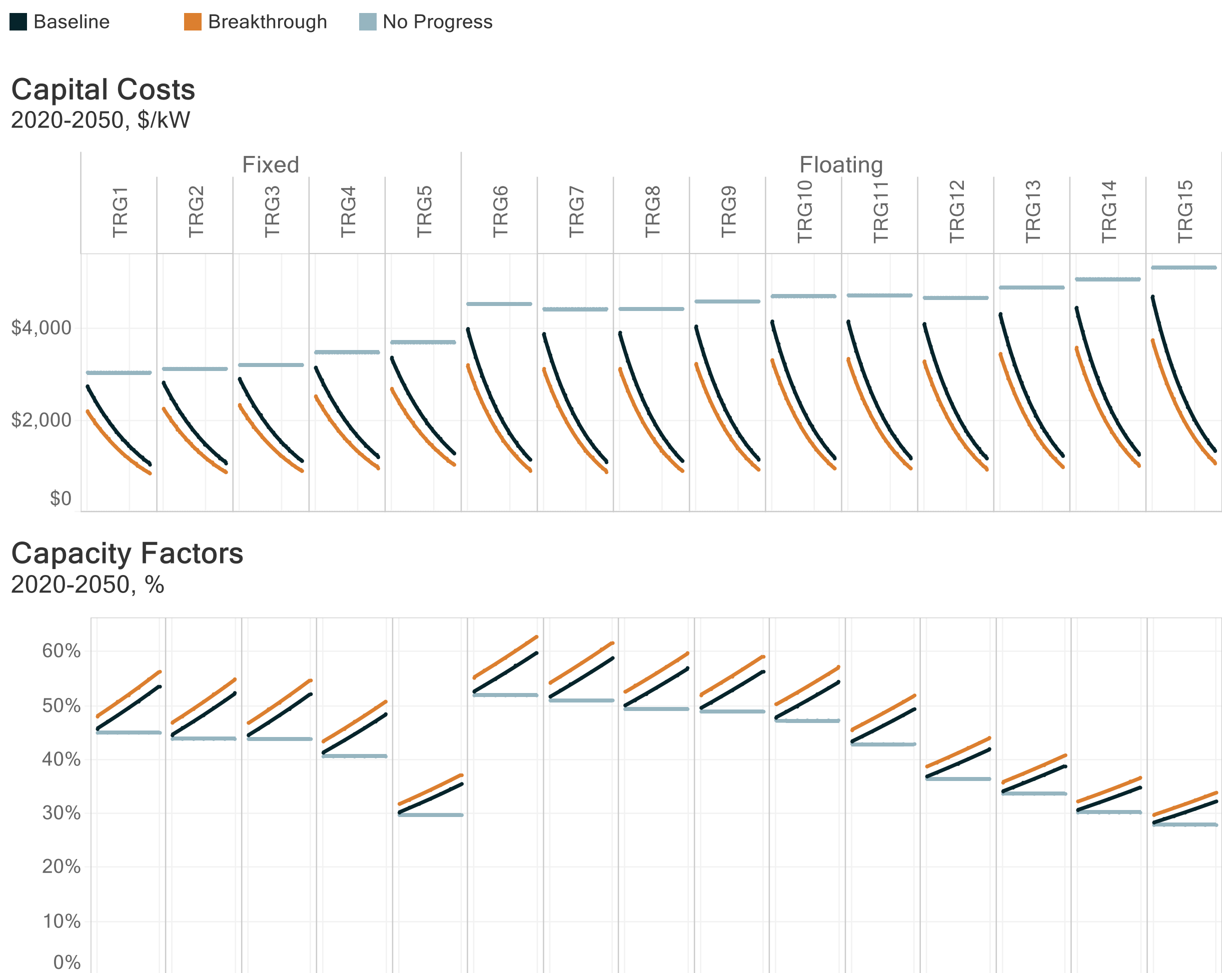
3.3.1. Overview

Offshore wind is a nascent technology in the U.S. with only one commercial plant in Rhode Island (Block Island Wind Farm) and another under construction in Virginia (Coastal Virginia Offshore Wind project). However, there is strong market interest, particularly from states along the Atlantic that lack access to high-quality onshore wind. Many of these states have offshore wind procurement mandates as part of broader clean electricity policies, and sustained deployment is necessary to realize future cost reductions.

To characterize offshore wind cost and performance trajectories, we use projections from NREL's 2019 ATB, which provides alternative projections for 15 TRGs of which five represent fixed-bottom offshore wind technology and ten represent floating offshore wind technology.[6] The Baseline uses NREL's "Mid Technology Cost" scenario, which shows significant early and sustained cost declines. The Breakthrough trajectory uses their "Low Technology Cost" scenario, which anticipates earlier cost reductions and maintains the declining trajectory seen in the Baseline. Capacity factors increase for all resource categories for the Baseline and Breakthrough trajectories.

[6] See NREL (2019).

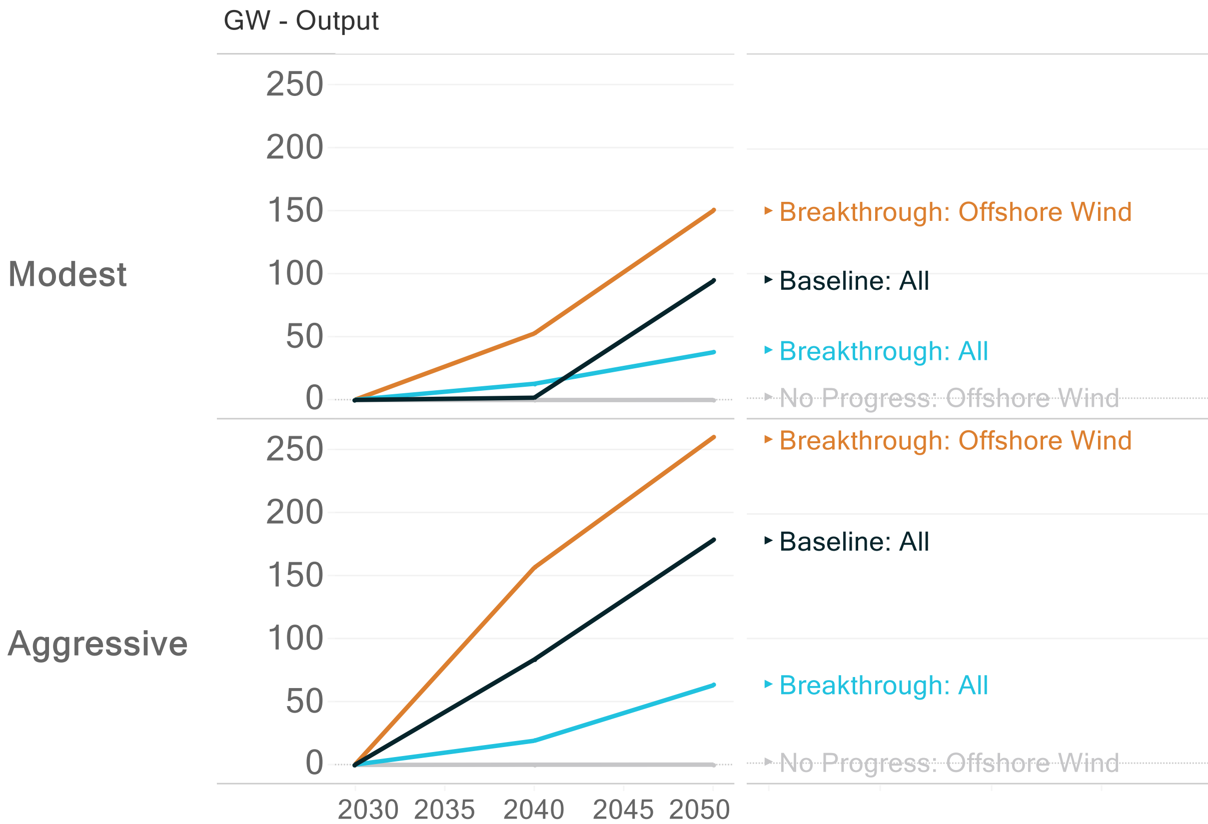
Figure 15
Offshore Wind Capital Cost and Performance Assumptions



3.3.2. Deployment

Offshore wind is deployed at scale under Baseline technology progress due to its key role as a low-carbon resource in coastal regions with limited availability of onshore wind (e.g., Florida and New England).. A breakthrough in offshore wind technology alone expands the map for deployment, with lower quality resources becoming economically viable in the Southeast, the Great Lakes, as well as in California and the Pacific Northwest. Deployment falls substantially relatively to Baseline levels when all technology areas realize a breakthrough due to competition from advanced nuclear and remote onshore wind enabled via new inter-regional transmission.

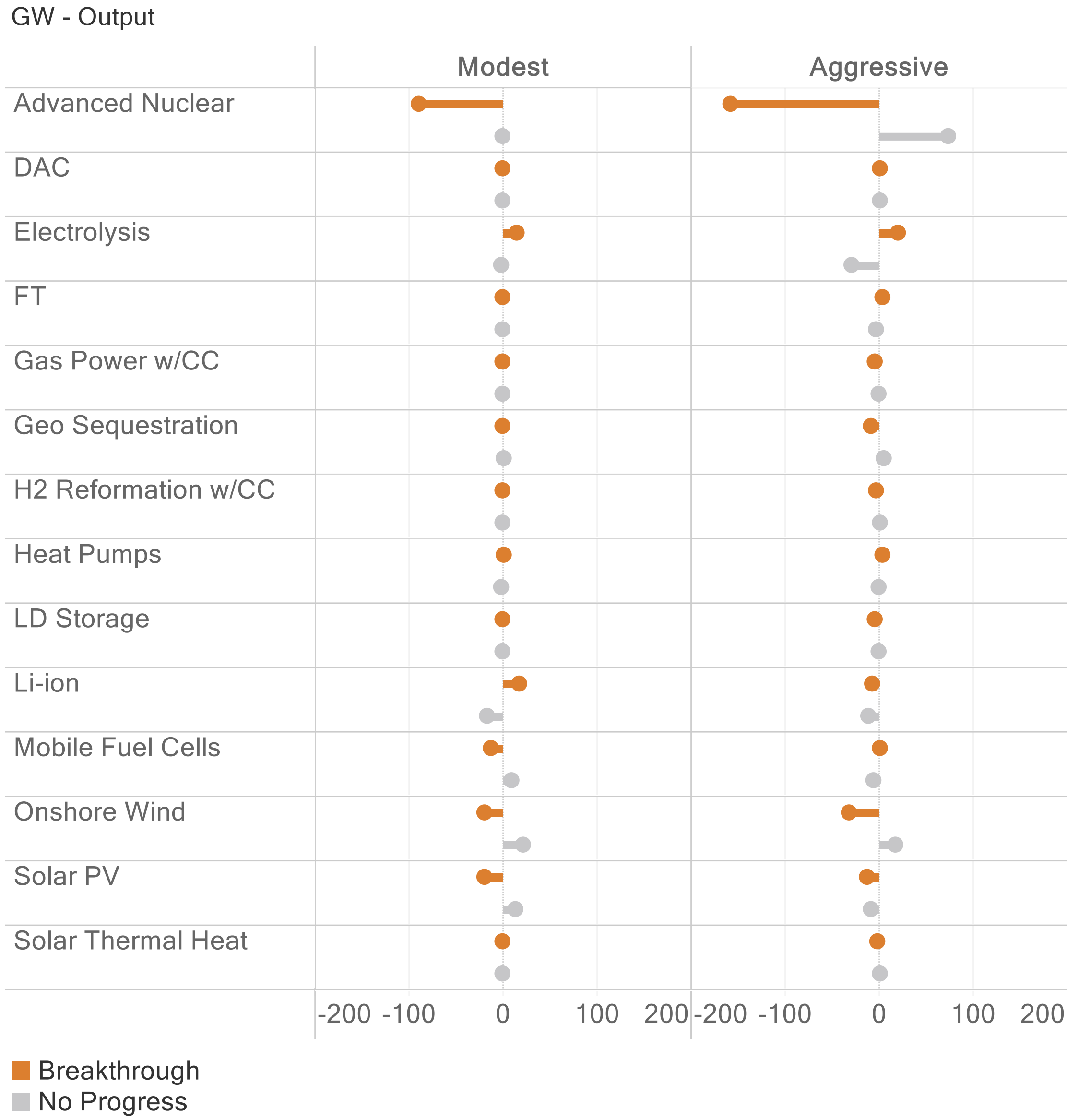
Figure 16
Offshore Wind Deployment



3.3.3. Technology Interactions

The competitiveness with other zero-carbon generation resources is shown in Figure 17. Advanced nuclear is the primary competitor to supply zero-carbon energy in regions that would otherwise deploy offshore wind. Solar and onshore wind are competitive to a lesser extent, with offshore competing against lower quality resources or resources with higher associated transmission costs.

Figure 17
Offshore Wind Deployment Relative to the Baseline Trajectory

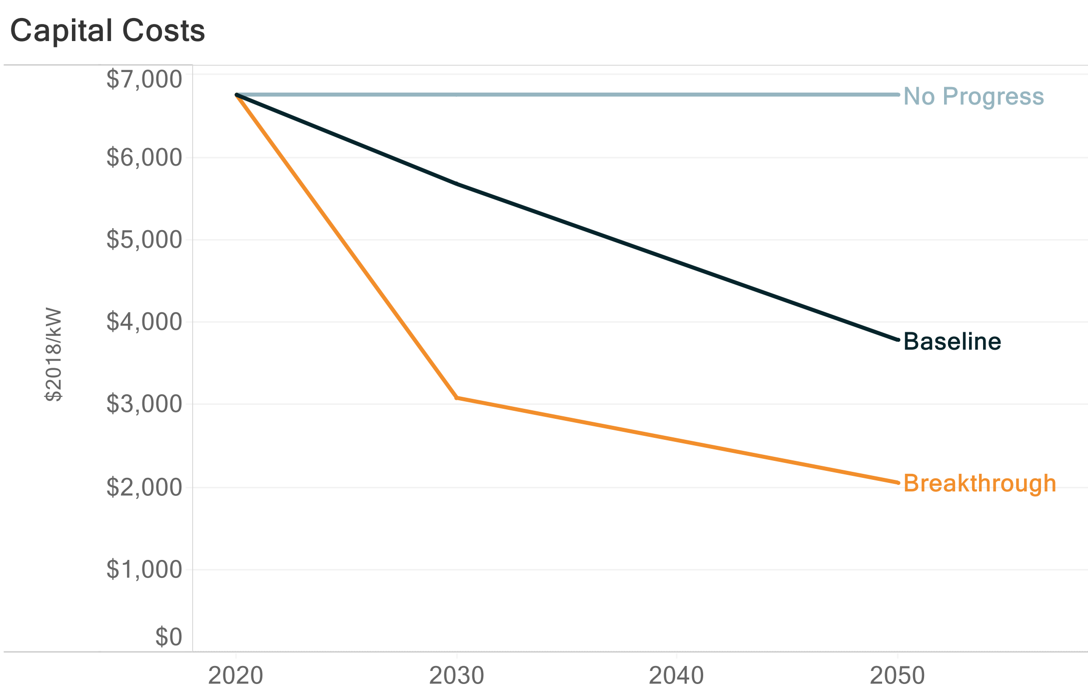


3.4. Advanced Nuclear

3.4.1. Overview

Advanced nuclear technologies include a range of reactor types and plant capacities. These differ from conventional nuclear reactors and are expected to incorporate advantages such as modularization. We derive projections of advanced nuclear capital costs from Energy Options Network's (EON) survey of multiple advanced reactor companies, which developed cost data for advanced nuclear plants with a standardized process.[7] Our Baseline capital cost in 2050 represents the average cost target, while our Breakthrough cost represents the minimum cost target.

Figure 18
Advanced Nuclear Capital Cost Assumptions



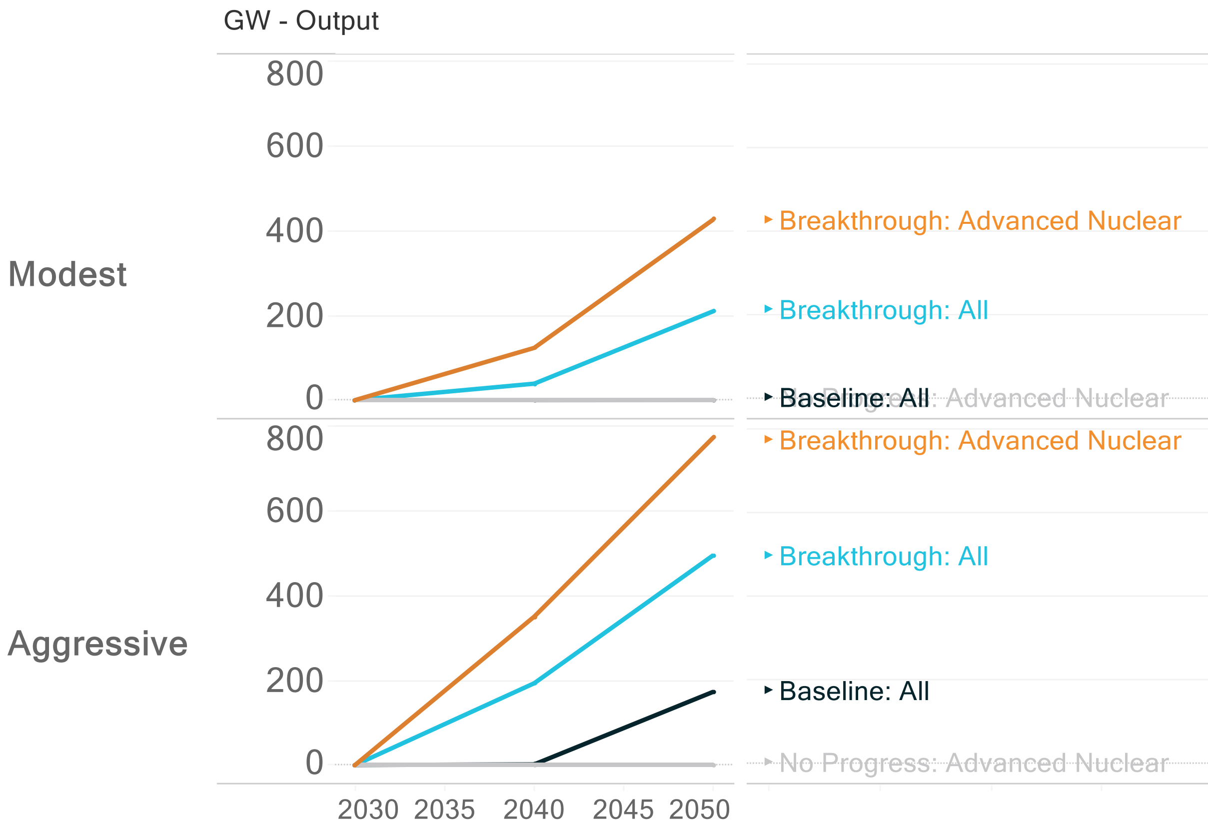
[7] See EON (2018).

3.4.2. Deployment

Baseline assumptions for all technologies yields 0 GW of new nuclear at a Modest policy ambition and 170 GW with an Aggressive level of policy ambition. When nuclear experiences breakthroughs not seen by other technologies, deployment increases to 430 GW in the Modest policy ambition case and 780 GW in the Aggressive policy ambition case. Either of these results would obviously represent a nuclear renaissance compared to current levels of nuclear power in the U.S. (~100 GW). In cases where all technologies experience breakthroughs (Breakthrough: All) deployment decreases due to the increased competitiveness of alternative low-carbon generation sources. This level of deployment would need not only need best-case technological cost declines but mass production of such a technology to scale at this speed, standardization of installation so that development timelines could be shortened, and increased confidence in the safety of reactors and societal acceptance of nuclear power more generally. In short, the challenges are immense and may not be surmountable in the timeline suggested by this analysis, but the opportunity exists for significant nuclear deployment even with continued reduction in the costs of renewables. Whether these cost trajectories are realistic is the subject of significant debate and this analysis takes no position on that question.

Failure to achieve the Baseline technology trajectory (e.g., No Progress) results in no new nuclear even with Aggressive policy. New nuclear demonstrates a wider range of deployment outcomes relative to renewable technologies due to higher cost uncertainty. Advanced nuclear deployment is highly regional, with competitiveness primarily in areas with limited high-quality onshore or offshore wind resources.

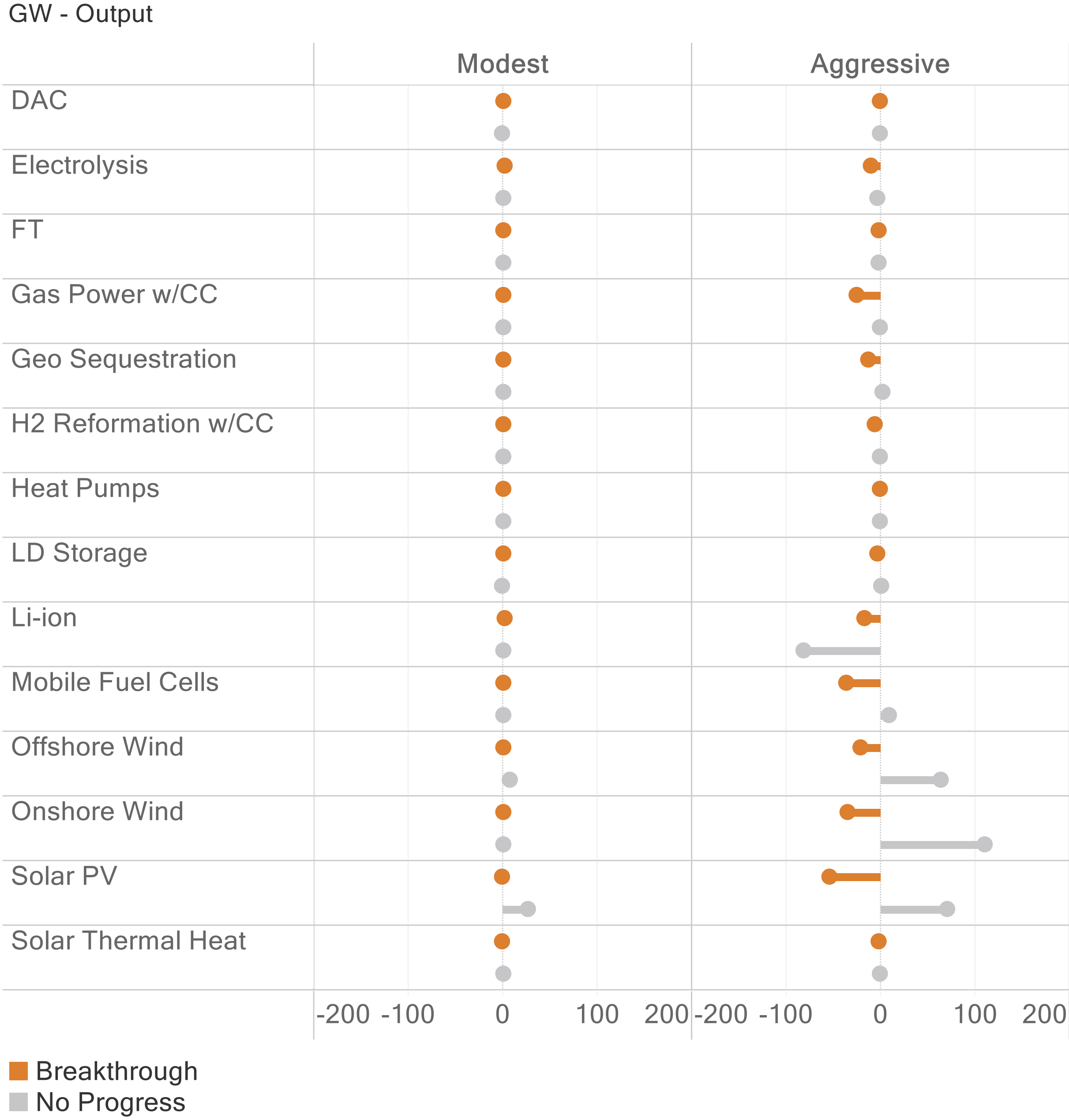
Figure 19
Advanced Nuclear Deployment



3.4.3. Technology Interactions

Figure 20 summarizes advanced nuclear's competitiveness with other technologies, which is primarily confined to technologies in the electric sector. Deployment increases significantly when renewable technologies do not realize progress. Specifically, nuclear's highest level of deployment is realized when wind technologies do not achieve their Baseline trajectory. Solar PV breakthroughs reduce the deployment of nuclear because solar as a resource is ubiquitous and if the cost of energy is low enough it can compete for a large portion of nuclear's market share even with the complementary technologies like storage that are necessary to deploy it at significant shares of available generation.

Figure 20
Advanced Nuclear Deployment Relative to the Baseline Trajectory

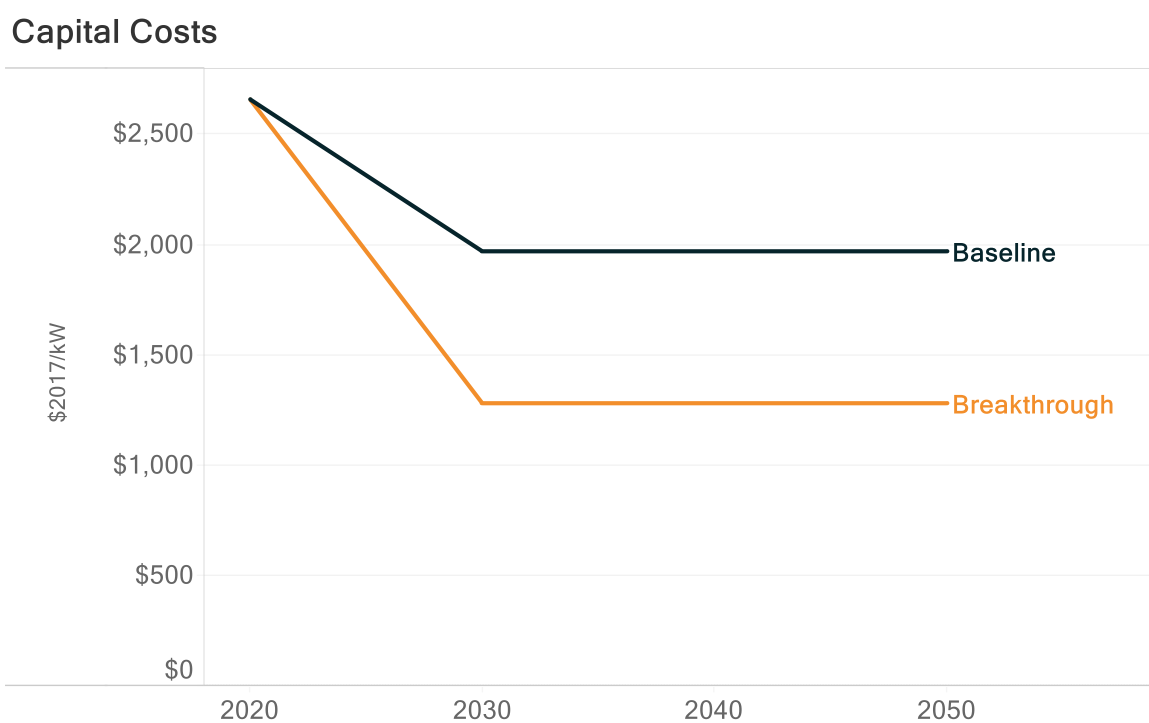


3.5. Gas Power with Carbon Capture

3.5.1. Overview

Gas-fired power plants with carbon capture represent an option to mitigate electric power sector emissions. For this analysis we model a NET Power (oxyfuel) power plant and use an IEA technical report on future cost and performance to derive trajectories for this analysis.[8] The Baseline trajectory uses the IEA's projections, while the Breakthrough trajectory assumes capital costs are 35% lower. We assume a 90% capture rate for the Baseline and a 100% capture rate with a technology breakthrough.

Figure 21
Gas Power with Carbon Capture Capital Cost Assumptions

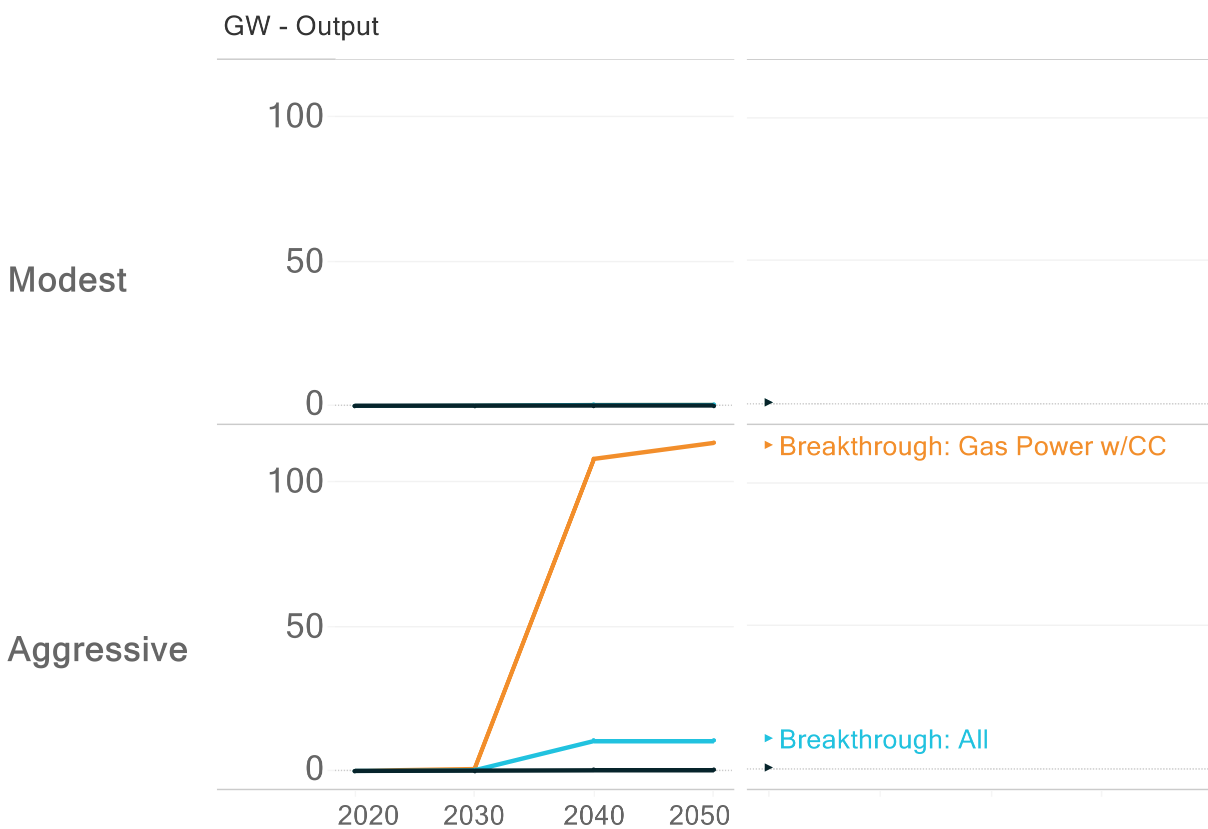


[8] See IEA (2015).

3.5.2. Deployment

Gas-fired power plants with carbon capture play a very limited role in the power sector across technology trajectories and policy ambition levels. Under Baseline trajectories, no resources are deployed, while a breakthrough in the technology would result in approximately 110 GW of deployment. Generally, the technology is sited in areas with limited onshore wind potential like the Southeast and California. Without a breakthrough, it is competitive against offshore wind opportunities in these areas. When all technologies have breakthroughs, it is not competitive against offshore wind.

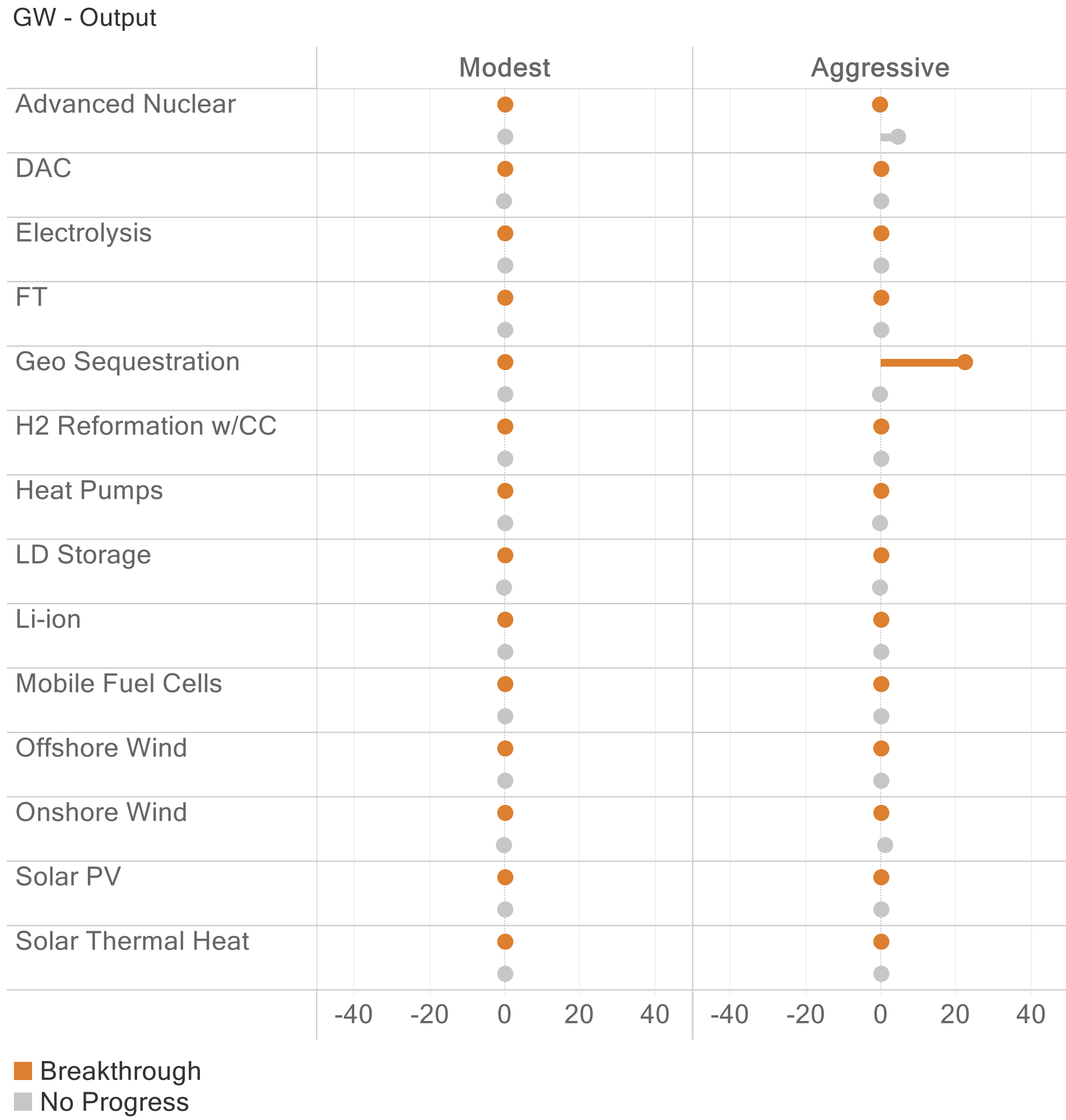
Figure 22
Gas Power with Carbon Capture Deployment



3.5.3. Technology Interactions

Geologic sequestration is an important component of the economics of gas-fired power plants with carbon capture, and a reduction in sequestration costs complements carbon capture at power generation facilities. This finding illustrates the role that these plants play, providing energy in regions with limited renewable resource potential, not as a complementary resource to regions flush with renewables. This is contrary to the role sometimes imagined for these plants as reliability resources with limited run-times. In our analysis, even under Breakthrough cost targets, it is cheaper for gas turbines without CCS to play that role. If 100% clean electricity is necessitated, then the use of zero-carbon fuels burned in these turbines is far more economic than trying to pay the incremental cost of carbon capture (and the supporting pipelines and sequestration infrastructure) in extremely limited run-hours.

Figure 23
Gas Power with Carbon Capture Deployment Relative to the Baseline Trajectory



3.6. Long-Duration Storage

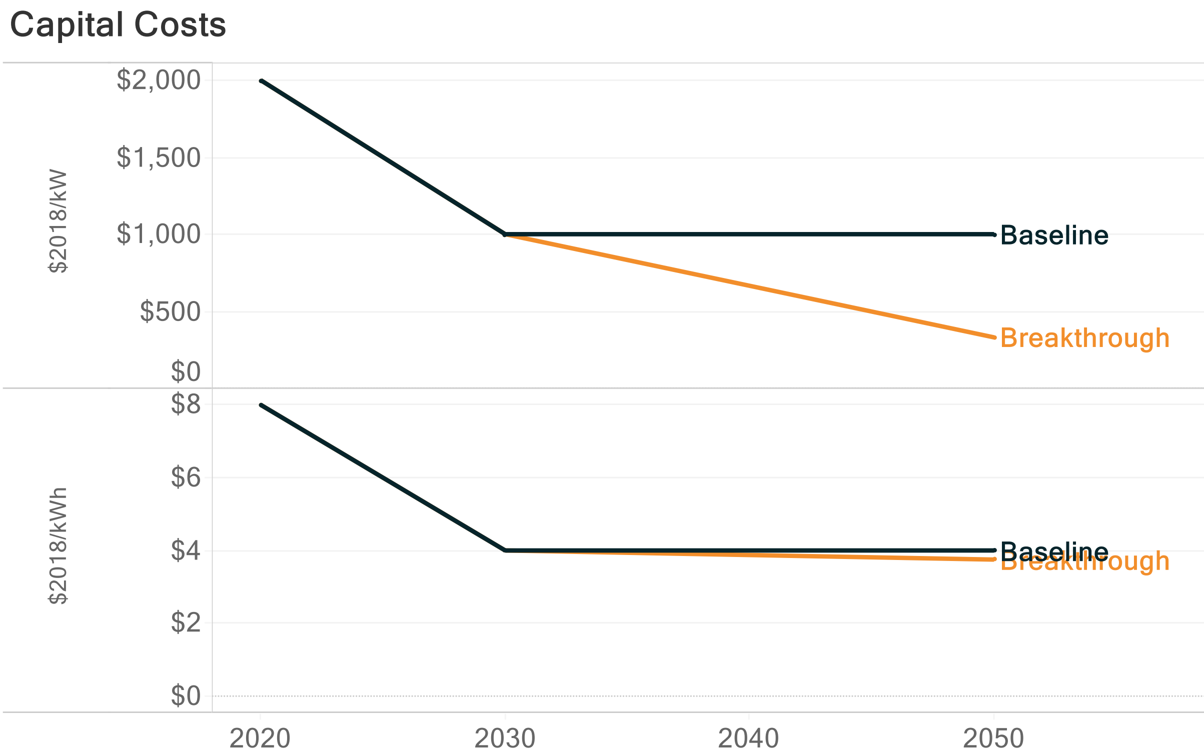
3.6.1. Overview

Long-duration (LD) storage shifts renewable electricity generation from periods of oversupply to periods of sustained low renewable output. This contrasts with battery energy storage systems, which have short durations (e.g., 2- to 8-hours) and are intended for diurnal shifting of energy (e.g., shifting solar generation to the late afternoon and evening of the same day). LD storage needs durations of days or longer because: (a) electricity supply-demand imbalances occur over seasons; and (b) the resource is often intended to enable a 100% renewable electricity system and completely replace gas peaker plants that operate during high net-load hours.

We use publicly available cost trajectories for LD storage from a Form Energy analysis, which has developed an aqueous air battery technology able to provide 150 hours of storage.[9] r We assumed under No Progress, that the technology would not be commercialized. We used their *High Cost Scenario* to represent the 2030 point for our Baseline trajectory. We used their *Low Cost Scenario* to represent the potential for long-duration storage by 2050 for our Breakthrough trajectory. We used efficiency points consistent with both scenarios (50% in the *High Cost Scenario* and 45% in *the Low Cost Scenario*).

[9] See Table 2 of Form Energy (2020).

Figure 24
Long-duration Storage Capital Cost Assumptions



3.6.2. Deployment

LD storage deployment is dependent on realizing breakthroughs and there is zero deployment under Baseline and No Progress trajectories. A breakthrough in LD storage with Modest policy ambition results in 20 GW (970 GWh) of deployment. This increases to 50 GW (2,470 GWh) with the same trajectory under Aggressive policy ambition.

This result is not surprising, because long-duration storage is a "last mile" technology in electricity, seeing large-scale economic deployment only at very high levels of variable renewable penetration. When there are breakthroughs in all technologies ("Breakthrough: All"), there is a significant reduction in deployment due to increased competition for potential renewable overgeneration needed to charge the LD storage facilities.

The model optimally selects the duration of the storage facility, but due to a lack of understanding of how the costs scale at different durations, we use a minimum duration for this cost profile at 50 hours. This result (the deployed storage constrained by the minimum duration) suggests that these cost and performance trajectories would be more valuable if they could be scaled down in terms of duration. It also suggests that costs would need to be substantially lower to see economic deployment of much longer durations (e.g., 100 hours). In our modeling, at the duration selected, these facilities operated as "medium-term" capacity resources, but the model still maintains significant gas-fired power plants in all runs to achieve reliability during tail events of fallow renewable production.

Figure 25
Long-duration Storage Deployment: Capacity

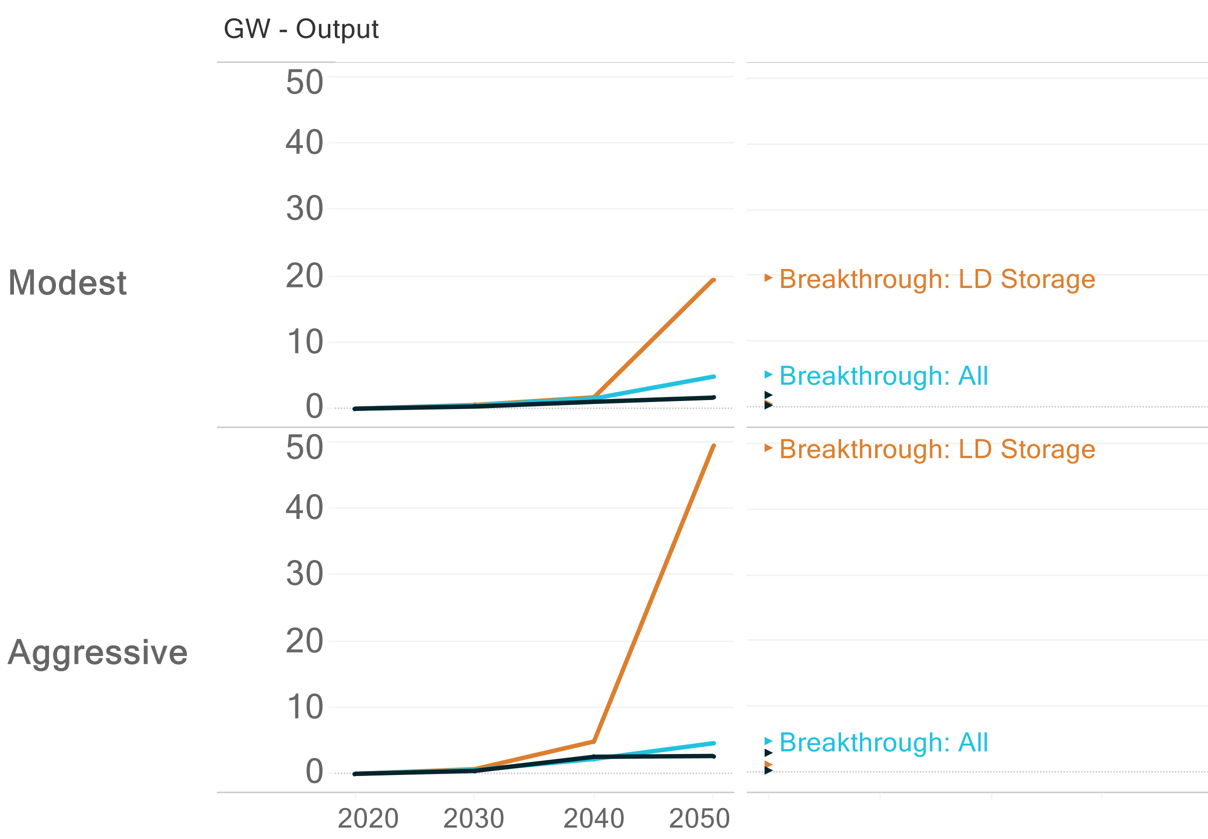
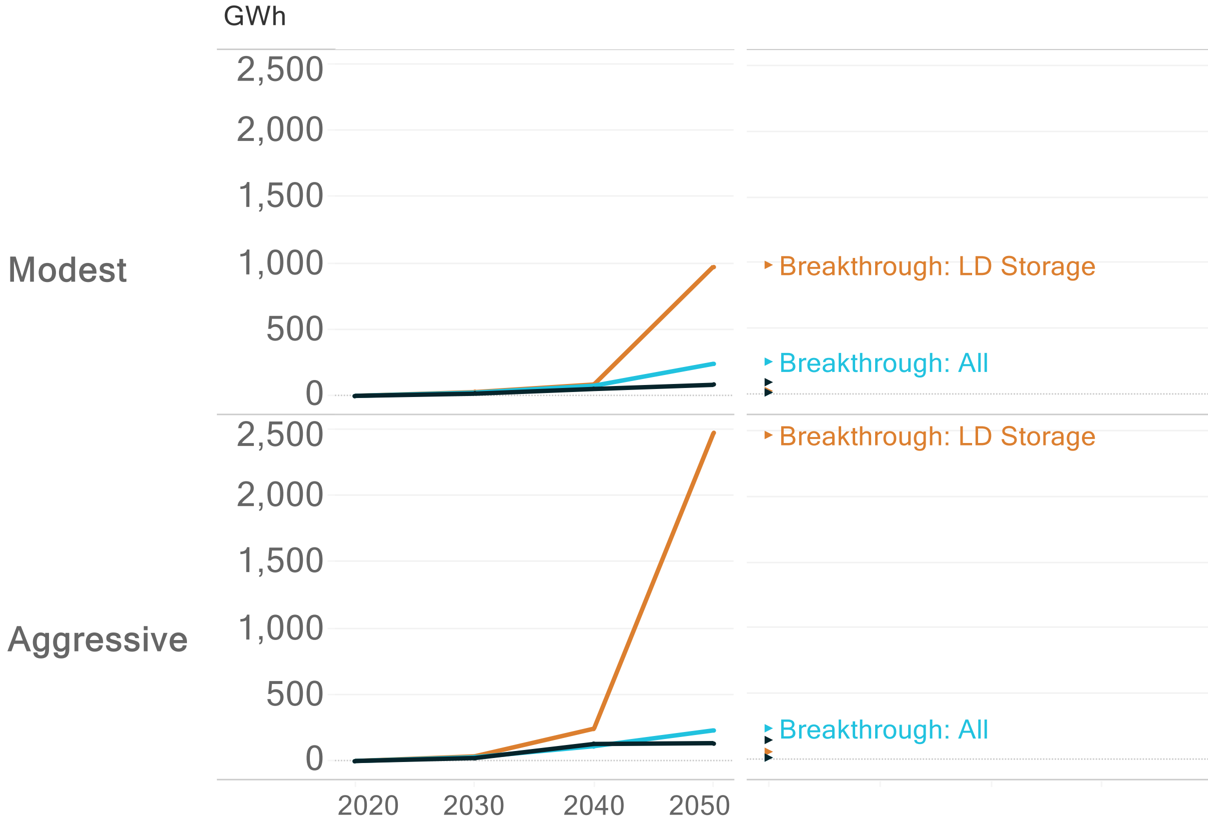
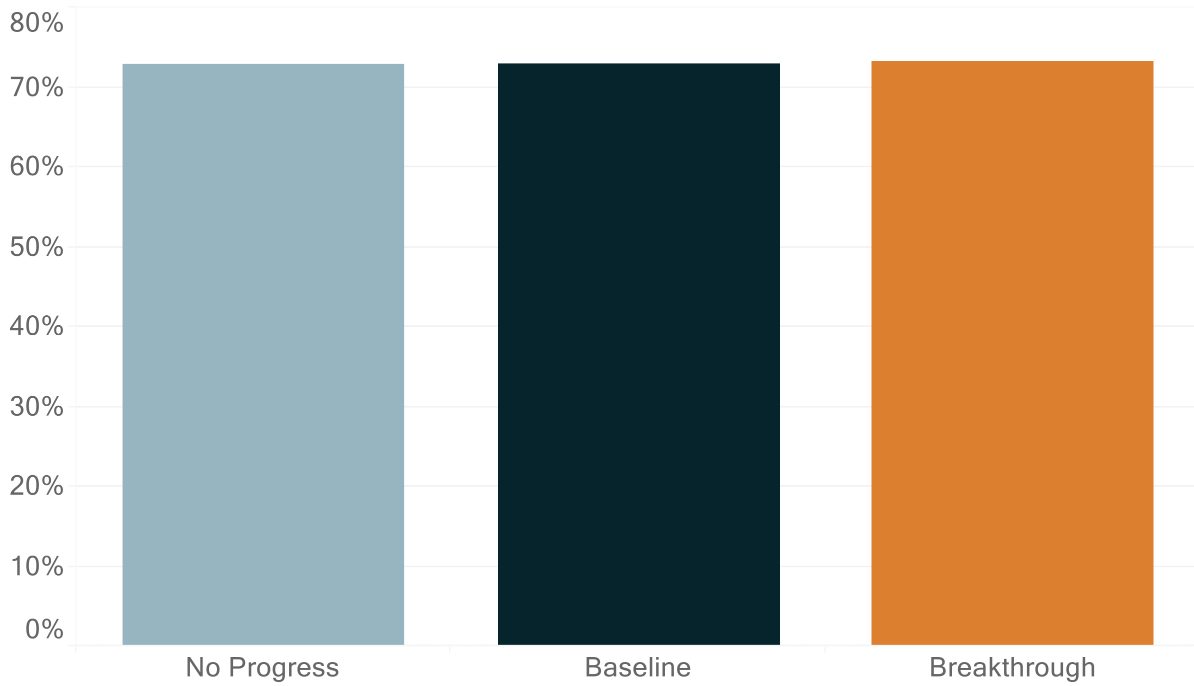


Figure 26
Long-duration Storage Deployment: Energy



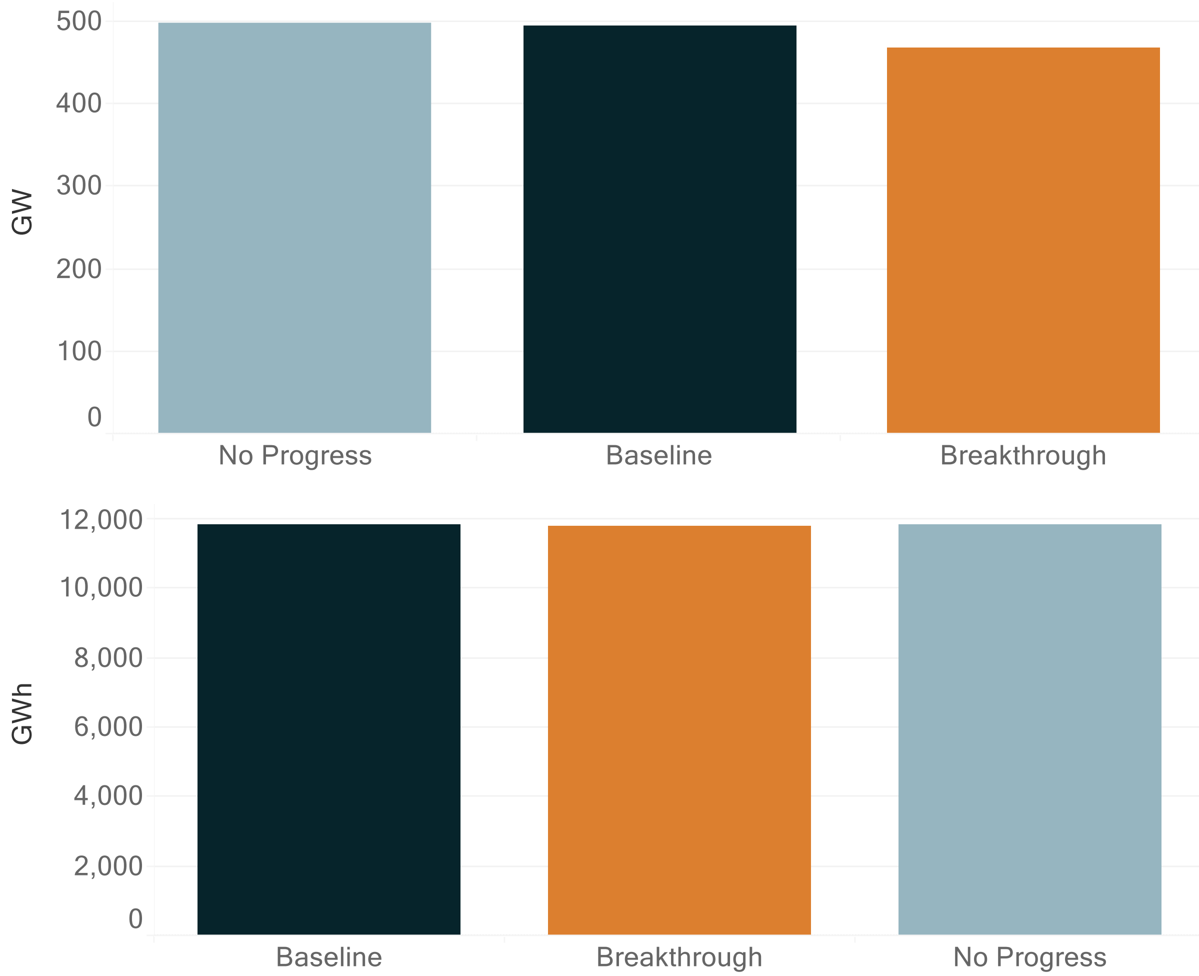
Despite some of the rhetoric, this deployment has very little impact on the integration of variable renewable energy (VRE) onto the grid. In other words, very high levels of wind and solar penetration (~70-75%) are achieved regardless of long-duration storage deployment. This is primarily due to the coupling of the electricity and fuels sectors (e.g., hydrogen electrolysis is a flexible electricity demand resource) and the availability of gas-fired power plants to address over- and under-generation periods in a highly renewable electricity grid. The figure below shows the share of generation that is VRE with No Progress, Baseline, and Breakthrough tech trajectories.

Figure 27
Impact of LD Storage Technology Progress on VRE penetration



The main impact to the system is in the reduction in a nominal amount of capacity from gas generators. While there are laudable aims for reducing gas generation and its greenhouse gas and local air pollution impacts, this is already accomplished without long-duration storage. The minor change in capacity therefore has even less of an impact than it initially suggests.

Figure 28
Impact of LD Storage Technology Progress on Gas-fired Resource Capacity

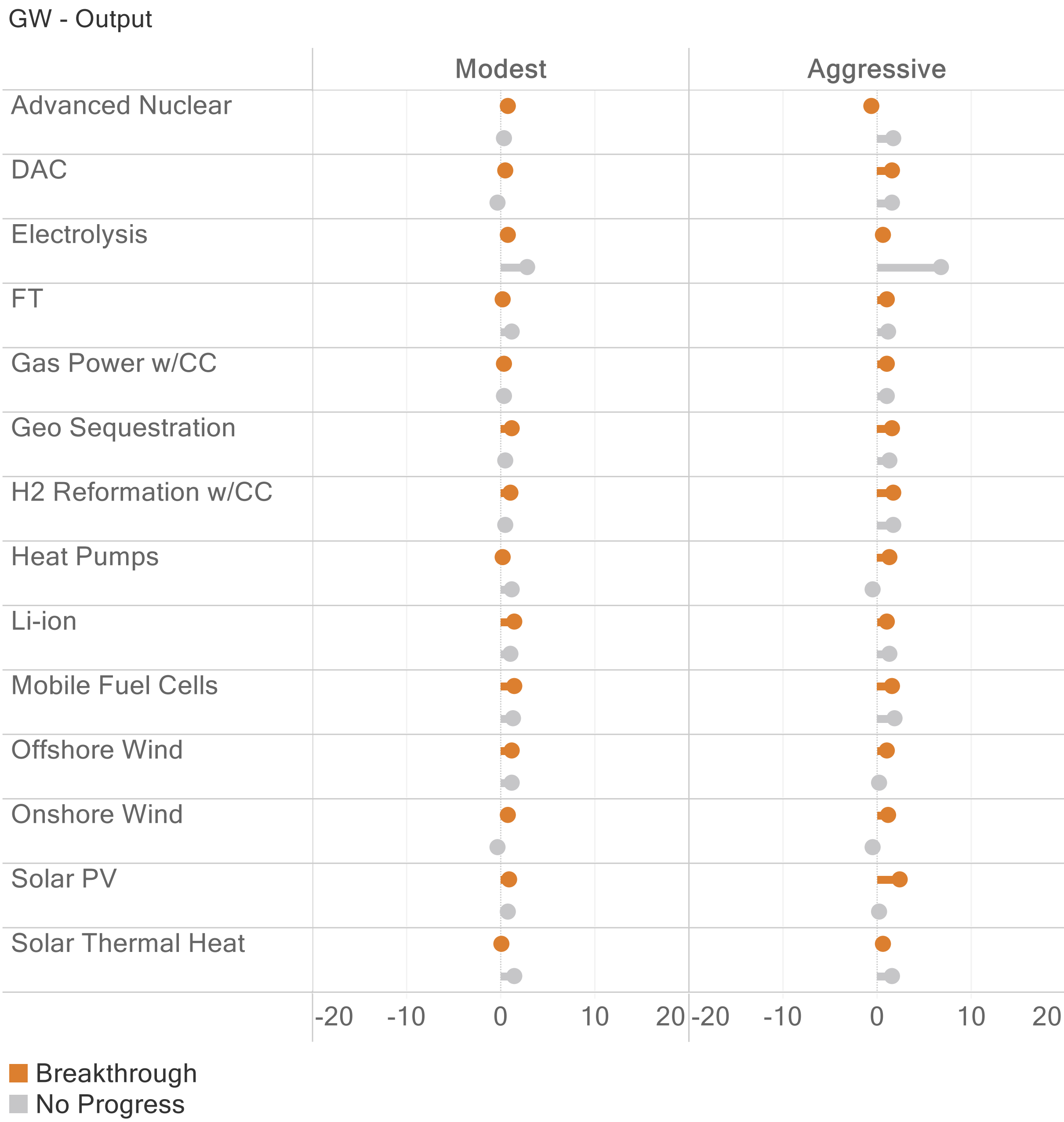


3.6.3. Technology Interactions

LD storage's competition includes technologies that can productively use renewable overgeneration and balance supply and demand in the electric sector. Electrolysis competes with long-duration storage and a lack of progress in this technology provides incremental but limited upside for LD storage deployment.

Figure 29

Long-duration Storage Capacity Deployment Relative to the Baseline Trajectory



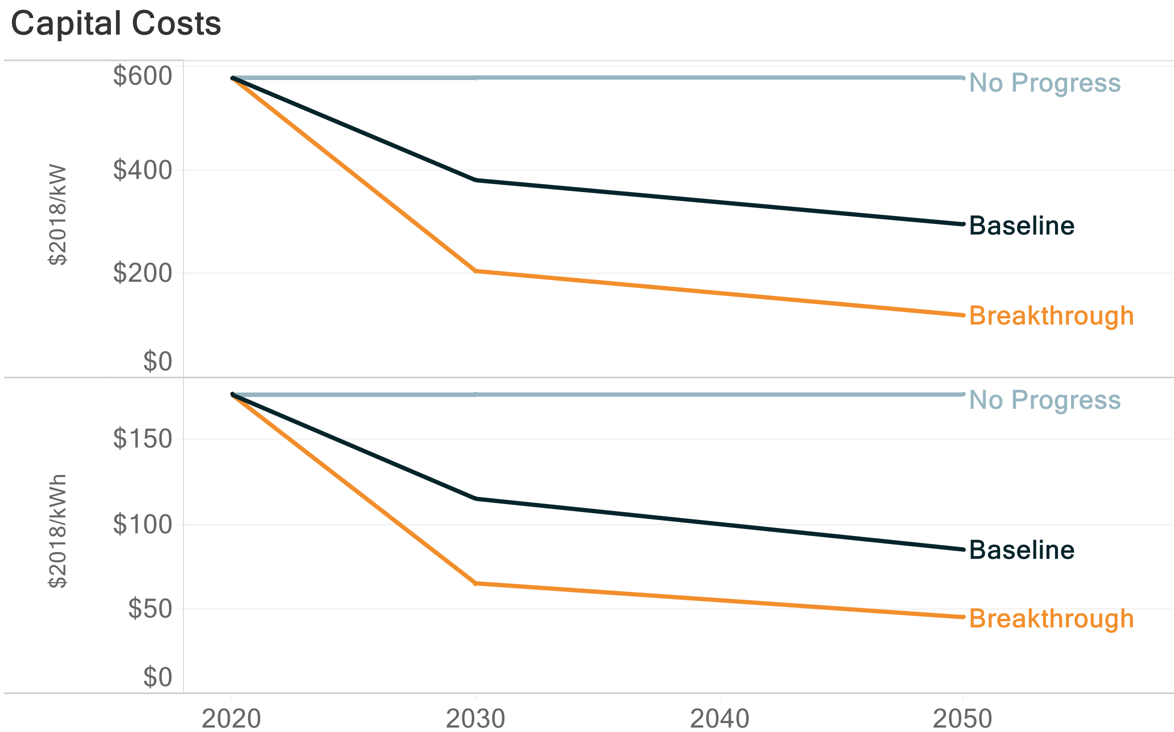
3.7. Li - ion

3.7.1. Overview

Lithium-ion (Li-ion) batteries are likely to play a critical role in a decarbonized energy system through two applications: (1) grid-scale energy storage resource in the electric sector; and (2) the battery pack for electric vehicles. We use li-ion capacity ($/kW) and energy ($/kWh) cost component projections from an NREL study of utility-scale battery storage.[10] For grid-scale batteries, we use both the capacity and energy cost projections, and RIO determines the optimal duration. For vehicles, we apply the energy cost projections to represent the battery pack cost component of an electric vehicle's capital cost. We present results for grid and vehicle applications separately.

[10] See Cole and Frazier (2019).

Figure 30
Li-ion Capital Cost Assumptions: Capacity (Top) and Energy (Bottom)



3.7.2. Deployment

3.7.2.1. Grid Scale

Li-ion deployment in the electric sector largely occurs under Aggressive policy ambition with approximately 30 GW (170 GWh) under the Baseline trajectory. Deployment increases fourfold when the technology realizes its own breakthrough and more than halves when all technologies realize a breakthrough because other technologies compete for the same renewable overgeneration. The average duration is approximately 4 to 8 hours across model runs, which is used to shift solar generation during daylight hours to non-daylight (off-peak) hours.

Figure 31
Grid-scale Li-ion Capacity Deployment

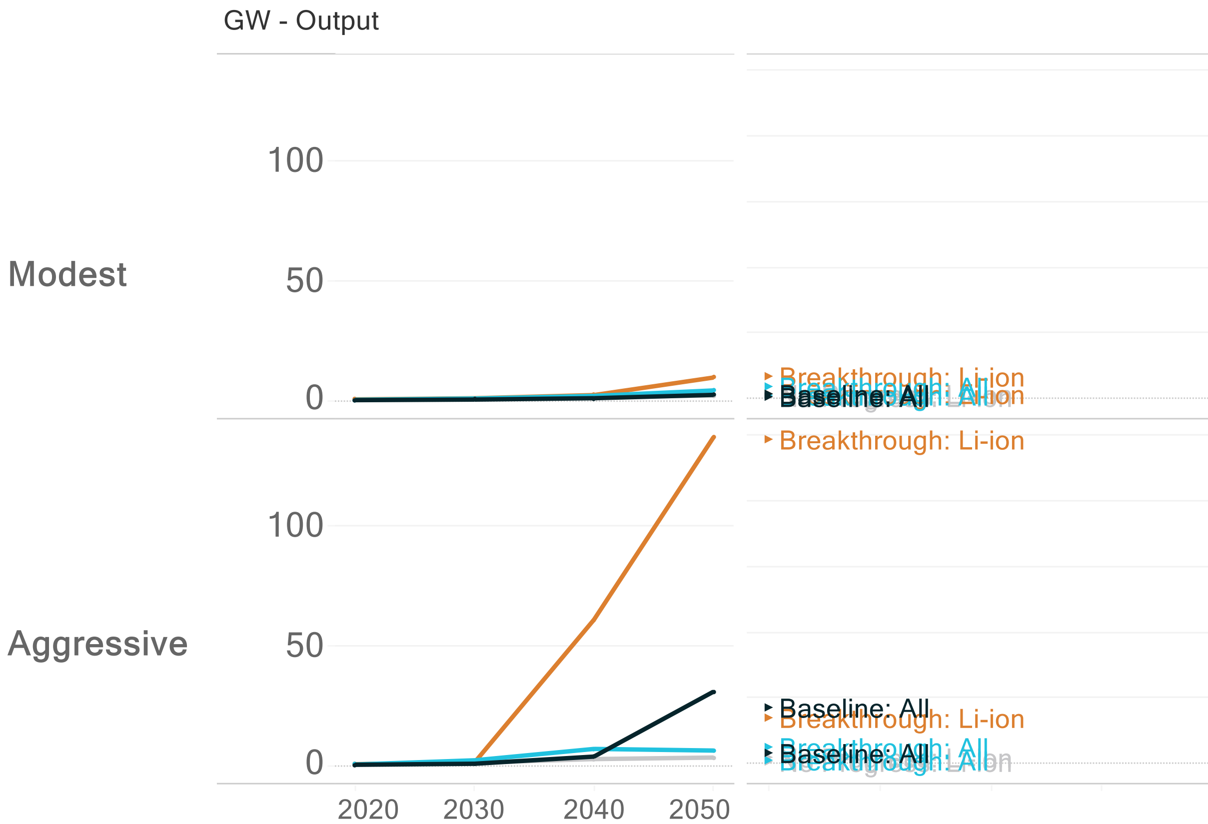
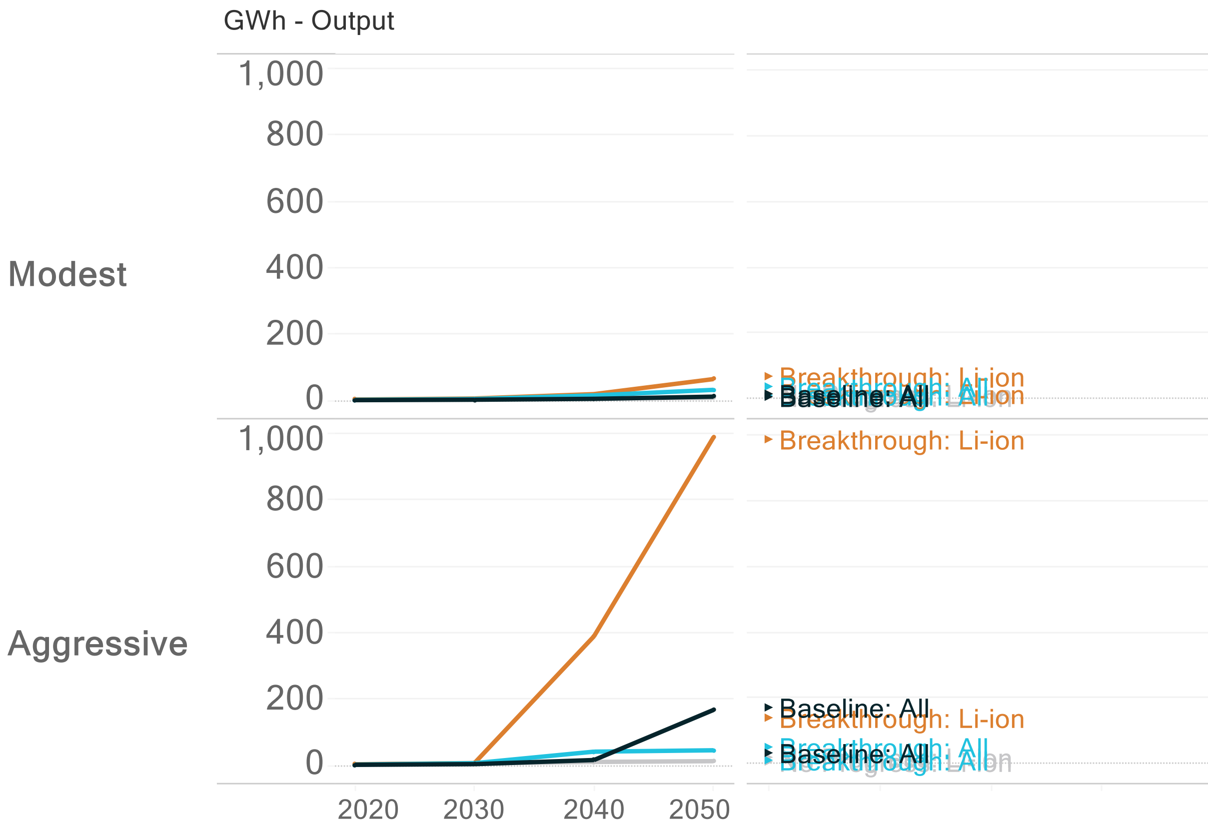


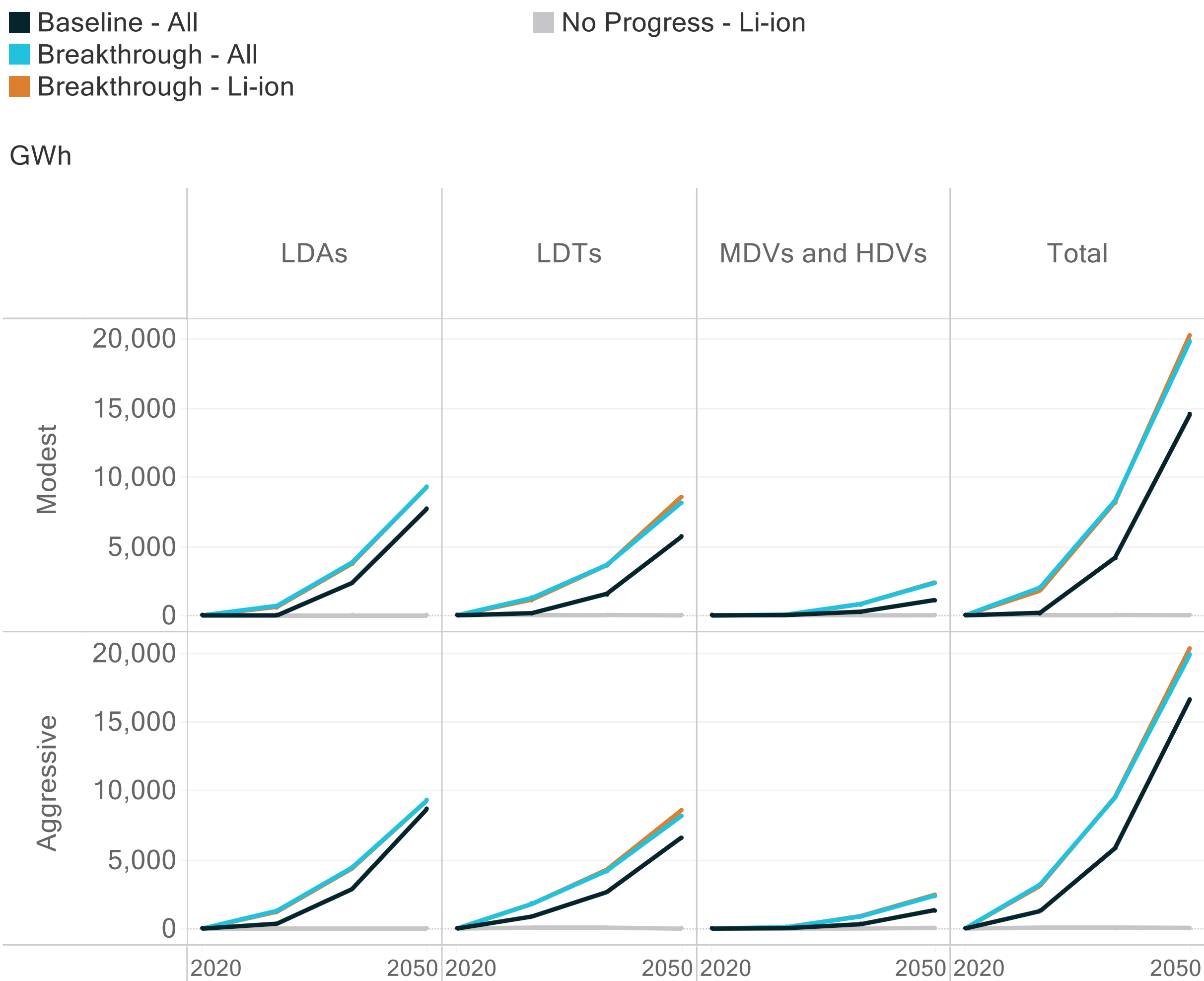
Figure 32
Grid-scale Li-ion Energy Deployment



3.7.2.2. Vehicles

Deployment of li-ion batteries is order of magnitudes larger in vehicle applications than it is on the grid and proliferates *under either* level of policy ambition when baseline progress is achieved. A breakthrough for li-ion batteries accelerates light-duty vehicle adoption and increases the overall deployment in freight applications.

Figure 33
Vehicle Li-ion Deployment

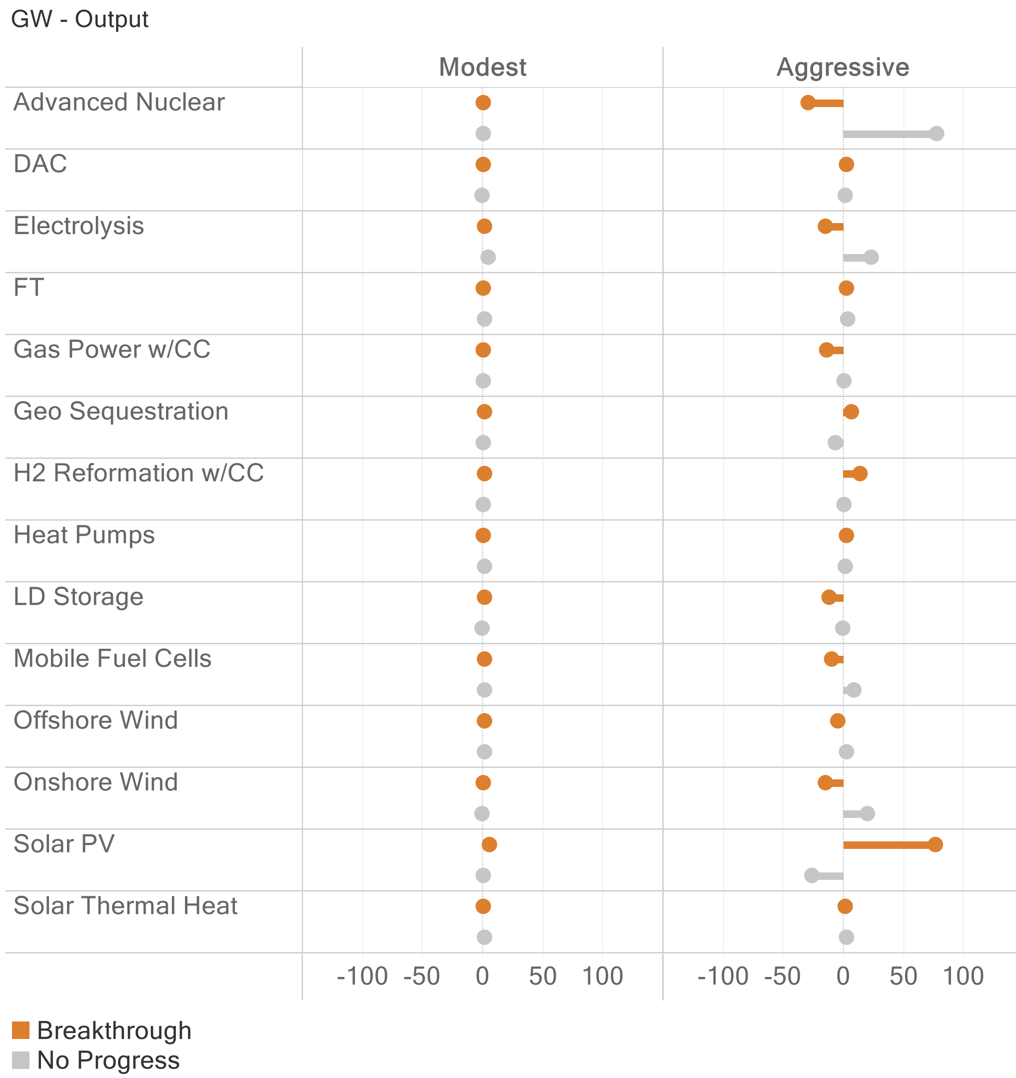


3.7.3. Technology Interactions

3.7.3.1. Grid-Scale

Solar PV is highly complementary to li-ion deployment in the electric sector, and a breakthrough in solar costs would triple grid-scale li-ion deployment under an Aggressive policy ambition. On the other hand, no progress for solar costs would nearly avoid all li-ion deployment. If advanced nuclear is unable to realize baseline progress, then grid-scale li-ion would benefit since lower nuclear deployment would increase renewable deployment and demand for balancing.

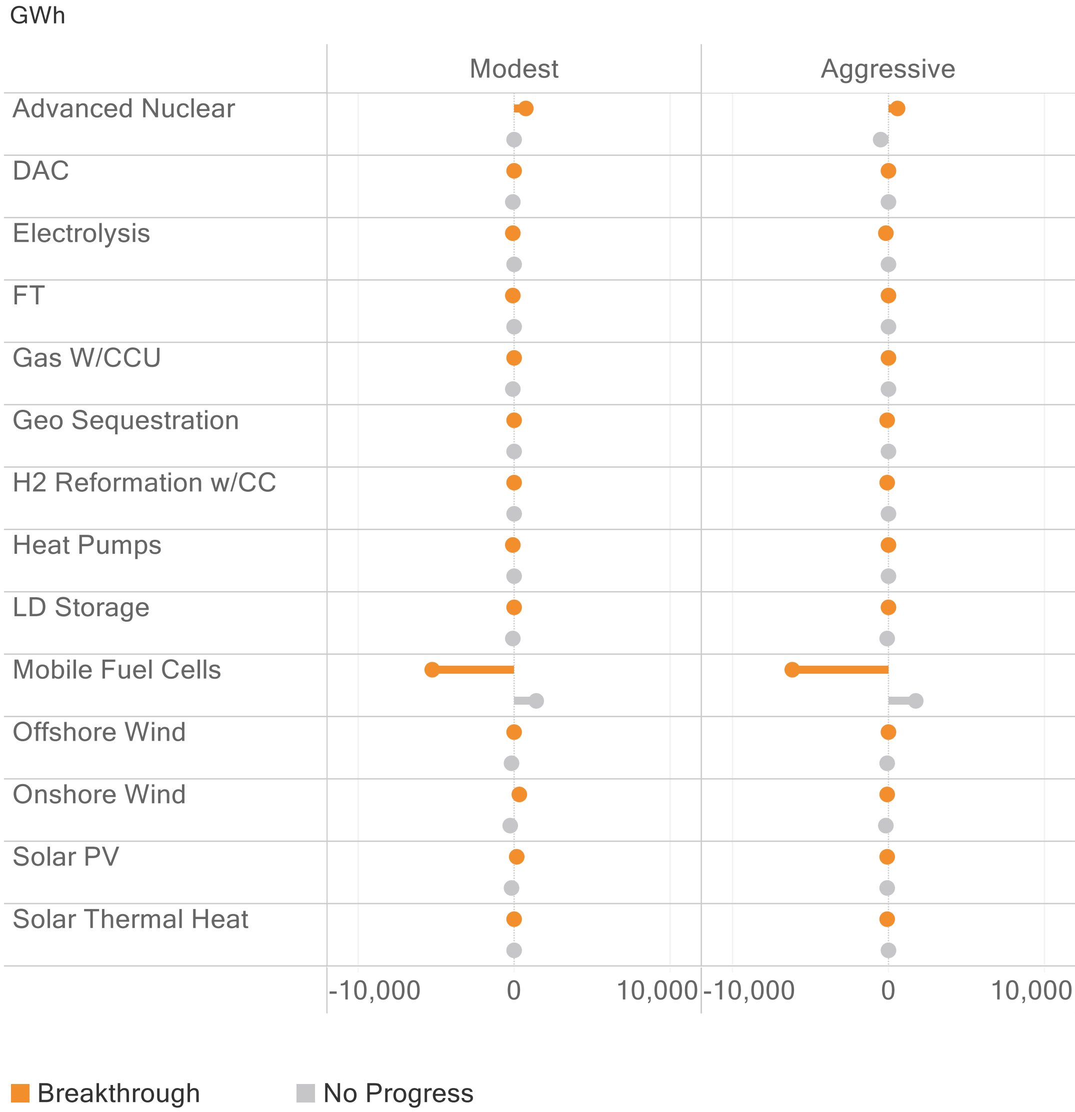
Figure 34
Grid-scale Li-ion Deployment Relative to the Baseline Trajectory



3.7.3.2. Vehicles

The only significant competitor with vehicle batteries is fuel cell technology, with fuel cells potentially able to compete with battery vehicles if a breakthrough is achieved. Ultimately, if a universal breakthrough for all technologies is achieved (e.g., for both fuel cells and batteries), then battery vehicles are the dominant technology of choice, specifically in light-duty applications.

Figure 35
Vehicle Li-ion Deployment Relative to the Baseline Trajectory



3.8. Hydrogen Electrolysis

3.8.1. Overview

Electrolysis is a hydrogen production technology that converts clean electricity to hydrogen and oxygen by splitting water in a unit called an electrolyzer. Since the process uses renewable electricity as an input, it provides carbon-free "green hydrogen" that is advantageous to unabated gas reformation, which produces "grey hydrogen".[11] Electrolysis can provide large-scale, demand-side flexibility to the electric sector by consuming electricity during overgeneration periods. The produced hydrogen can be used directly (e.g., in a fuel cell vehicle) or as a feedstock in another application (e.g., power-to-gas methanation). Electrolysis demonstrates significant interactions with other technology areas. Technologies such as wind and solar are inputs to electrolytic hydrogen production and are a significant determinant of its ultimate $/kg cost. The output of electrolysis (green hydrogen) is an input to technologies such as FT synthesis and fuel cell vehicles.

Baseline capital costs, which decrease by 80% below today's costs, are from an International Renewable Energy Agency (IRENA) report.[12] A breakthrough in electrolysis, based on Bloomberg New Energy Finance projections, assumes capital costs below $100/kW by 2050.[13] Efficiency trajectories beyond the base level (e.g., 70%) are based on our expert judgement.

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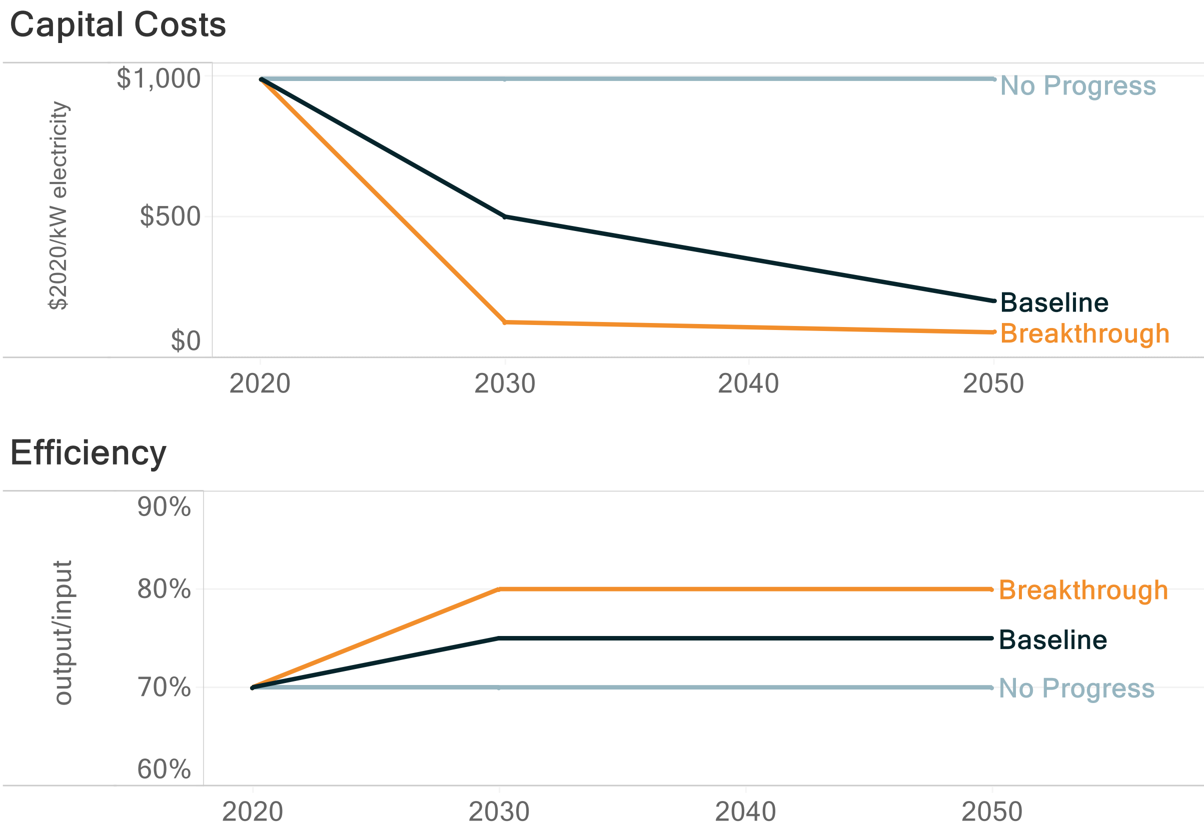
[11] "Blue hydrogen" or gas reformation with carbon capture is discussed in section 3.9.

[12] See IRENA (2019).

[13] See BNEF (2019).

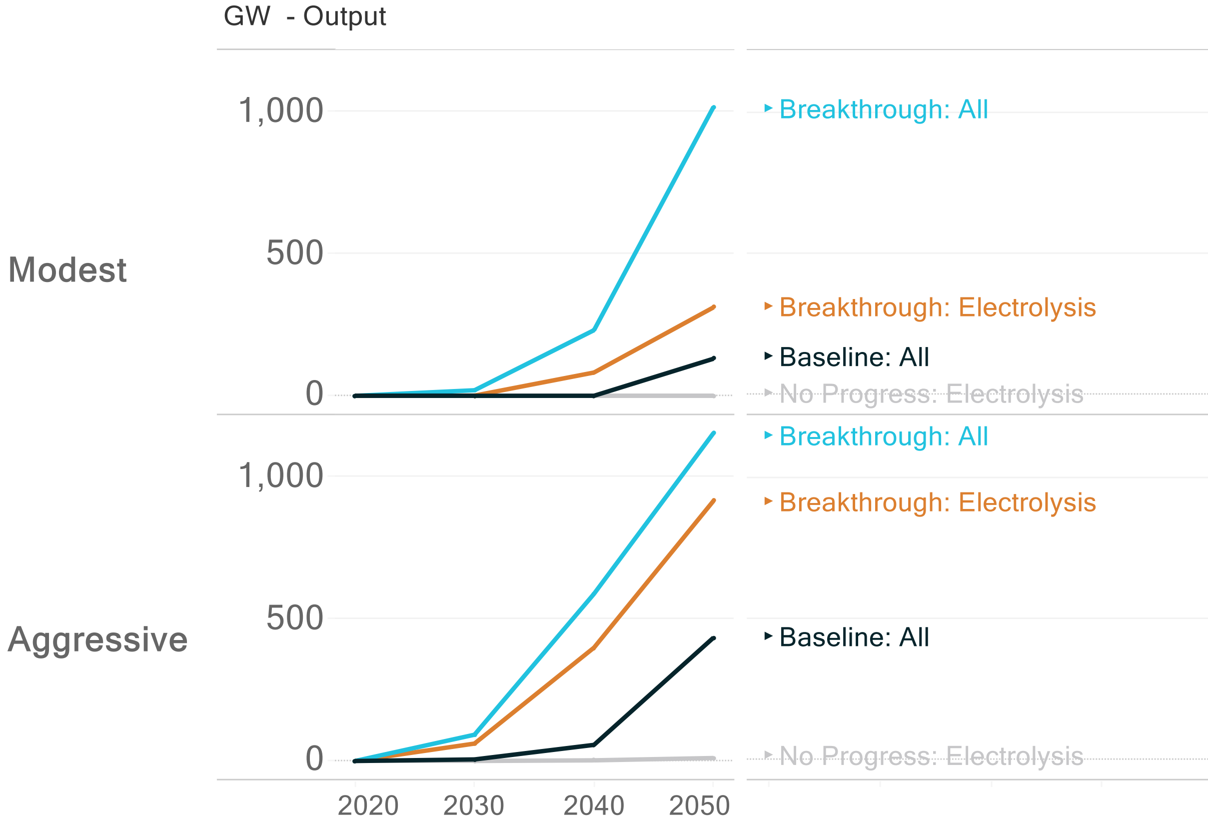
Figure 36
Electrolysis Capital Cost and Performance Assumptions



3.8.2. Deployment

Although a breakthrough in electrolysis alone has a significant impact on deployment, a breakthrough in the energy inputs for electrolysis (e.g., wind and solar) have an even more significant impact. Even at a Modest policy ambition level, electrolysis realizes significant deployment when all technologies realize a breakthrough.

Figure 37
Electrolysis Deployment



Renewable technology breakthroughs, specifically onshore wind and solar, drive additional deployment for two reasons. First, lower primary energy costs means that electrolytic hydrogen is more economically attractive elsewhere in the economy. Second, a principal economic driver is to economically deploy a higher share of variable renewable generation and the limit to this share is the ability to make economic use of overgeneration conditions on the grid. Electrolysis is a solution to this issue and allows for the integration of higher levels of renewable generation.

The marginal cost of producing hydrogen from electrolysis varies across regions, as shown in Figure 38. The marginal cost ranges from approximately \$1.7 to \$2.8/kG with No Progress, with the upper range occurring in regions that have limited onshore wind availability such as New York and New England. Marginal costs decline to \$1.4 to \$2.0/kG under Baseline assumptions and further decrease to \$1.2 to \$1.8/kG with a breakthrough for electrolysis only. When all technologies realize a Breakthrough trajectory, the range further declines to \$0.8 to \$1.2/kG. The decrease in the marginal cost of electrolytic hydrogen production understates the impact of technology breakthroughs, because as the costs of electrolytic hydrogen increase with volume as less and less of the energy used to run the electrolyzers would be otherwise economically curtailed. R&D breakthroughs lower the price even while increasing the volume of production substantially.

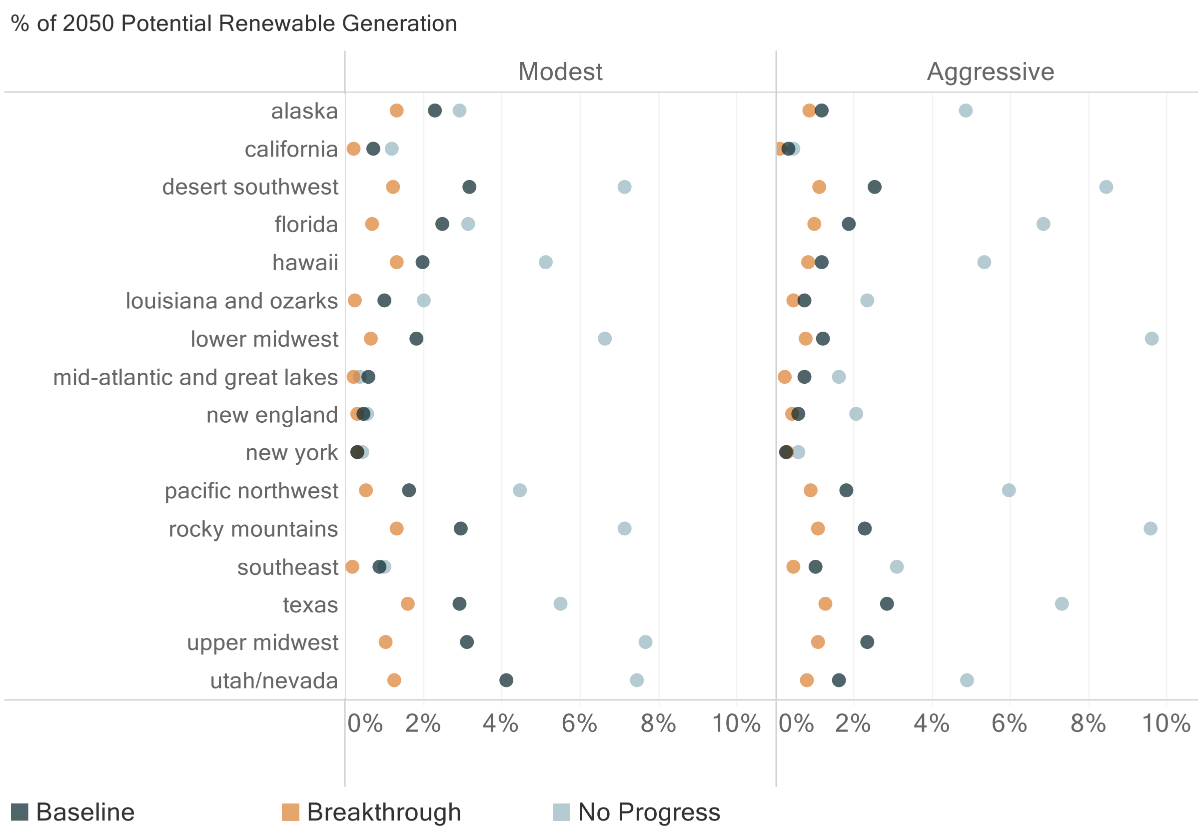
Figure 38

Regional H_2 Marginal Price, 2050: Aggressive Policy Ambition

We can identify the impact that electrolysis R&D has on the electricity system by assessing the share of renewable generation that is economically curtailed between scenarios. Electrolysis can enable higher shares of generation that comes from low levelized cost of electricity renewables by operating flexibly, reducing the frequency of curtailment hours. This benefit is two-fold: (1) otherwise spilled renewables are converted into valuable zero-carbon fuels, reducing emissions; and (2) it allows for a higher share of generation to come from renewables, increasing their competitiveness against higher-cost thermal resources on the electricity system that are only being selected because additional renewables would otherwise be curtailed.

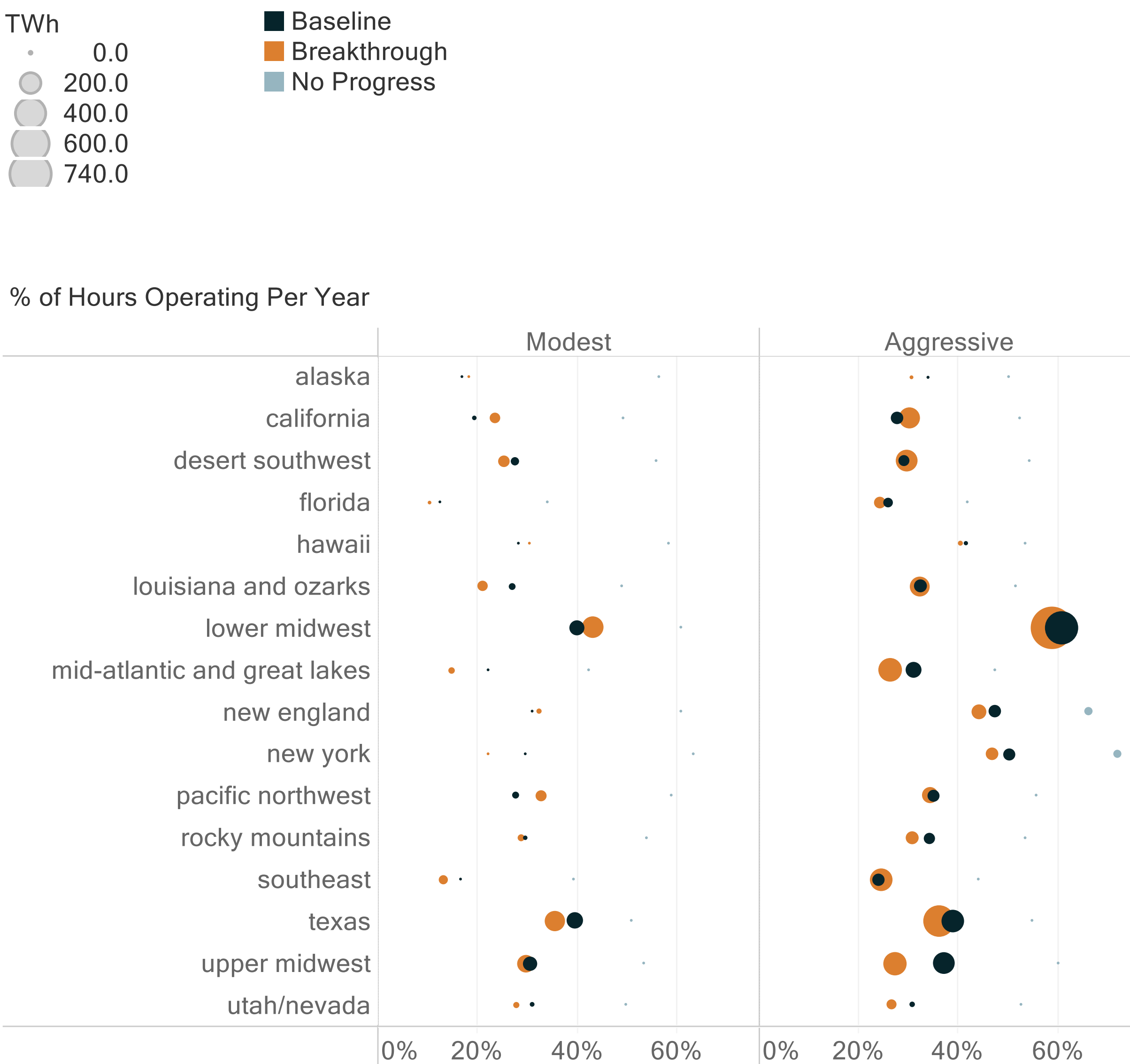
Figure 39 shows the average curtailment of renewable generation by region in 2050. No progress for electrolyzers results in the highest curtailment levels, which imposes large economic costs to the energy system. Curtailment is mitigated with baseline and breakthrough technology progress.

Figure 39
Regional Curtailment of Renewable Generation, 2050



The key to reducing curtailment in this context is the ability of electrolysis to operate economically at low capacity factors. Technologies with low capital costs offer the ability to cover their fixed investment costs across fewer hours, operating as a complement to renewables by demanding energy only during times of excess supply. This economic behavior is illustrated along the performance trajectories examined in Figure 40. Lower capital cost projections (e.g., Breakthrough) means that the average electrolyzer runs only during the most acute periods of overgeneration on the electricity system. Baseline cost and performance tends to result in a higher average capacity factor, because it is economic to supply them with a higher share of non-curtailed renewable energy. Higher capital cost projections (e.g., No Progress) results in such a limited volume of electrolyzers that there is available curtailment to access in almost all hours.

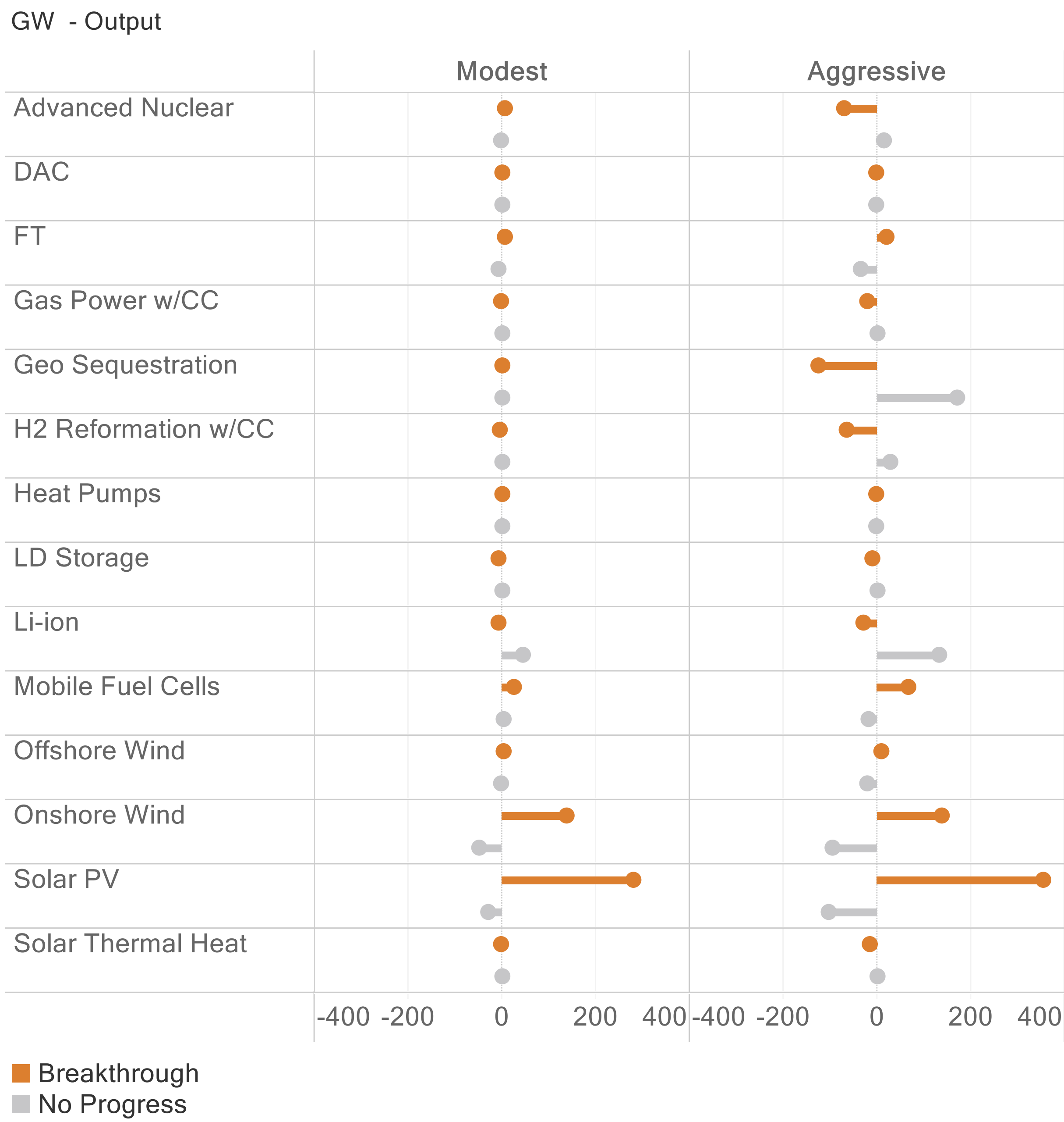
Figure 40
Regional Electrolysis Capacity Factors, 2050



3.8.3. Technology Interactions

As shown in Figure 37, electrolysis is a technology that has a high level of complementarity with breakthroughs in other areas given that its deployment peaks when we have breakthroughs across all technologies. This means that coupled R&D breakthroughs provide a multiplier effect in terms of deployment for electrolysis. The specific technologies that are responsible for this are principally onshore wind and solar PV. The significant competitor to electrolysis is geologic sequestration because both compete for the same captured CO_2 resources. Hydrogen from electrolysis is a feedstock for carbon capture and utilization (to produce synthetic hydrocarbons), while geologic sequestration is the alternative, with the sequestered CO_2 offsetting continued fossil hydrocarbon use.

Figure 41
Electrolysis Deployment Relative to the Baseline Trajectory

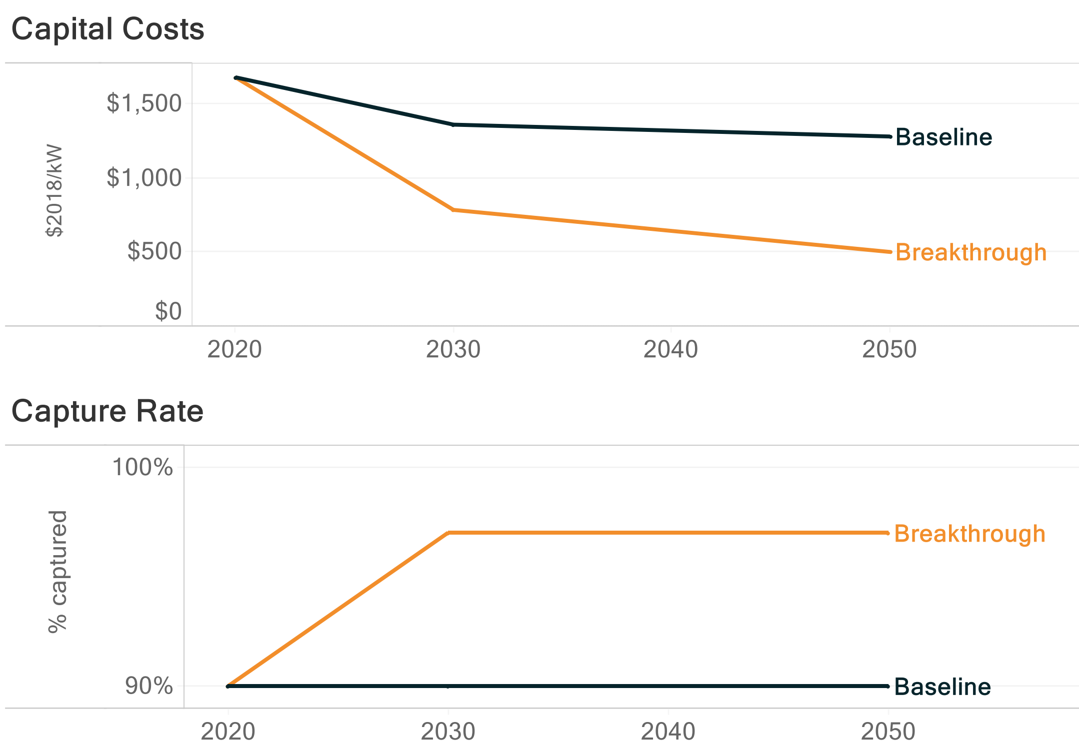


3.9. Gas H_2 With Carbon Capture

3.9.1. Overview

Methane reforming with carbon capture ("gas H_2 with carbon capture") produces hydrogen from natural gas while capturing CO_2 in the process. Between 90% to 97% of the CO_2 is captured while producing "blue hydrogen". We use the International Energy Agency's (IEA) *G20 Hydrogen* report to characterize the Baseline cost and performance trajectory, which maintains a 90% capture rate but assumes modest capital cost improvements.[14] We use cost and capture projections from the HyNet North West hydrogen project to characterize the Breakthrough trajectory.[15]

Figure 42
Gas H_2 with Carbon Capture Capital Cost and Capture Rate Assumptions



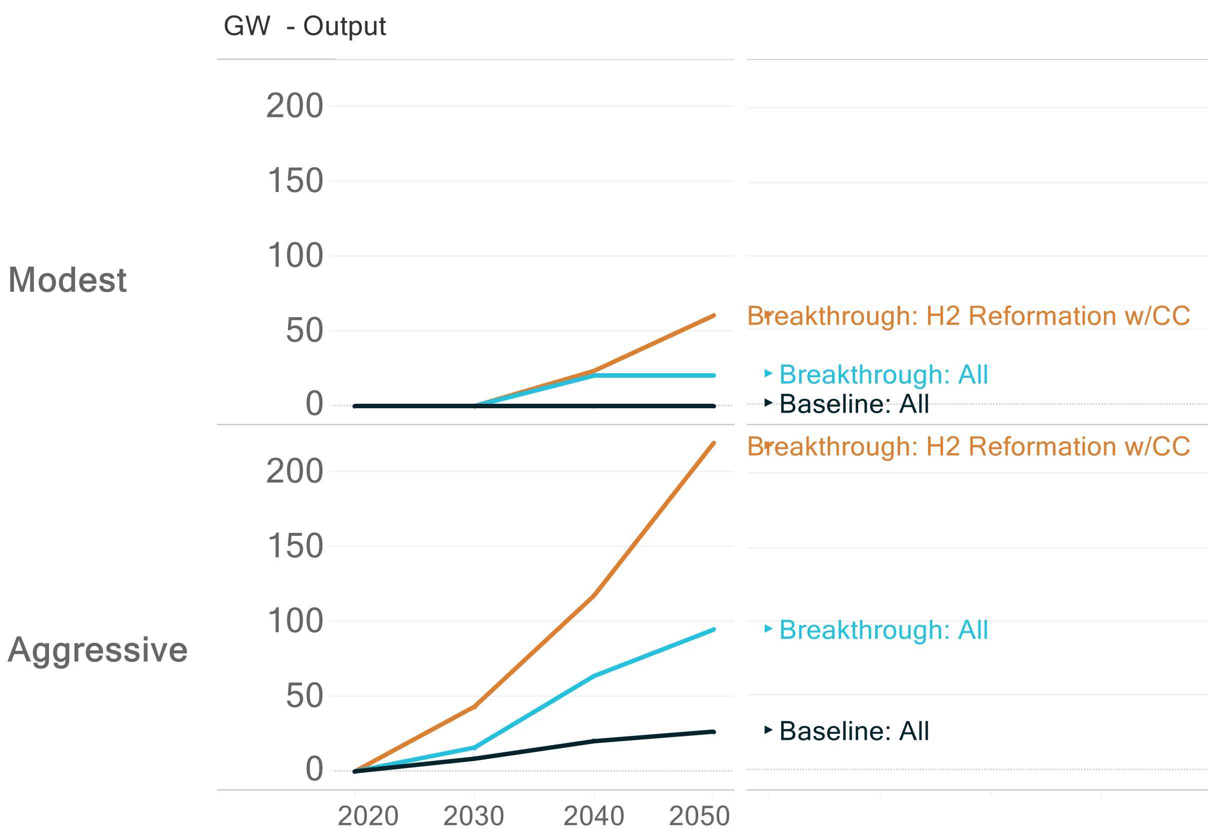
[14] See IEA (2019).

[15] See HyNet (2019).

3.9.2. Deployment

Hydrogen produced from methane reforming with carbon capture only realizes meaningful deployment if the technology realizes a breakthrough in its cost and capture rate. Even with this breakthrough, its market share is limited by other hydrogen production technologies, specifically electrolysis and biomass gasification with carbon capture. Under the most optimistic scenario for deployment (aggressive policy ambition and a breakthrough for H2 Reformation w/CC), its share of total hydrogen production is 50% in 2050, while its share is typically below 10% across alternative policy and technology trajectories.

Figure 43
Gas H_2 with Carbon Capture Deployment

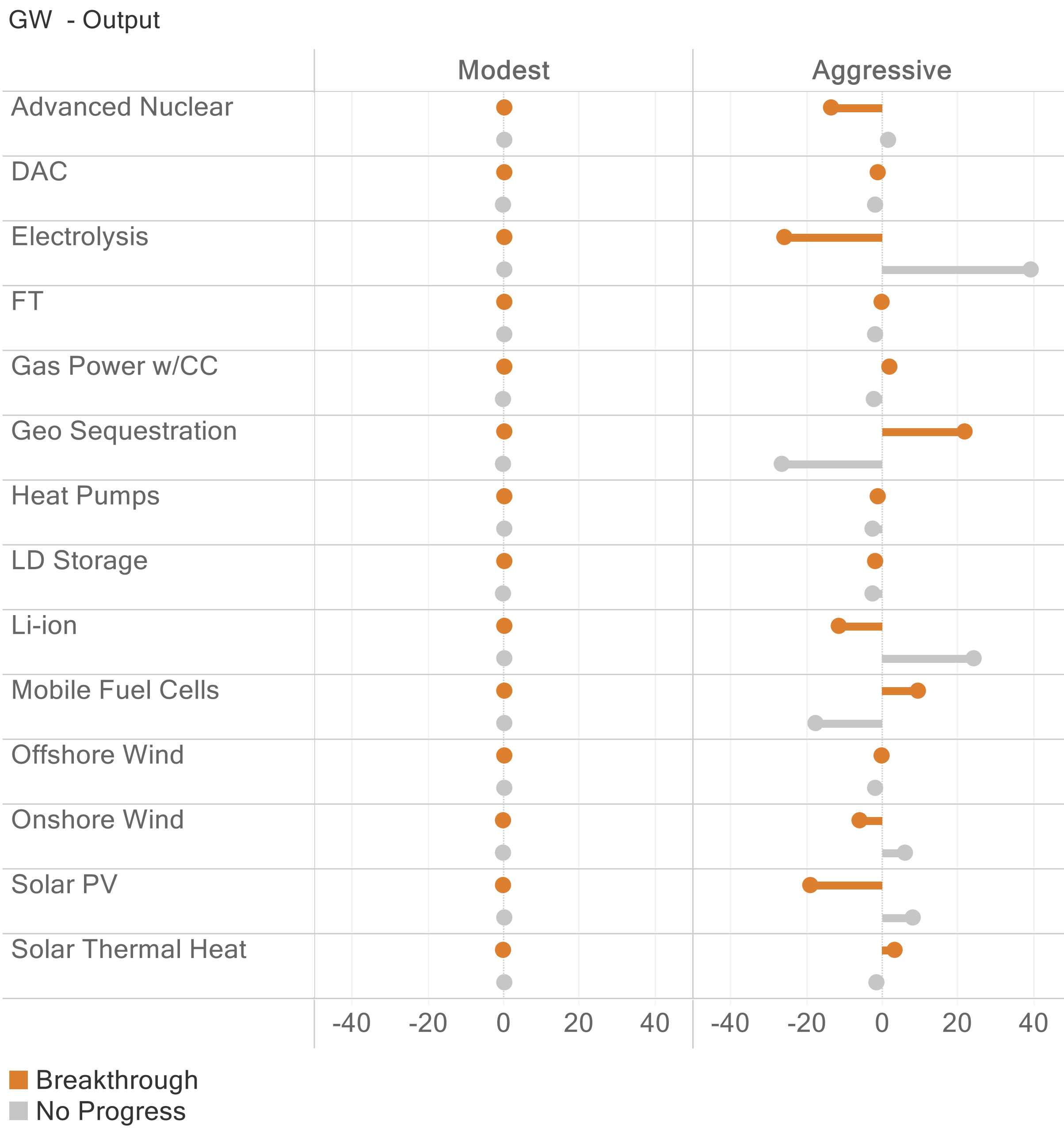


3.9.3. Technology Interactions

Deployment for Gas H_2 Reformation w/CC increases if electrolysis fails to achieve its Baseline trajectory, or if geologic sequestration and mobile fuel cells achieve a breakthrough, which increases demand for CO_2 and H_2, respectively.

Figure 44

Gas H_2 with Carbon Capture Deployment Relative to the Baseline Trajectory



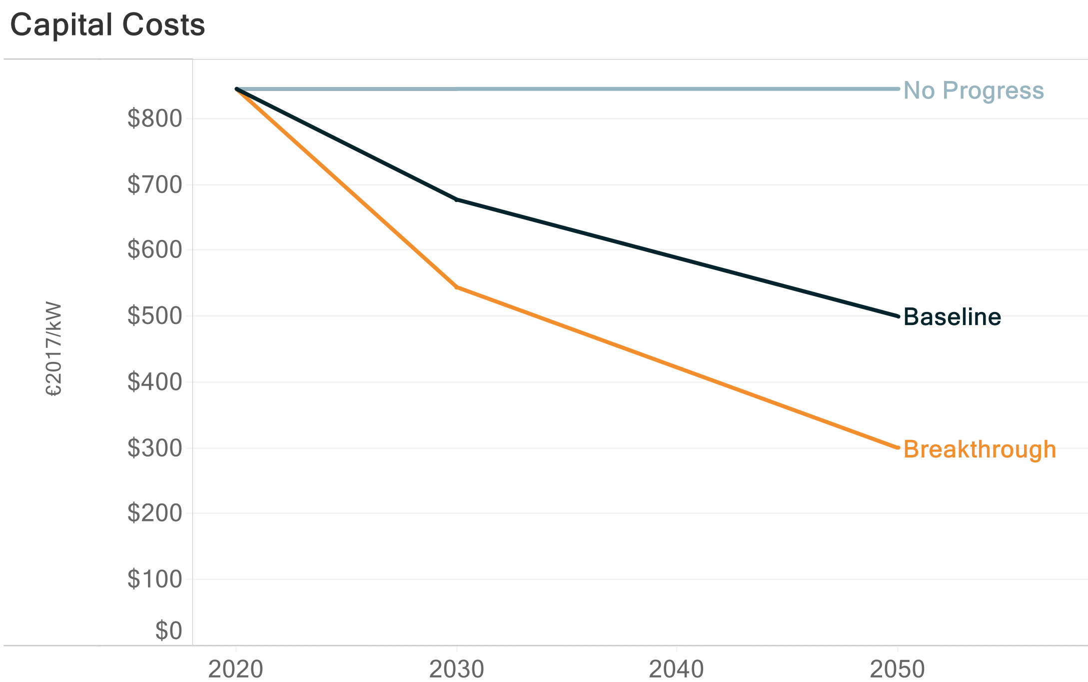
3.10. Fischer–Tropsch Fuel Synthesis

3.10.1. Overview

Fischer-Tropsch (FT) fuel synthesis uses hydrogen and carbon monoxide to produce a synthetic liquid fuel. Depending on the feedstock source, the synthetic fuel can be bio- and electric-derived (e.g., biomass-to-liquid and power-to-liquid). We use cost projections for FT fuel synthesis from a study commissioned by Agora Verkehrswende, Agora Energiewende, and Frontier Economics.[16] We apply these trajectories, shown in Figure 45, in the modeling of stand-alone FT plants that use zero-carbon hydrogen feedstocks and captured carbon to create synthetic hydrocarbons (power-to-liquid). We also apply these trajectories to our projections of integrated Bio-FT plant costs (biomass-to-liquid). In summary, our FT cost projections affect both the economics of electric- and bio-based synthetic fuels.

[16] See Agora (2018).

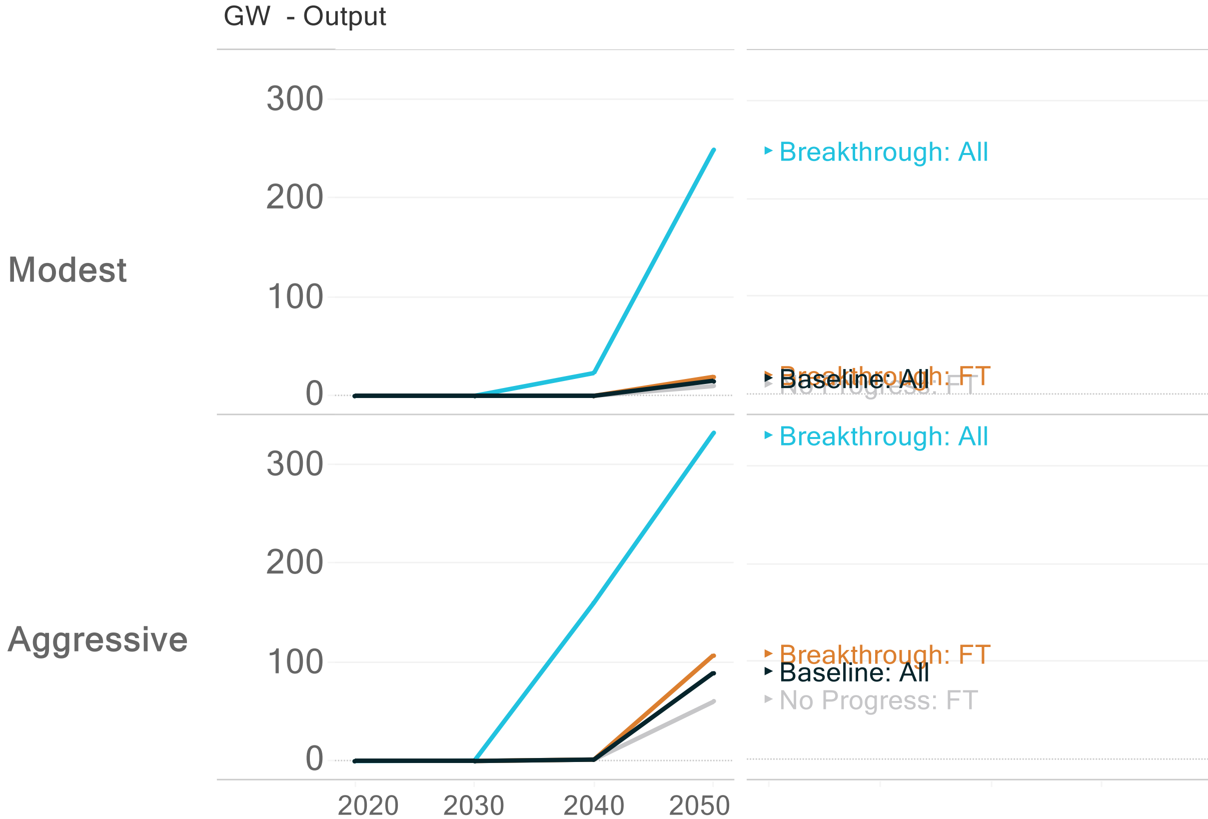
Figure 45
FT Fuel Synthesis Capital Cost Assumptions



3.10.2. Deployment

Drop-in fuel replacements are some of the most expensive emissions reductions measures, and under modest policy, FT synthesis deployment is generally not significant against low fossil fuel prices unless universal technology breakthroughs where all components of the zero-carbon fuel production chain see reduced cost and increased performance (zero-carbon electricity generation; captured carbon; and hydrogen feedstocks). However, synthetic fuel is necessary to achieve net-zero targets in the long-term, which means a significant deployment under all technology trajectories when coupled with Aggressive policy ambition. The most significant deployment of FT synthesis under Aggressive policy is realized when coupled with breakthroughs in all technologies.

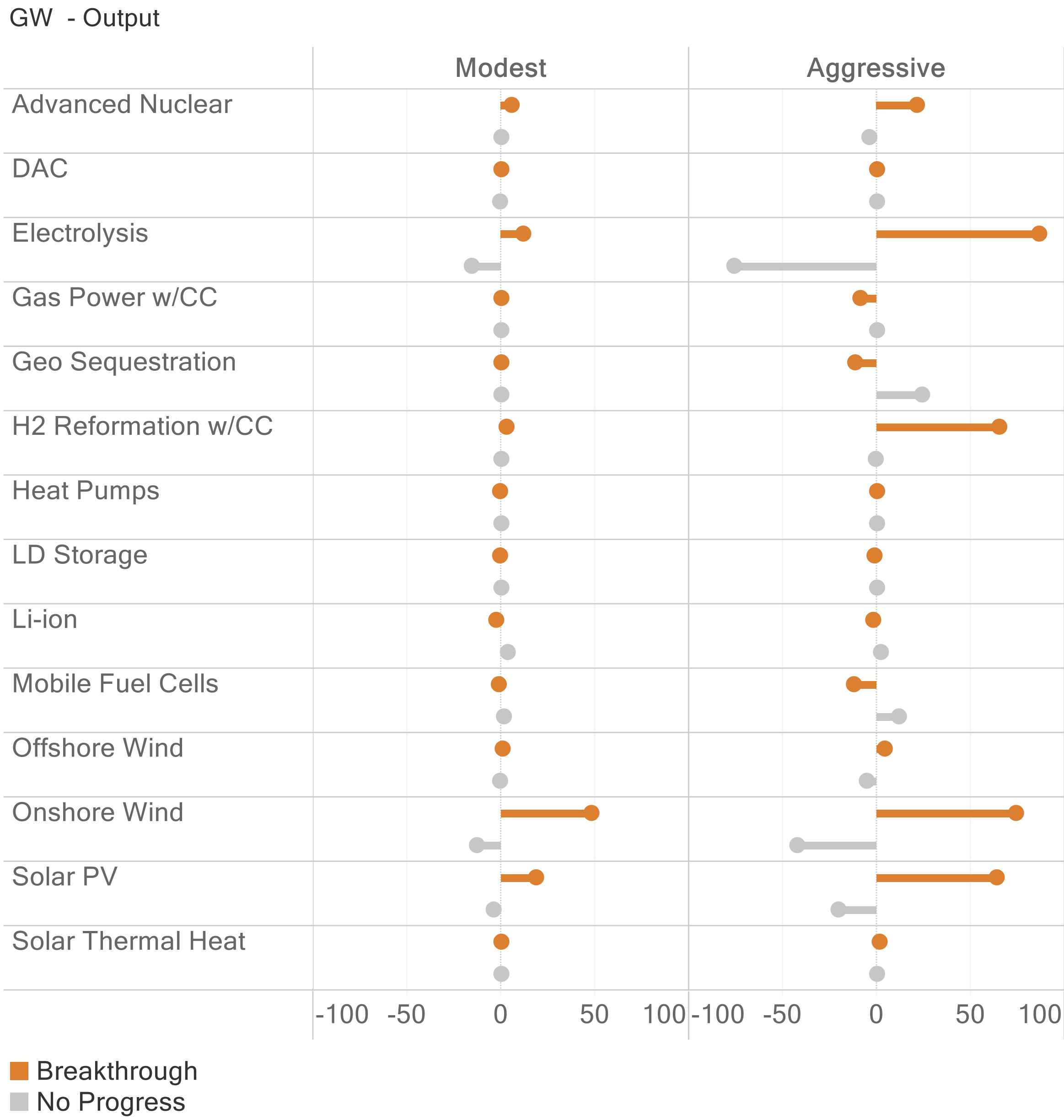
Figure 46
FT Fuel Synthesis Deployment



3.10.3. Technology Interactions

As discussed in the section above, FT synthesis deployment rises with breakthroughs in technologies that are used as inputs. Breakthroughs in electrolysis, onshore wind and solar all complement FT synthesis. Since hydrogen is a necessary feedstock for synthetic electric fuel production, failure to achieve Baseline costs for electrolysis will negatively impact deployment.

Figure 47
FT Fuel Synthesis Deployment Relative to the Baseline Trajectory

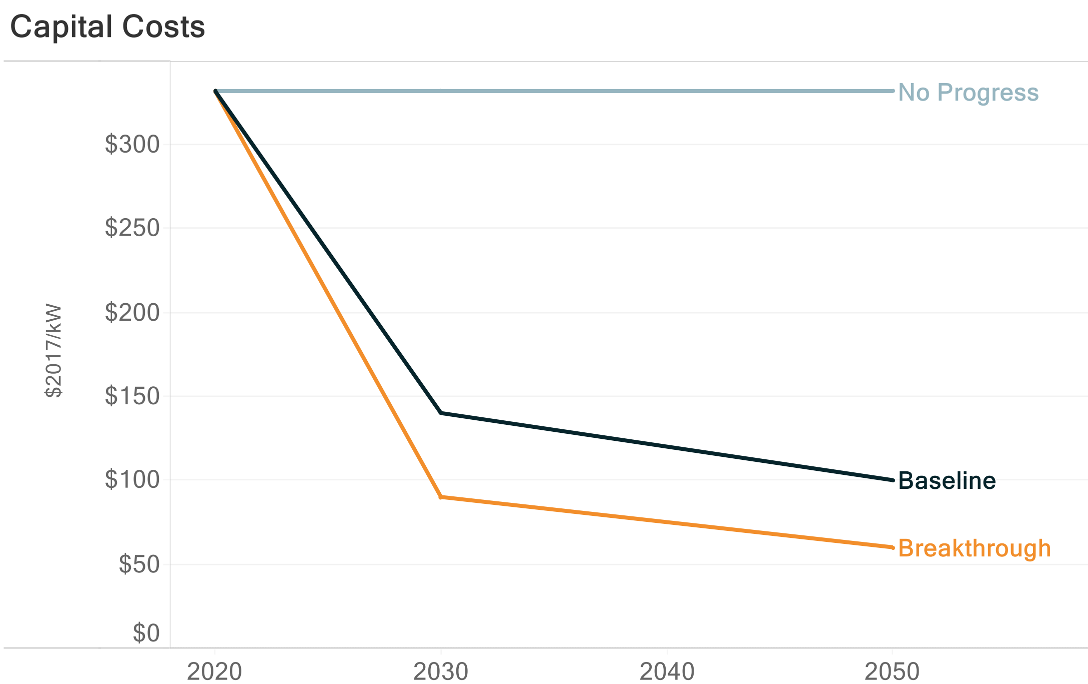


3.11. Mobile Fuel Cells

3.11.1. Overview

Fuel cell electric vehicles are powered by converting hydrogen to electricity using a fuel cell. Although there are alternative applications for fuel cells (e.g., distributed generation), they are most promising for mobile applications, particularly for freight transportation. Figure 48 summarizes fuel cell capital cost trajectories. Today's fuel cell costs are derived from the International Council on Clean Transportation (ICCT), and projections are based on a study published in the Proceedings of the National Academy of Sciences (PNAS).[17] Baseline capital costs use the upper estimate from PNAS, while a Technology Breakthrough assumes the median estimate from PNAS.

Figure 48
Mobile Fuel Cell Capital Cost Assumptions

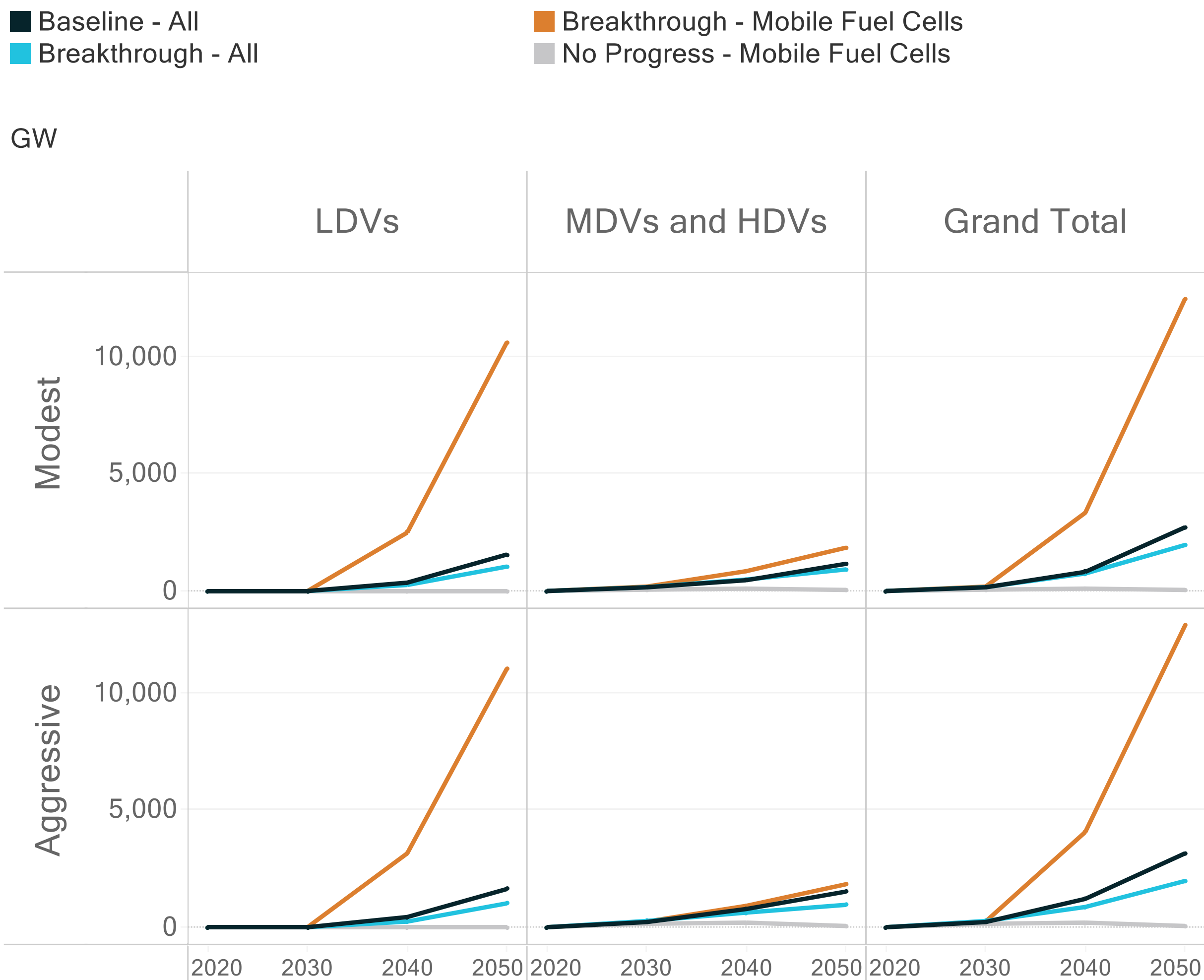


[17] See ICCT (2017) and Whiston et al. (2019).

3.11.2. Deployment

Minimal fuel cells for vehicles are deployed unless the technology realizes its own breakthrough while other technologies remain on a Baseline trajectory. This result is consistent across both Modest and Aggressive policy ambition and highlights the competitive advantage of electric vehicles.

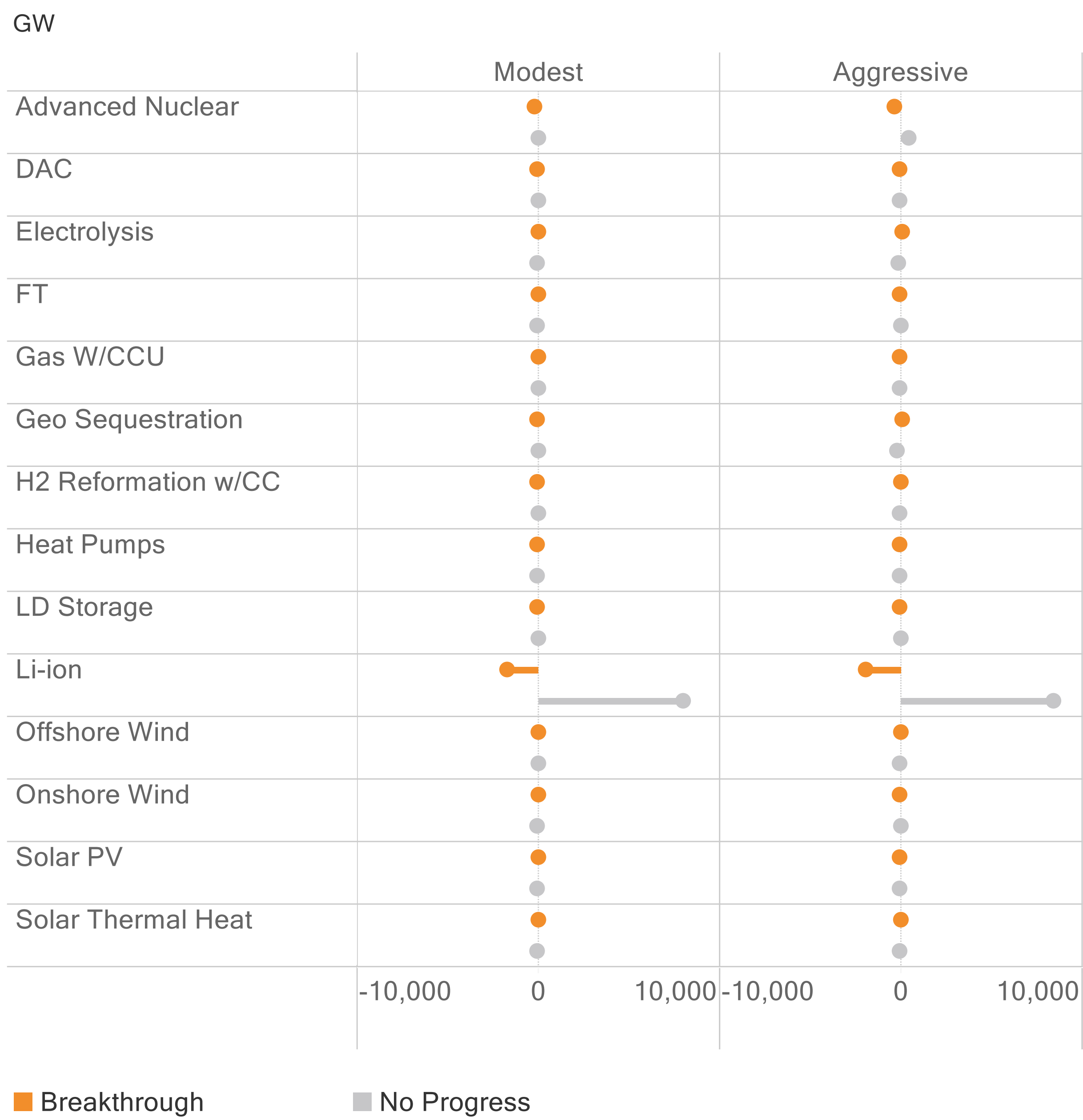
Figure 49
Mobile Fuel Cell Deployment



3.11.3. Technology Interactions

Mobile fuel cells demonstrate minimal interactions with other technology areas, as shown in Figure 50. No progress for li-ion represents the only meaningful upside for deployment, with all other technology areas showing muted impacts.

Figure 50
Mobile Fuel Cell Deployment Relative to the Baseline Trajectory



3.12. Heat Pumps

3.12.1. Overview

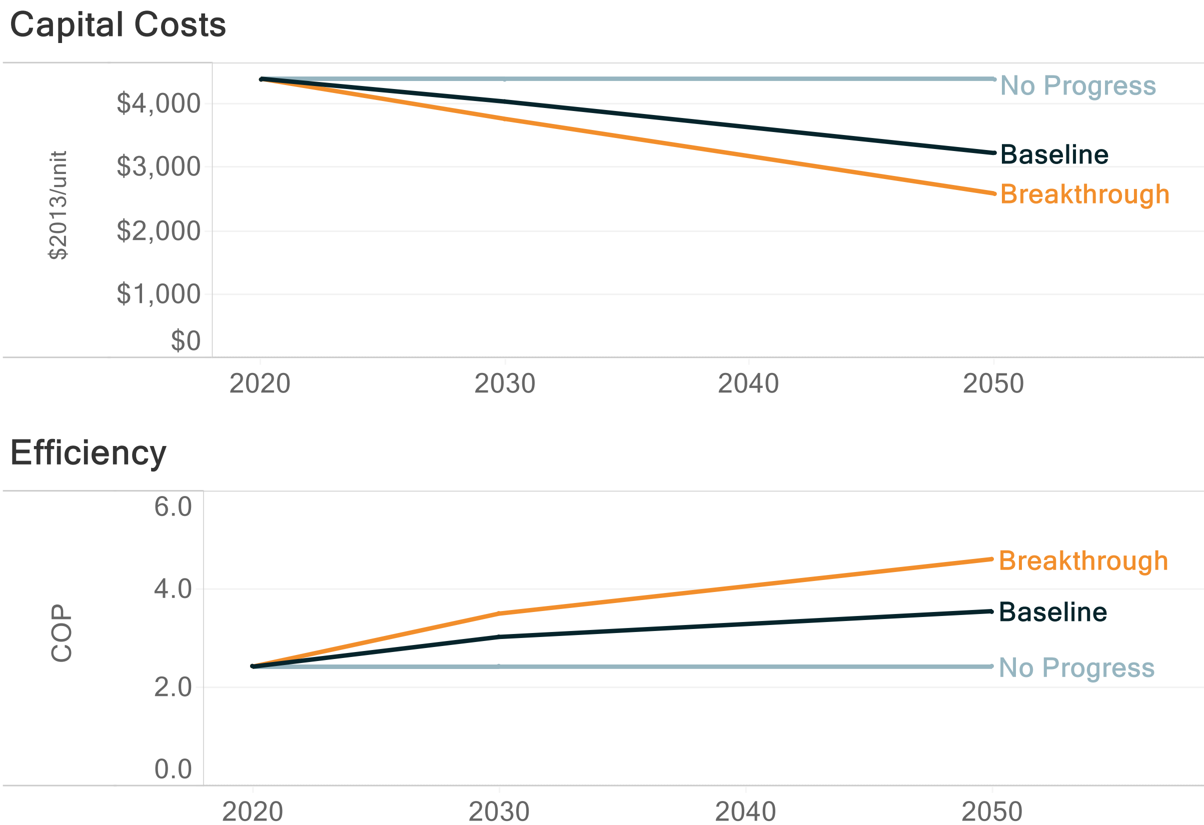
Heat pumps are a more efficient way to heat buildings than conventional alternatives like gas furnaces. Air-source heat pumps use electricity to transfer heat between a residence and the outside and are a promising technology to decarbonize buildings when paired with clean electricity. During the past decade, there has been significant improvements to the heating performance at low temperature conditions, which allows for deployment beyond temperate climates.

For this study, we consider the economic adoption of residential air-source heat pumps using cost and performance projections from NREL's Electrification Futures Study, as summarized in Figure 51.[18] The Baseline trajectory follow's NREL's 'Moderate Advancement' trajectory, while the Breakthrough trajectory follows the 'Rapid Advancement' projection.

[18] See Jadun et al. (2017).

Figure 51

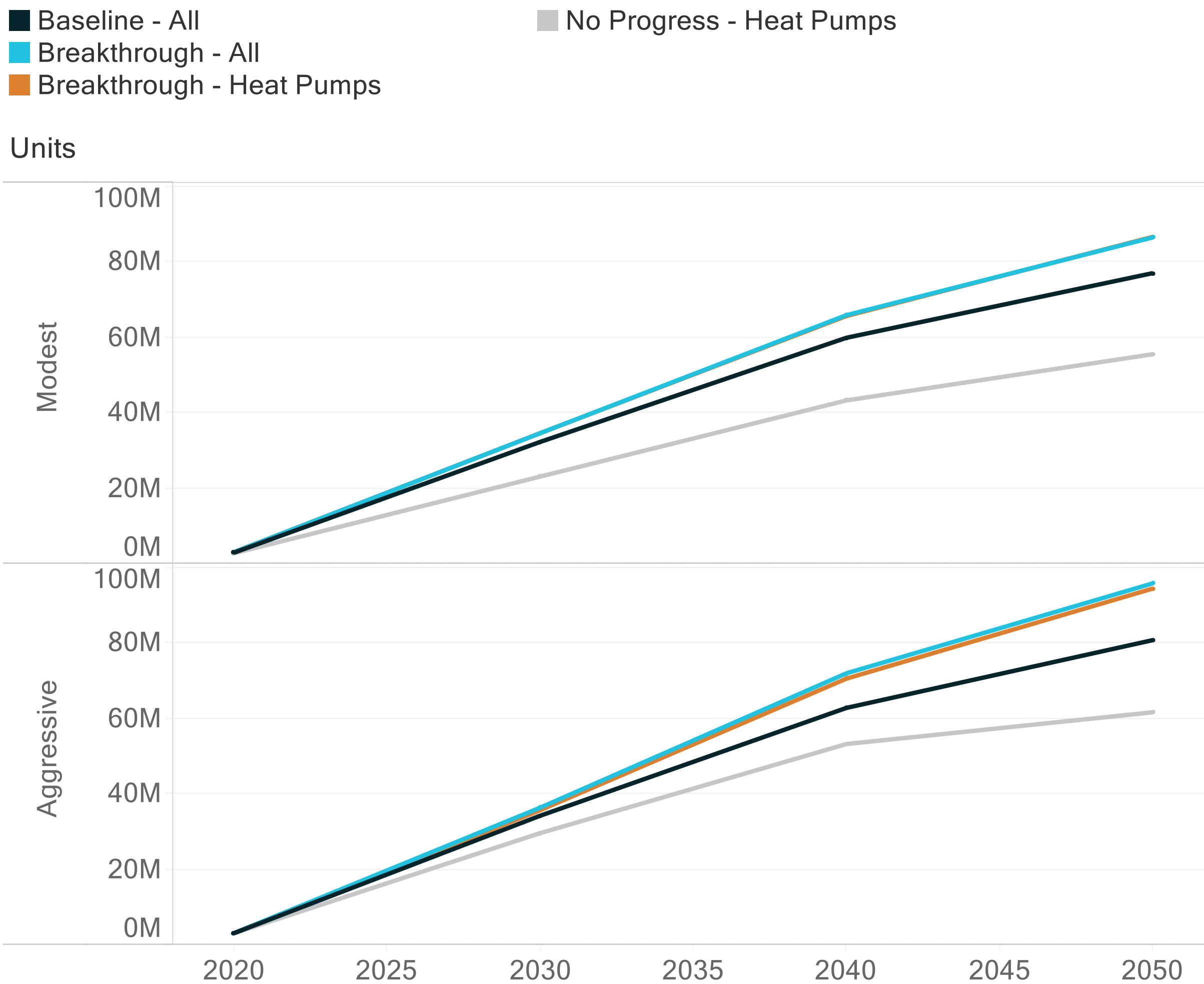
Residential Air-Source Heat Pump Capital Cost and Efficiency Assumptions



3.12.2. Deployment

Figure 52 shows deployment of heat pumps during the next three decades across policy and technology trajectories. Deployment is significant – growing to upwards of 55 million units by 2050 – even in the case of technological failure and modest policy. In other words, heat pump deployment is significant across cost trajectories since it is a low-cost strategy to decarbonize building space heating. R&D, reflected in lower capital costs and higher efficiencies, helps to reduce consumer costs. Deployment rises above baseline levels either when heat pumps or all technologies achieve breakthroughs. In the latter case, this is due to lower electricity input costs.

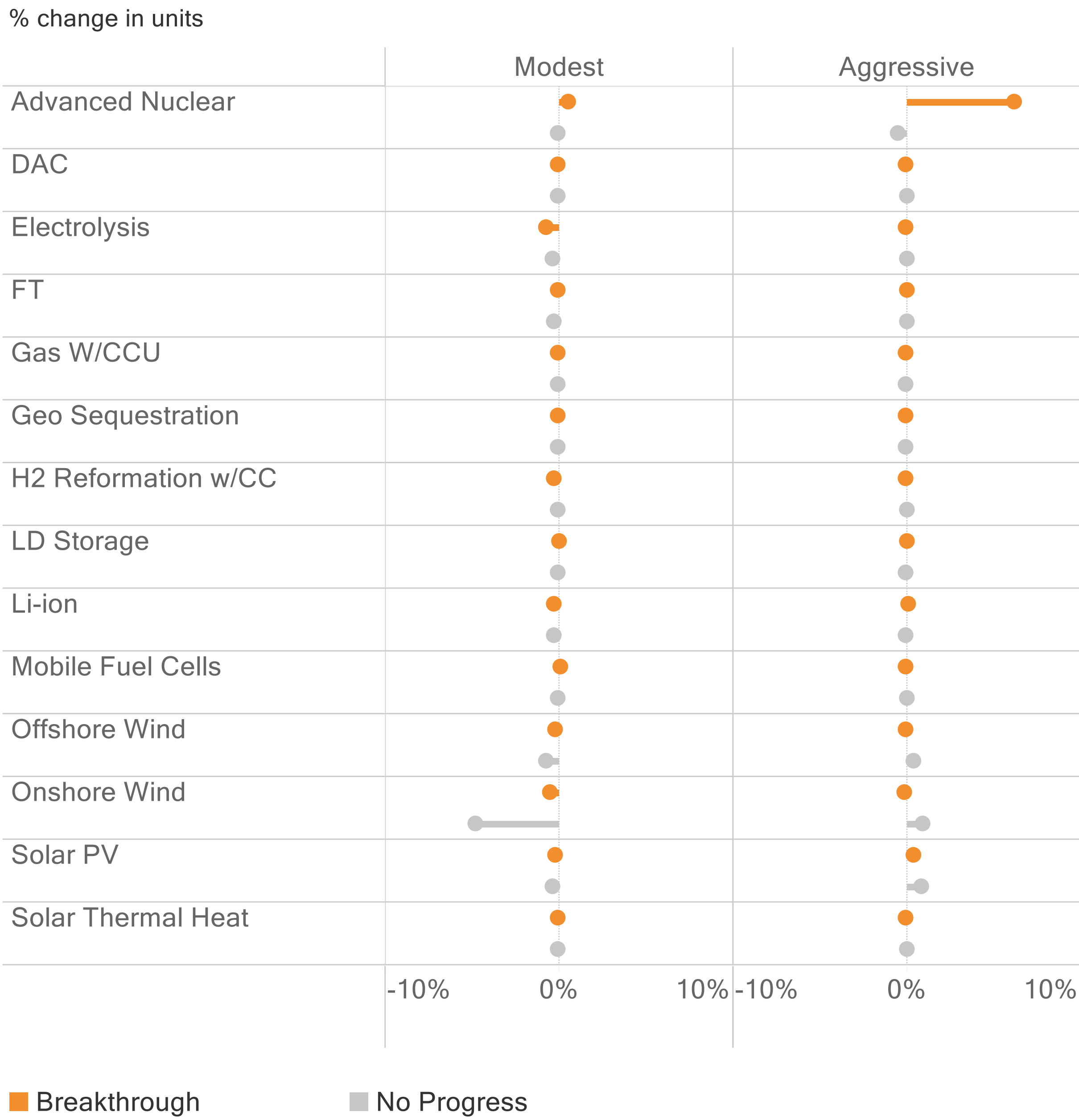
Figure 52
Residential Air-Source Heat Pump Deployment



3.12.3. Technology Interactions

Air source heat pump adoption shows minor interactions with other technology areas, and instead depends more on its own cost and performance trajectory. The limited interactions are generally regional differences in deployment depending on technology progress of clean electricity resources. For example, the proliferation of nuclear from a technology breakthrough could provide low-cost electricity that would incentivize further heat pump adoption, and this is typically in regions with colder climates.

Figure 53
Residential Air-Source Heat Pump Deployment Relative to the Baseline Trajectory

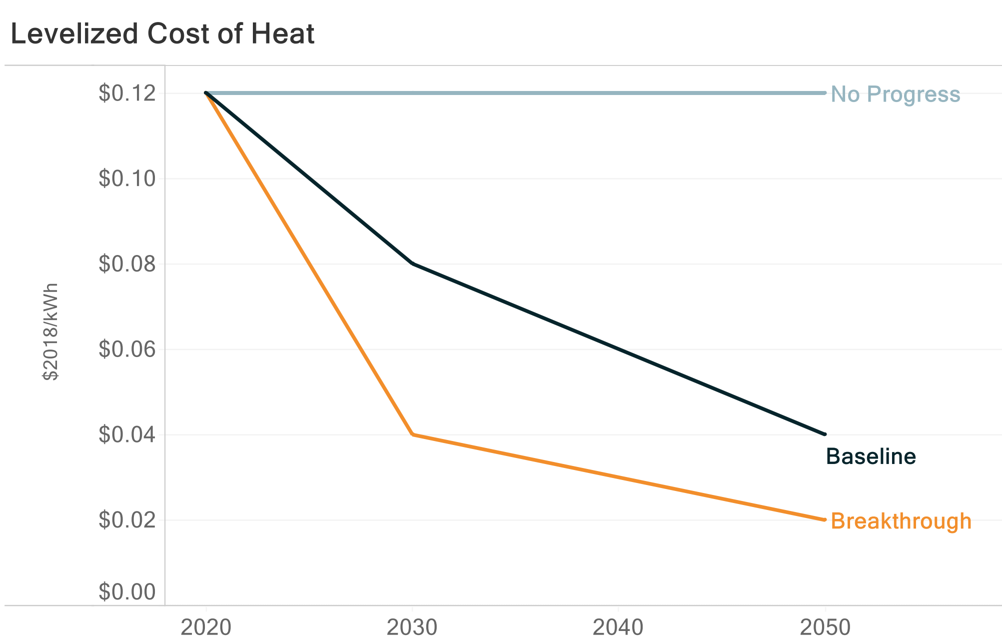


3.13. Solar Thermal Heat

3.13.1. Overview

Solar thermal is a technology that can be used to supply heat directly to industrial processes to avoid the use of fuel in industry. This is accomplished by collecting the sun's thermal energy and using the heat for industrial processes that today are overwhelmingly provided by fossil fuels. Heat demand and heat quality can vary considerably across industrial processes. In addition, the heterogeneity of industrial processes and industrial locations will likely complicate the story of industrial heat deployment. These results are therefore only directional in terms of the ultimate role solar thermal may play at the costs modeled here. We derived these cost trajectories, shown in Figure 54, from an IEA-ETSAP/IRENA study.[19] The Baseline levelized cost of heat is two-thirds below today's cost, while a technology breakthrough realizes a cost of 2 cents per kWh.

Figure 54
Solar Thermal Levelized Cost of Heat Assumptions



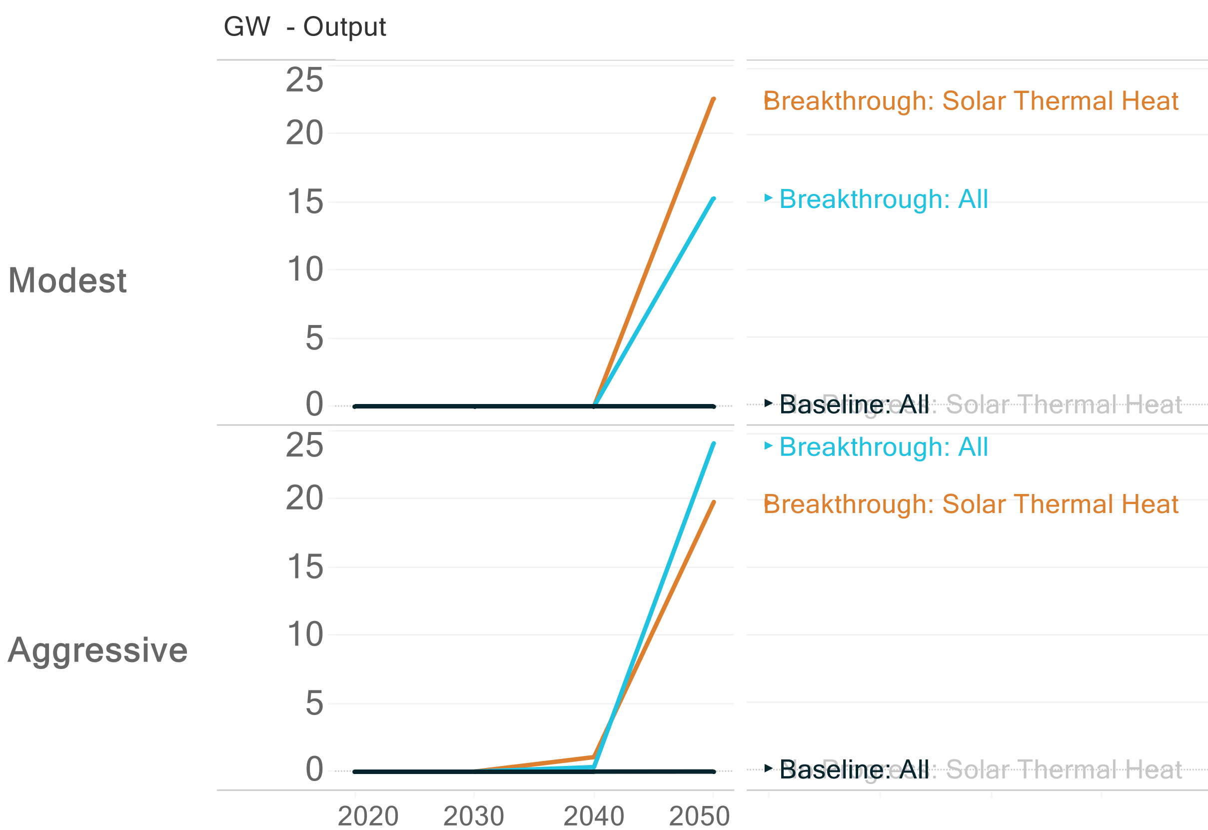
[19] See IRENA (2015).

3.13.2. Deployment

Solar Thermal Heat requires a technology breakthrough to realize significant levels of deployment, as shown in

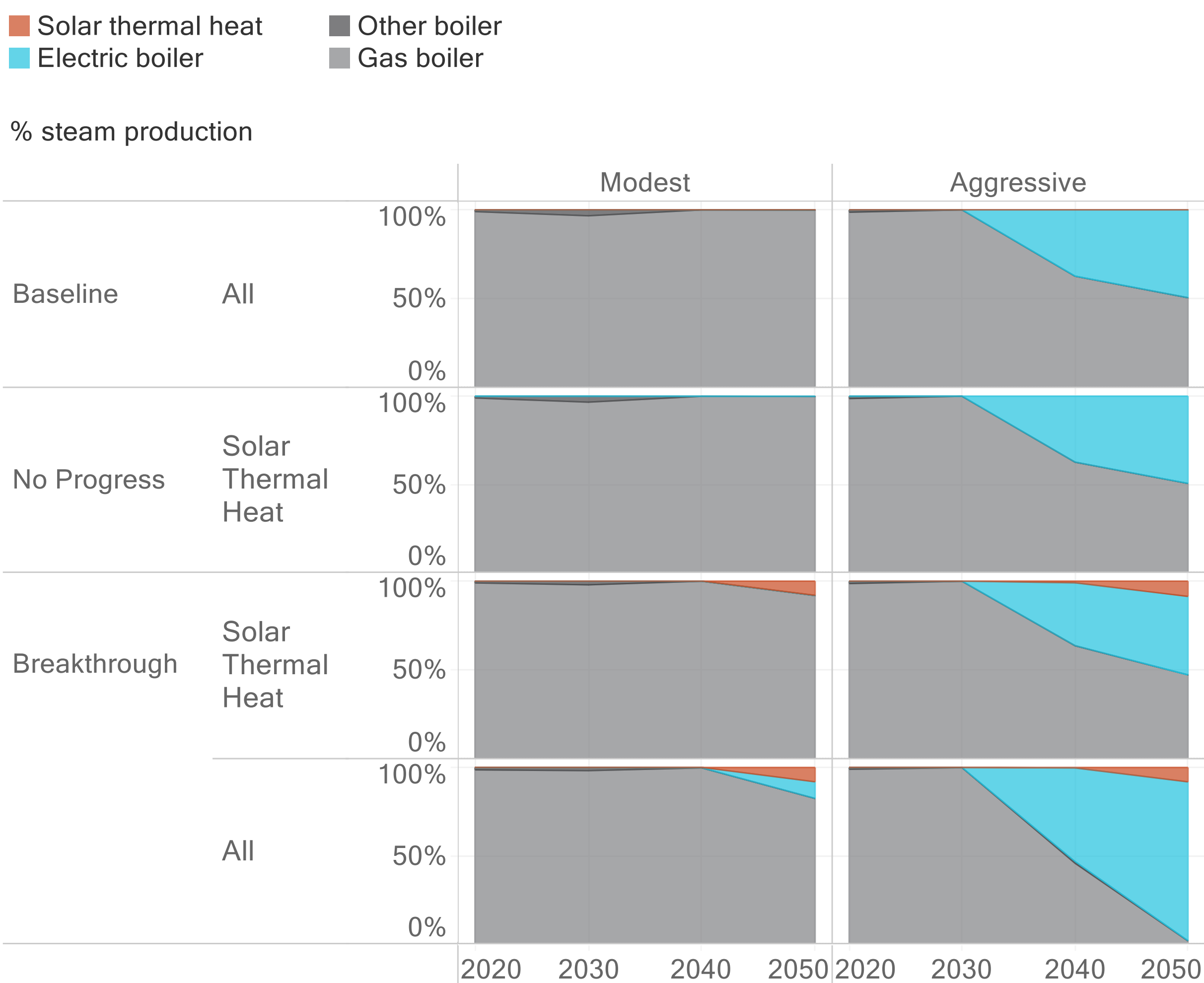
Figure 55. The large hurdle to deployment is due to key characteristics of competing gas and electric boilers that affect the economics of supplying steam: (1) gas boilers have very low variable costs due to the relatively low cost of natural gas; and (2) electric boilers can provide steam without emitting CO_2 and provide balancing to the electric sector, which solar thermal heat does not. Deployment with a breakthrough for solar thermal heat is lower under an aggressive policy context than a modest policy context because the emissions imperative (i.e., net-zero) attracts competition from electric boilers.

Figure 55
Solar Thermal Heat Deployment



Industrial solar thermal heat is relatively agnostic to technology progress in other technology areas, as well as policy ambition. Figure 56 shows the share of steam (heat) provided by boilers and solar thermal heat. Solar thermal heat provides approximately 10% of steam in 2050 if and only if the technology achieves a breakthrough. In all other policy and technology scenarios, only the shares of gas versus electric boilers vary depending on the relative cost of electricity.

Figure 56
Steam Production Share by Technology



3.13.3. Technology Interactions

Solar thermal heat deployment has no interactions with the technology areas considered in this study, as shown in Figure 57. This is because: (1) the technology does not use electricity as an input to produce heat; and (2) demand for heat (steam) does not scale significantly with deployment of other technologies (e.g., hydrogen demand scales with FT synthesis deployment).

Figure 57
Solar Thermal Heat Deployment Relative to the Baseline Trajectory

3.14. Direct Air Capture

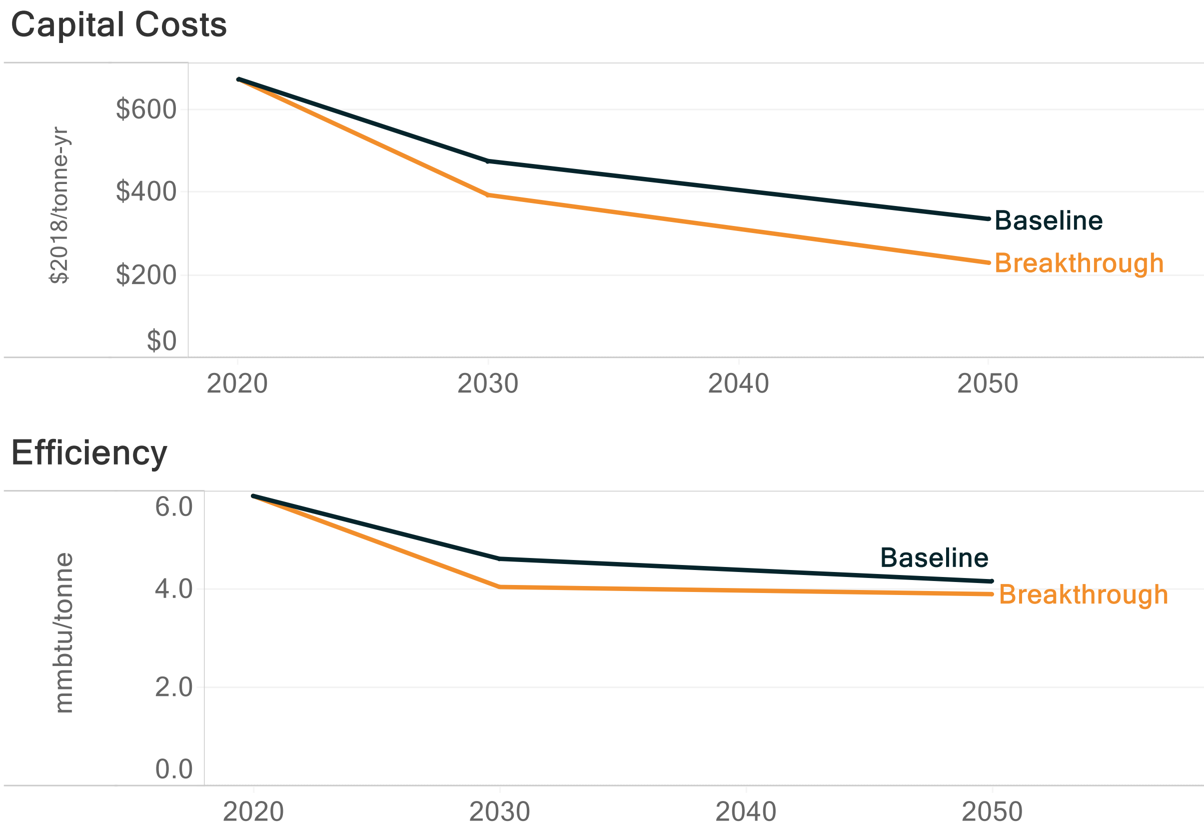
3.14.1. Overview

Direct air capture (DAC) is a technology that captures CO_2 from the ambient atmosphere. This is an alternative method of carbon capture, which typically involves capturing concentrated streams of CO_2 from sources such as power plants or industrial facilities that use biofuels (e.g., BECC). DAC is an energy-intensive process, and its economics depend heavily on energy input costs (electricity). Deployment is also affected by the availability and cost of alternative negative emissions technologies (BECCS), natural sequestration options (e.g., land sinks), and geologic sequestration opportunities.

Our technology trajectories are derived from a 2019 study published by the Rhodium Group which used learning rates to estimate future capital costs.[20] Baseline capital cost trajectories assume a 10% learning rate, which reduces capital costs to approximately $330 per tonne CO_2 by 2050, while the Breakthrough trajectory assumes a more aggressive learning rate of 15%. Our technology progress trajectories include declining energy usage per ton captured. Since the ultimate cost of DAC is related to the energy input necessary to capture carbon at low atmospheric concentration, then efficiency is an important parameter when examining its potential viability in emissions reduction scenarios.

[20] See Larsen et al. (2019). We assume 10 doublings by 2030 and 100 doublings by 2050.

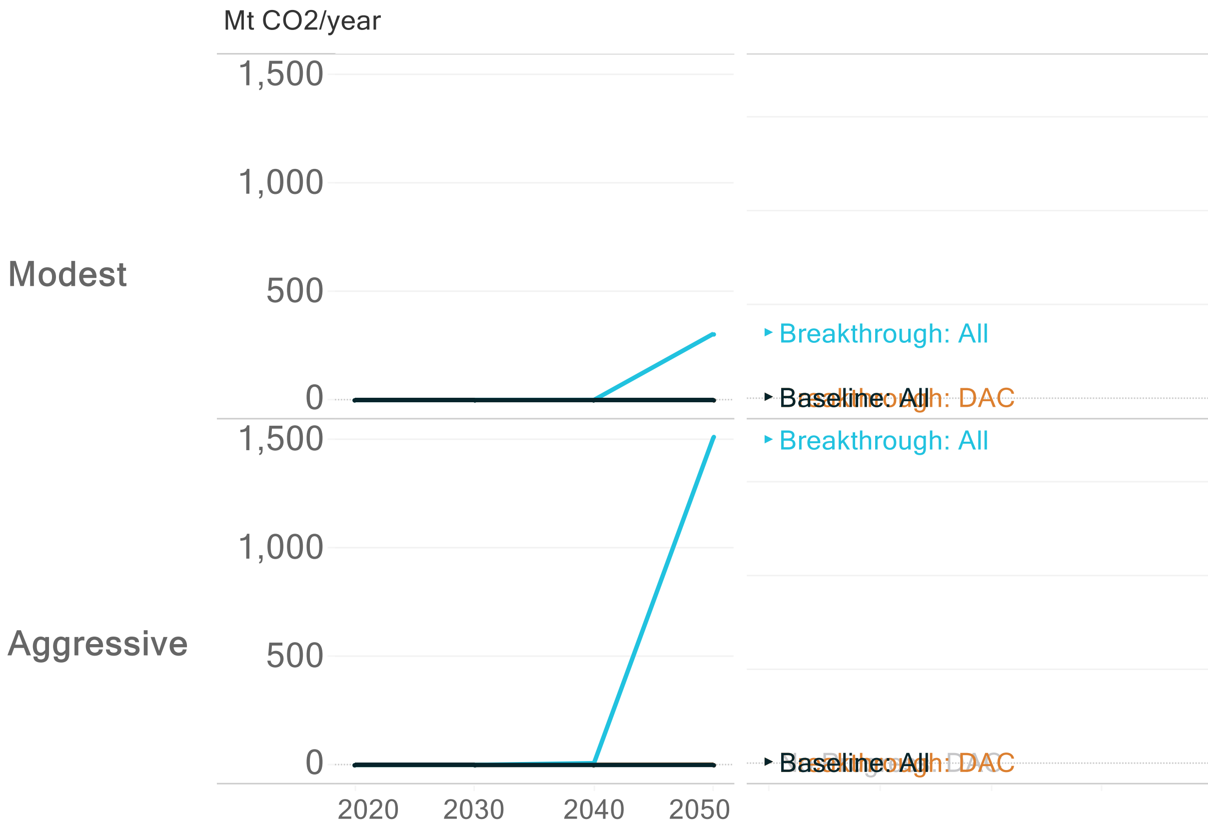
Figure 58
Direct Air Capture Capital Cost and Performance Assumptions



3.14.2. Deployment

Figure 59 illustrates the importance of other technologies to the value chain of DAC. Significant deployment only occurs when all technologies realize a breakthrough with deployment reaching 300 MMTCO2/yr under Modest policy ambition and increasing to 1,500 MMTCO2/yr with Aggressive policy ambition. Since DAC is a link in a chain, cost-effective deployment is driven by: (1) zero-carbon energy input costs (e.g., electricity); (2) hydrogen costs when the captured CO_2 is utilized as a feedstock for zero-carbon fuels; or (3) geologic sequestration costs when the capture CO_2 is stored.

Figure 59
Direct Air Capture Deployment



3.14.3. Technology Interactions

Figure 60 highlights the necessity for multiple components of the chain to realize technology breakthroughs in order for DAC to proliferate. A breakthrough in solar costs does increase DAC deployment, but individual breakthroughs in other components are not enough to affect deployment. Large-scale deployment (e.g., greater than 100 MMTCO2 per year) requires breakthroughs for both renewables, as well as electrolysis (CCU) and/or sequestration (CCS) costs.

Biomass availability and cost, although not an technology area of this study, would significantly affect DAC deployment since it represents an alternative source of captured CO_2. Lower biomass availability and/or higher cost would likely increase DAC deployment, and vice versa.

Figure 60
Direct Air Capture Deployment Relative to the Baseline Trajectory

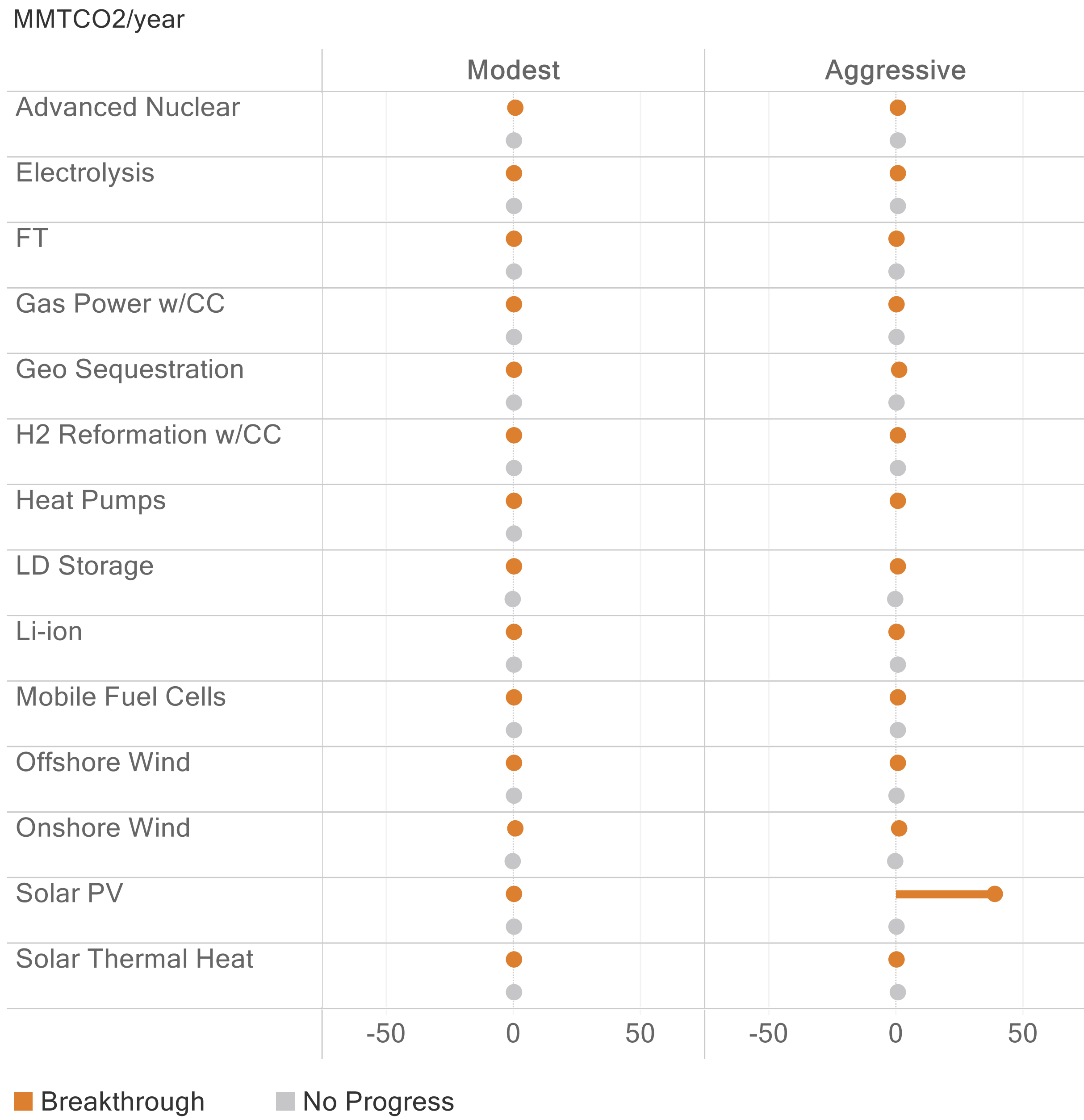
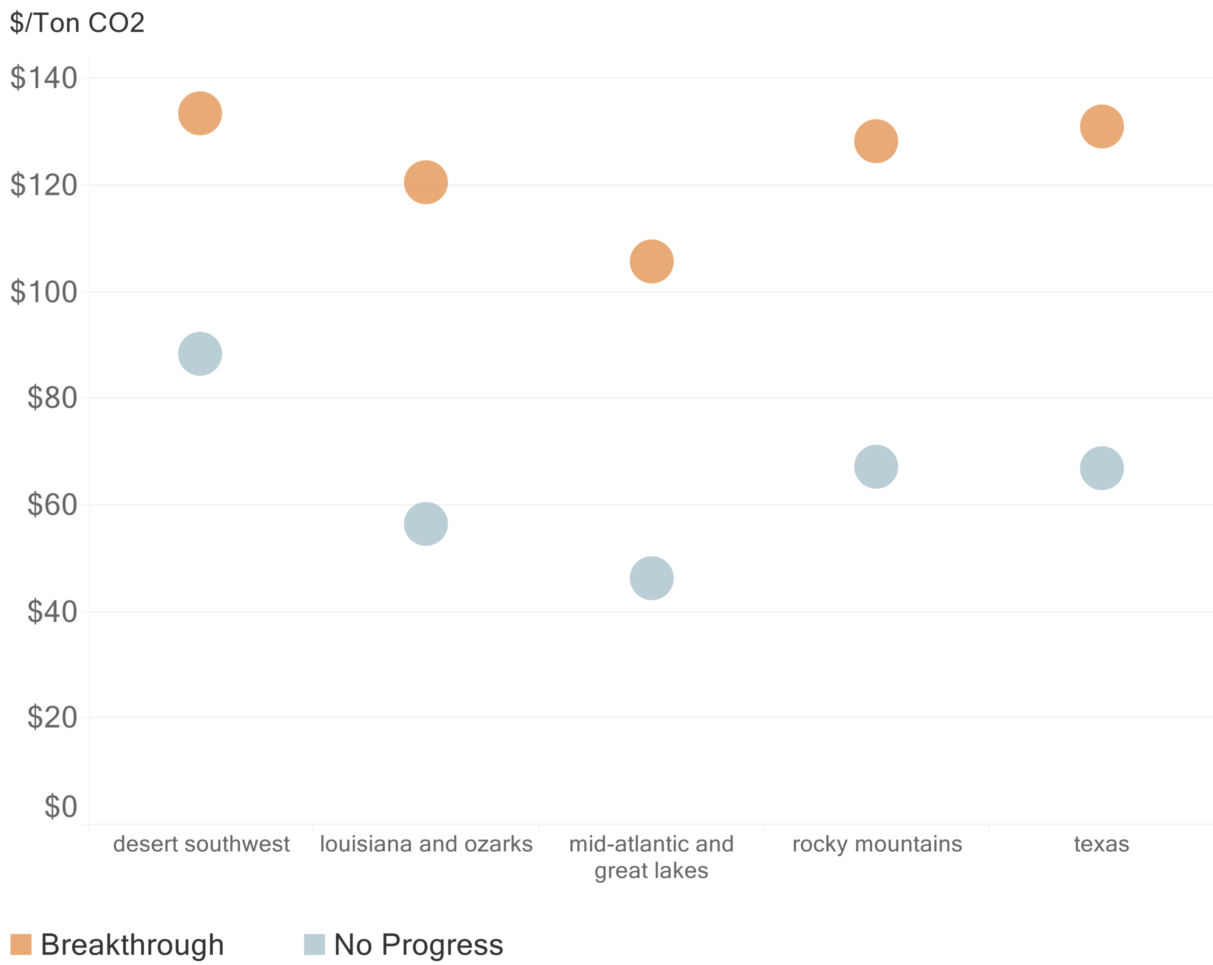


Figure 61 shows the importance of sequestration costs in regions with significant DAC deployment. This figure represents the marginal price of CO_2 capture from a negative emissions technology (NET), either DAC or bioenergy with carbon capture. When a NET can achieve this marginal price, it is deployed. With a breakthrough in sequestration, this marginal price increases, allowing DAC to have a relatively high cost of capture carbon ($110-$130/tonne). With no progress in sequestration, DAC has to achieve a lower cost of delivered carbon, with all marginal prices less than $100/tonne.

Figure 61

DAC Target Capture Price, 2050 under No Progress: Sequestration and Breakthrough: Sequestration



3.15. Geologic Sequestration

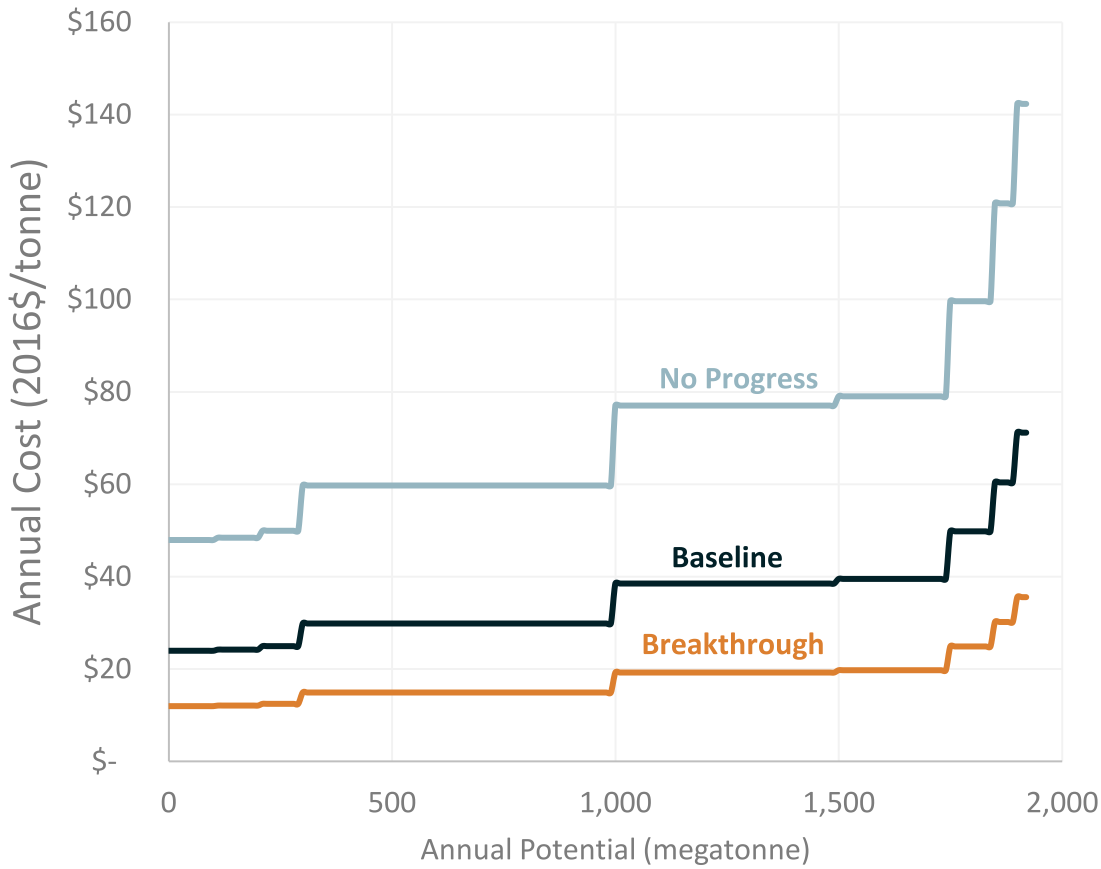
3.15.1. Overview

Geologic sequestration is the permanent storage of CO_2 in geologic formations. For this study, we rely on cost and potential of CO_2 storage in deep saline aquifers. Estimated potential varies considerably across the U.S., with a concentration in states along the Gulf Coast (e.g., Texas and Louisiana) and states with considerable natural resource extraction (e.g., Colorado and New Mexico). Regions with zero or minimal potential (e.g., Northeast) are assumed to be able to transport captured carbon to other regions with incremental transportation costs.

Our baseline sequestration cost and annual potential is derived from the National Energy Technology Laboratory's Saline Storage Cost Model.[21] As shown in Figure 62, approximately 1,000 megatonnes of sequestration is available at or below $30/tonne, and costs continue to rise upwards. We assume a Breakthrough in sequestration results in per-tonne costs that are 50% of Baseline costs, while No Progress is 200% of Baseline costs.

[21] See NETL (2017).

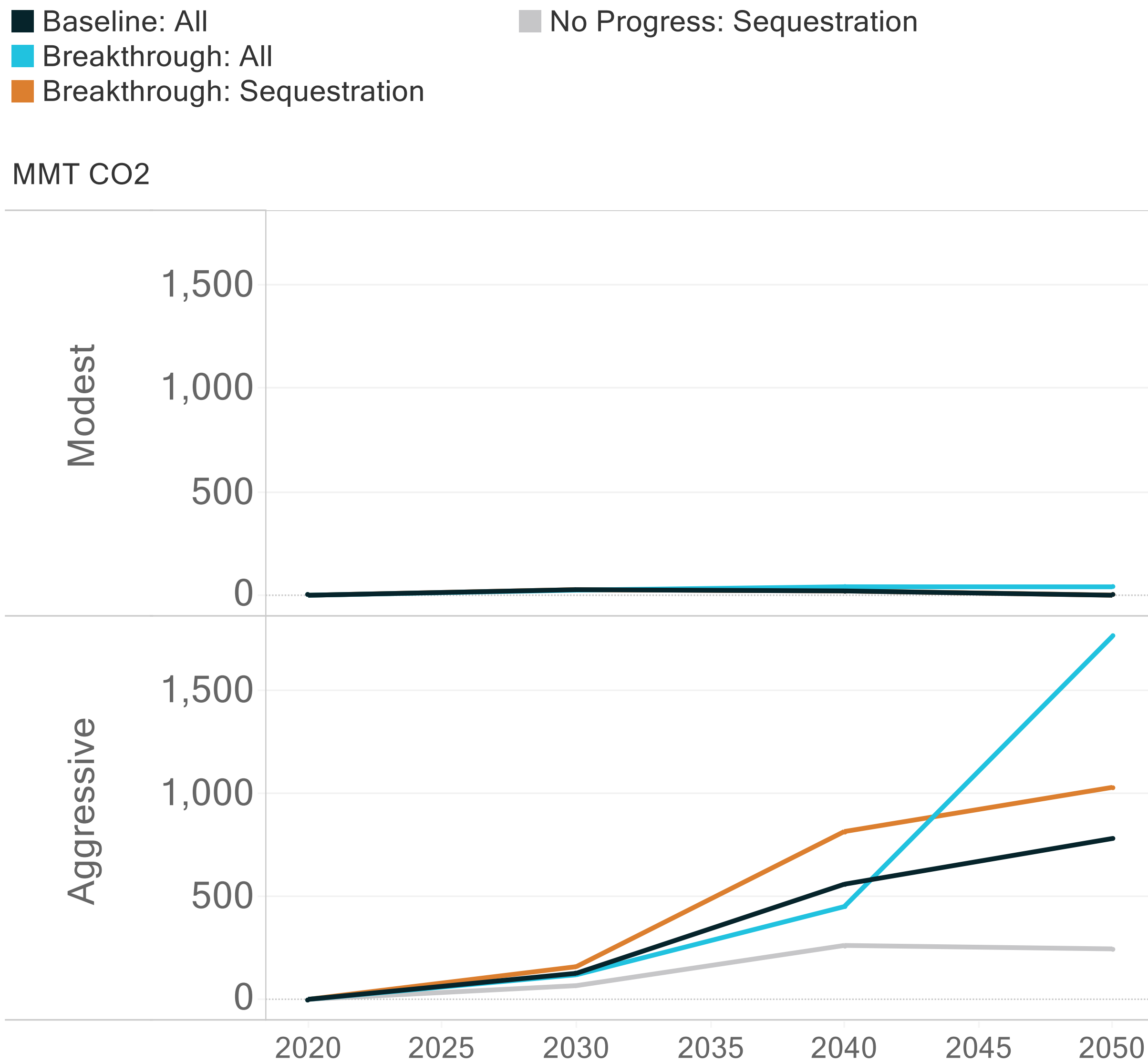
Figure 62
Geologic Sequestration Supply Curve, 2050



3.15.2. Deployment

Sequestration is a prevalent mitigation strategy with Aggressive policy ambition (e.g., net-zero energy system), but is not deployed with Modest policy ambition. Approximately 800 $MMTCO_2$ is sequestered in 2050 under baseline technology trajectory, and this increases to 1,000 $MMTCO_2$ with a breakthrough for sequestration and 1,700 $MMTCO_2$ when all technology areas realize a breakthrough. The increased supply of CO_2 in these scenarios largely comes from BECCS and DAC. If sequestration fails to reach its baseline trajectory, then deployment falls below 300 $MMTCO_2$ in 2050 and CO_2 is alternatively directed towards utilization.

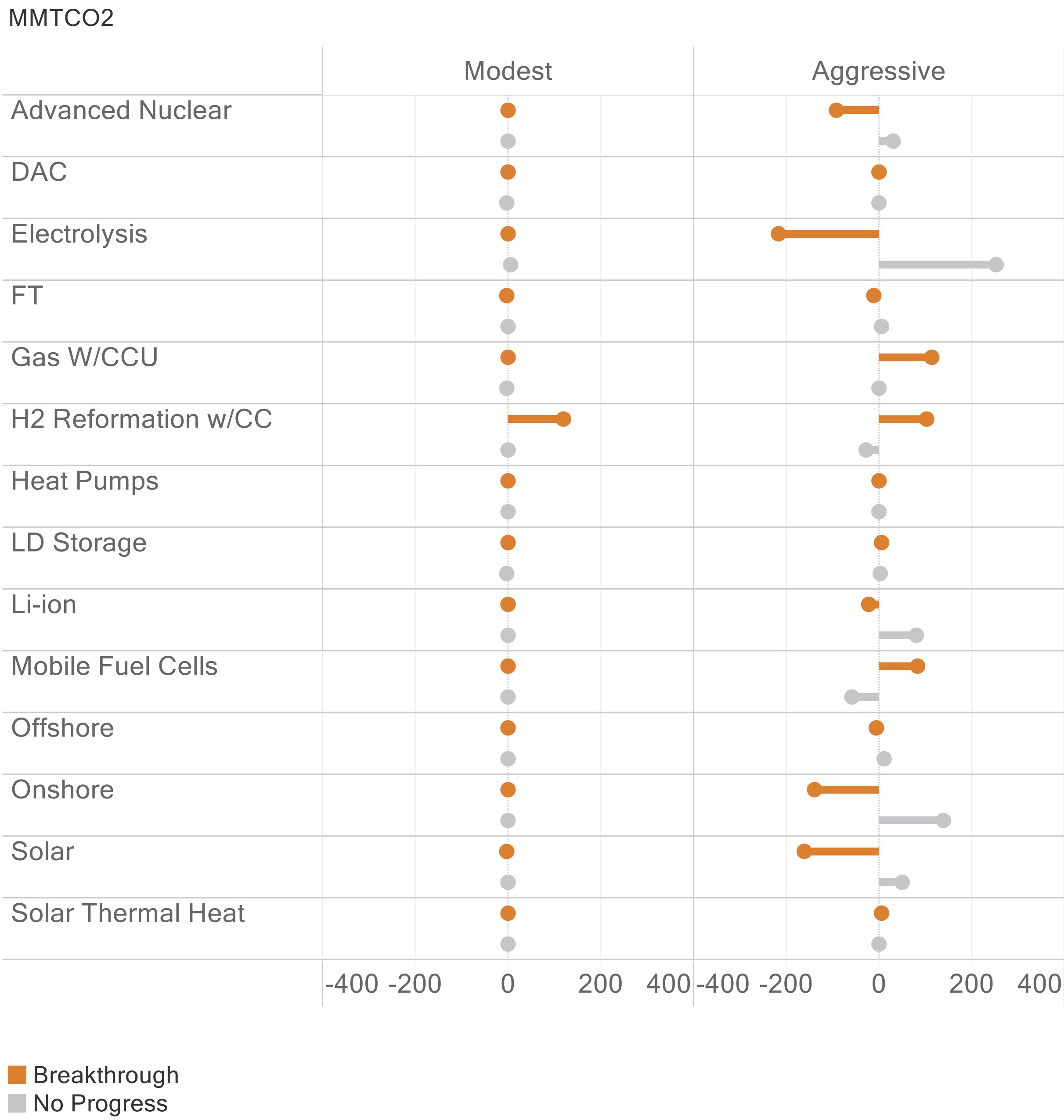
Figure 63
Geologic Sequestration Deployment



3.15.3. Technology Interactions

Figure 64 shows how alternative trajectories for other technology areas affect competition between the CCS and CCU value chains. Breakthroughs in electrolysis and renewable technologies improves the attractiveness of utilizing carbon and decreases sequestration deployment, while no progress in these technologies increases the attractiveness of storing carbon and increases sequestration deployment.

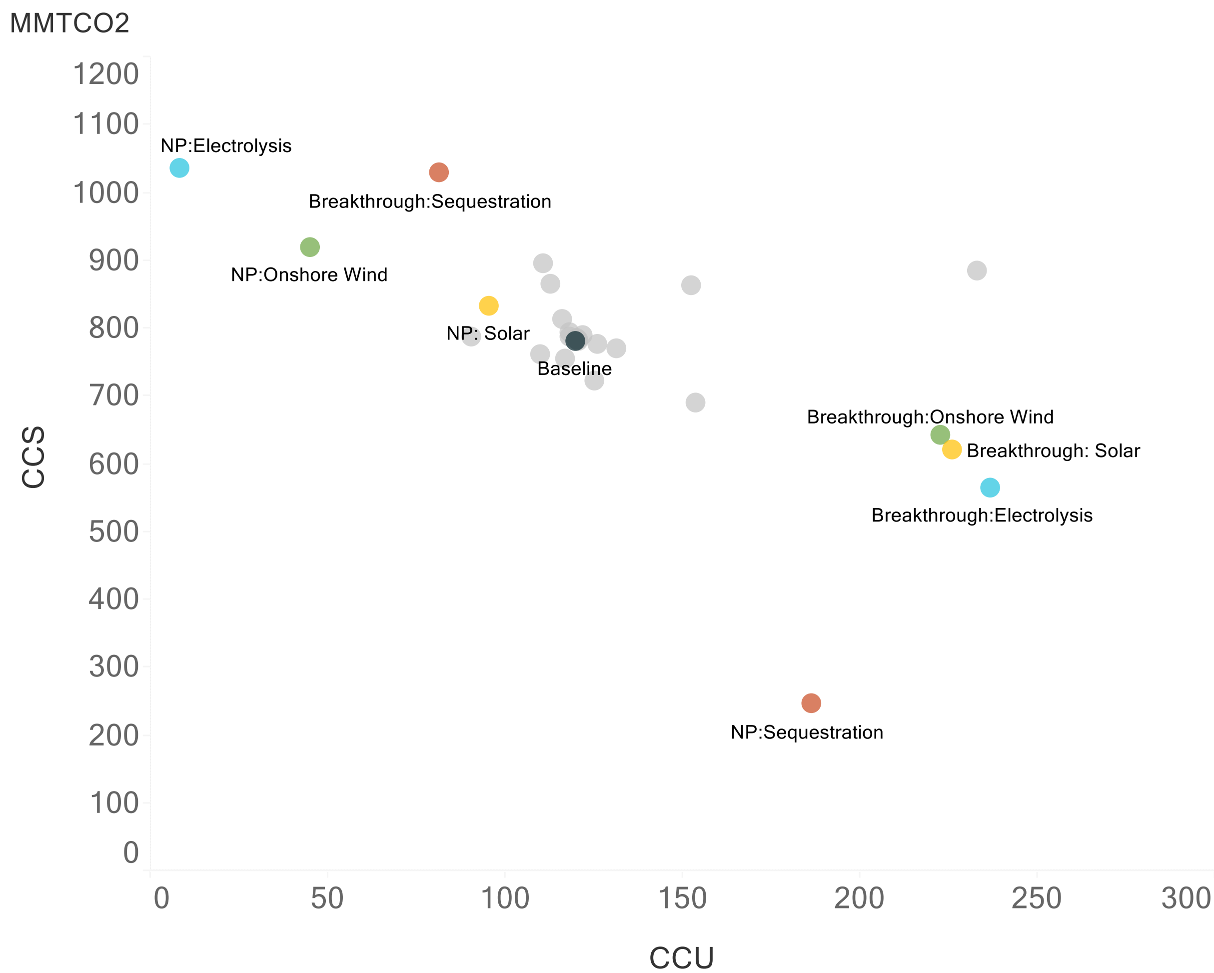
Figure 64
Geologic Sequestration Deployment Relative to the Baseline Trajectory



The competition between CCS and CCU is further illustrated in Figure 65, which plots CO_2 used for utilization (x-axis) against CO_2 geologically sequestered (y-axis) in 2050. Baseline carbon capture is approximately 900 MMT, with 120 MMT directed towards CCU and 780 MMT for CCS. Breakthroughs for electrolysis and renewables shift CO2 away from CCS towards CCU, and vice versa. The exception to this competition is when all technologies realize a breakthrough (not shown in the figure), which results in both CCU and CCS increases.

Figure 65

Carbon Capture Utilization and Storage, 2050: Aggressive Policy



3.16. Emissions Impacts

In this section, we discuss the impacts of R&D on energy-related CO_2 emissions outcomes. As discussed in section 2.4.2, we simulate achievement of both the Modest and Aggressive emissions targets assuming the *Baseline* technology trajectories. When the anticipated technology trajectories differ from the Baseline (e.g., *No Progress* or *Breakthrough*), realized emissions may deviate from the emissions targets, with no progress often increasing emissions above the target and technology breakthroughs decreasing emissions below the target.

Figure 66 compares annual emissions for the baseline against a scenario where all technologies achieve a breakthrough (“Breakthrough: All”) and a scenario where no progress is realized for any technology (“No Progress: All”). This is shown for the study’s two carbon policy ambitions, as well as no carbon policy ambition (Reference) to demonstrate the value of R&D in of itself. A universal breakthrough for all technology areas without carbon policy saves more than 1,000 MMT by 2050. At the Modest policy ambition, emissions are reduced to 1,100 MMT by 2050, which is far below the target of 2,500 MMT. A universal breakthrough with Aggressive policy realizes net-zero prior to 2050 and results in deep net negative emissions by 2050 due to additional synthetic fuel and CCS deployment.

The value of R&D is also apparent when assessing cumulative (2020-2050) emissions, as shown in Figure 67. Cumulative emissions with a universal breakthrough and Aggressive policy are less than half of the cumulative emissions with baseline technology progress and Modest policy ambition. If the study’s technology areas are unable to achieve their baseline cost and performance trajectories, then cumulative emissions under aggressive policy would increase by approximately 25 Gt, which is five years’ worth of present-day emissions.

Figure 66
Annual CO_2 Emissions

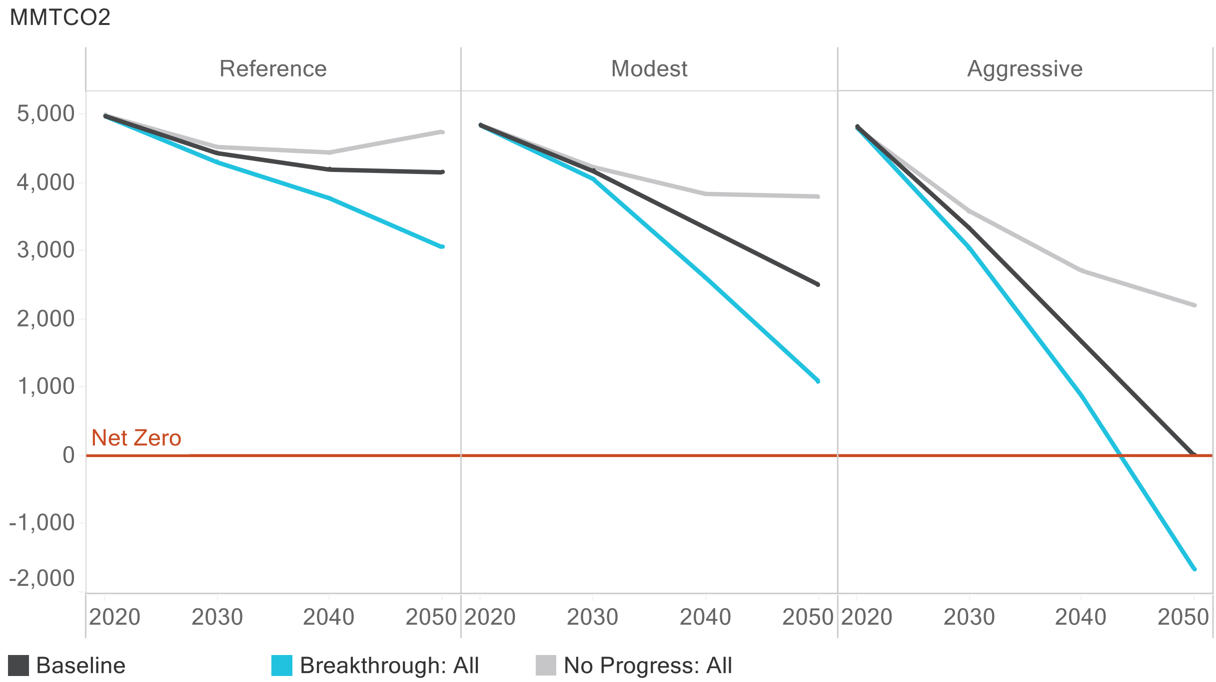


Figure 67
Cumulative CO_2 Emissions: 2020-2050

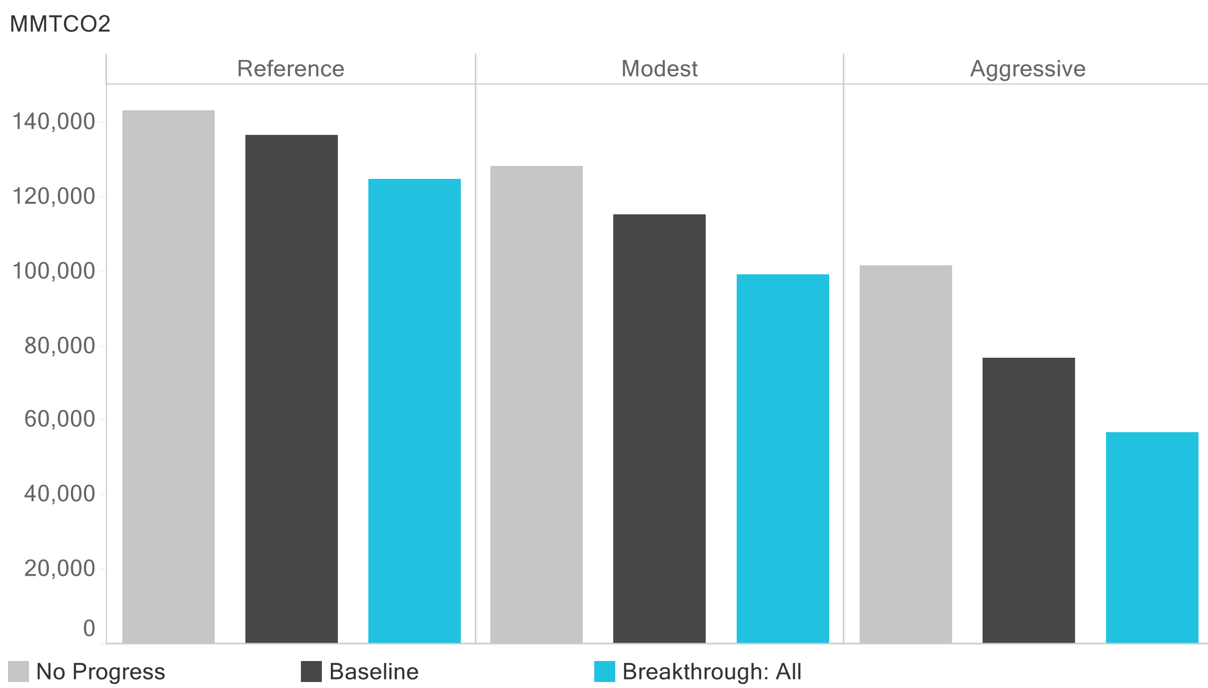
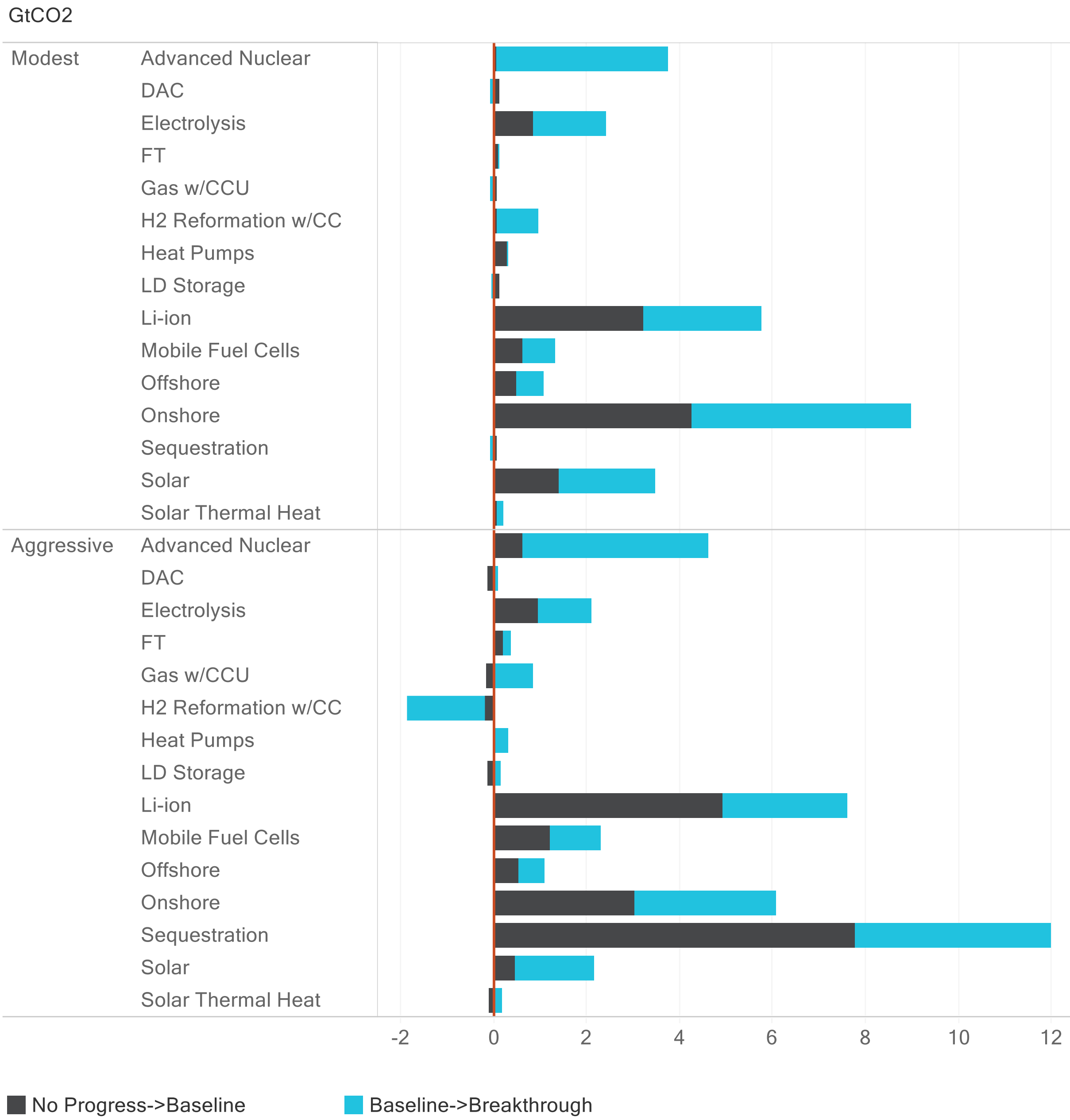


Figure 68 shows cumulative emissions impacts for *individual* technology areas rather than universal a breakthrough. Emissions savings are measured in two steps: (1) the impact from achieving baseline cost and performance for one technology area relative to no progress; and (2) the impact from achieving a breakthrough for one technology area relative to the baseline cost and performance. For individual technology areas, the impact may be minimal because: (a) technology progress for one technology area results in a substitution of clean technologies rather than displacing fossil emissions; or (b) deployment is minimal unless all technologies achieve a breakthrough instead of a single technology (e.g., direct air capture).

The ultimate trajectory of li-ion costs, specifically for vehicle applications, is hugely impactful as lower costs accelerates the timing and overall level of adoption, which translates into deep emissions reductions in the transportation sector at both levels of policy ambition. Technology progress for onshore wind plays a large role in emissions outcome by unlocking wind deployment in regions that would otherwise not be economic and encouraging more synthetic fuel production. Solar's emissions impact is smaller relative to onshore wind, because solar is already extremely competitive at providing a limited share of electricity demand. Emissions savings from nuclear only appear when the technology achieves a breakthrough, because its baseline trajectory is not especially competitive with renewables. However, a nuclear breakthrough would be valuable from an emissions perspective as it allows for more cost-effective decarbonization in regions with limited resource endowments.

Geologic sequestration, which had no deployment or emissions impact at Modest policy, shows significant potential to reduce emissions with Aggressive policy. Nearly 8 Gt CO_2 would be saved if its baseline costs are realized with an additional 4 Gt CO2 from a breakthrough, which highlights the important role CCS plays in cost-effectively achieving net-zero emissions. Emissions savings are negative for gas reformation with carbon capture when the technology achieves a breakthrough, because blue hydrogen production displaces supply from BECCS H_2, an important source of negative emissions.

Figure 68
Cumulative Emissions Savings from Tech Progress for Individual Technology Areas[22]



[22] Values in each bar are stacked.

4. Conclusions

4.1. Key Observations

Through this analytical exercise, we have identified areas of the energy system that would strongly benefit from additional R&D to deliver deep emissions reductions and lower costs. The highest priority, regardless of the policy context, is to continue the immense progress that has already been made in reducing costs and improving performance of renewable electricity generation technologies (**solar PV**; **onshore wind**; **offshore wind**). While some may assume that the low cost of renewables today suggests that their R&D can now be deprioritized, we find that continued cost and performance improvements significantly accelerate our ability to unlock an electricity system with very high levels of renewables and achieve cost-effective economy-wide decarbonization. First, continued technology progress for renewables enables fast emissions reductions in the electric sector, which is expected to decarbonize more quickly than other sectors. Second, low-cost renewables are complementary to hydrogen production (**electrolysis**), fuel synthesis (**Fischer-Tropsch**), and direct air capture of CO2 (**DAC**). These three technology areas benefit from lower electric input costs, but also enable more renewable deployment by providing large-scale, demand-side flexibility.

Advanced nuclear remains a potential silver bullet for decarbonization given its ability to provide reliable, low-cost electricity at all hours. This analysis suggests that breakthroughs in this technology, despite lagging behind renewable cost declines, would still be valuable and the resource could be competitive against lower resource-quality renewables in the medium to long-term. However, a true breakthrough is needed to play a major role and the question of whether that breakthrough can be achieved at reasonable cost is an open question.

On the consumer side, R&D should be directed towards reducing the cost of **li-ion** for electric vehicles and **heat pumps**, both of which would also benefit from lower-cost renewable electricity. Although consumer adoption decisions are less straightforward than other areas of the energy system, progress to reduce economic barriers should accelerate heat and transportation electrification.

Geologic sequestration is unique among the technology areas considered in that it's not an energy technology per se, but CCS is a feature of a net-zero energy system. There is significant value of continued progress to ensure large volumes of CO_2 can be stored in deep saline aquifers at reasonable cost.

Many of the remaining technology areas could benefit from additional R&D, but: (a) their impact is relatively small; (b) they demonstrate limited complementarity with the technology areas described above; and/or (c) their role is often as a "backup" technology. **Mobile fuel cells** are disadvantaged since their deployment is largely contingent on electric vehicle costs not continuing to decrease, the technology is more suited for trucks than automobiles, and interactions with other technology areas are limited.

Gas power plants with carbon capture are expected to only play a meaningful role in specific regions if renewable deployment fails to materialize due to non-economic barriers (i.e., siting). Although **long-duration storage** is commonly expected to proliferate with a renewable-heavy electric grid, it faces competition for renewable curtailment from other flexible loads that provide valuable products beyond the electric sector (e.g., electrolysis). Deployment could be affected by regional policy (e.g., 100% renewables instead of a technology-neutral 100% clean electricity standard) or the timing of competitor deployment.

Gas reformation with carbon capture's share of hydrogen production is expected to be limited due to the advantageous characteristics of electrolysis and biomass gasification with carbon capture (grid balancing and net-negative emissions, respectively). However, the ultimate competitiveness of the technology may rely on natural gas prices in a low-carbon economy and the availability of sequestration. **Solar thermal heat** deployment is constrained by geography and requires a breakthrough to overcome competitive disadvantages to gas and electric boilers.

4.2. Discussion

In a deep decarbonization context, systems thinking and context are imperative, and it's important to understand what the application of this framework implies for R&D funding and prioritization.

The first obvious and fundamental system context is the level of carbon policy ambition. This is implemented using a derived carbon price, but this is a model mechanic and not indicative of a preferred policy approach. Modeling results indicate that policy ambition is the most critical element to determining R&D priorities as well as relevant cost and performance targets. Relevant price and deployment potentials for many of the technologies investigated here are reflective of society's value of reducing emissions. Without this, there is no guiding principle to prioritize R&D.

Second, competitive landscapes are not always well understood. For example, some of the most critical breakthroughs for technologies is that it drives deployment in regions that are currently marginal. For onshore wind, the largest emissions impact comes from expanding the map of opportunity so that it can be deployed in areas currently considered marginal. This is just one example, but it can be applied to other technologies. Another example of a dynamic competitive landscape is that the 100th plant installed may face an entirely different set of economic challenges than the first. Electrolysis is an example where costs may increase with additional deployment as economic curtailment opportunities reduce, and biofuels that face higher costs for feedstocks is another place where such a phenomenon is possible.

Third, how technologies and approaches scale beyond cost trajectories is critical for understanding impact, because they are likely to be constrained in transforming our energy system by more than pure economics. Although cost targets are imperative for technologies, assessments of how they may reduce other barriers to technology adoption may be equally or more important. Are there wind technologies that reduce impacts on viewsheds to increase the social license for additional deployment? Can we overcome information barriers, old building codes, and principle-agent issues to enable rapid deployment of low-cost heat pumps? Are there battery technologies that can reduce the burden on rare-earth materials? Can nuclear technologies be deployed at existing (brownfield) sites as an uprate to currently operating facilities? Utilizing a framework such as the *Five Kinds of Capital* (financial, natural, produced, human and social) (Goodwin, 2003) to assess R&D may be useful to identify where non-economic barriers are likely to hinder economic deployment.

Finally, breakthroughs in one area may change the competitive price and performance points of technologies operating in another. Integrating technology programs across functions in low-carbon energy systems could provide additional insights. Examples include zero-carbon liquid fuels, carbon capture, carbon utilization and electricity balancing. Technology areas such as electrolysis and solar PV would fall into multiple programs.

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