Nuclear Power's Future Role in a Decarbonized U.S. Electricity System

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1 National Renewable Energy Laboratory
2 Electric Power Research Institute
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4 U.S. Environmental Protection Agency
5 U.S. Energy Information Administration

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Abstract

This study explores the roles of existing and next-generation nuclear power technologies in a decarbonized U.S. electricity system. Scenario analysis in four state-of-the-art electricity planning models explores the relative competitiveness of nuclear power across a wide range of policy and technology futures. Results from across the four models and scenarios reveal that disparate projections for nuclear power plant retirements are explained by different cost assumptions, and the economic deployment of new nuclear capacity requires a stringent emissions target or significant capital cost reductions. The combination of these drivers could result in substantial expansion of new nuclear power, which is operated more flexibly to complement widespread deployment of variable renewable energy technologies. Increasingly stringent emissions targets drive an evolution in the revenue streams for nuclear power plants and a pronounced increase in the cost point at which new nuclear capacity achieves competitiveness. More work is needed to refine cost projections and noneconomic factors that will influence the deployment of next-generation nuclear technologies.

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1 Introduction

Nuclear power has played an important role throughout the history of the U.S. electric sector, but its future role is uncertain. Most nuclear power plants in the United States have been operating for 30 to 50 years, typically with high-capacity factors and minimal fluctuations in their output due to their low short-run marginal costs. At the end of July 2022, in-service U.S. nuclear power plants totaled approximately 95 GW of capacity (EIA 2022).

Seven nuclear reactors (about 5.5 GW) retired between 2017 and 2022 due to sustained low natural gas prices, the growing deployment of zero-marginal cost generation, policy pressure, and the need for significant repairs or upgrades (EIA 2022). These drivers have been especially impactful for the half of the existing nuclear fleet that resides in deregulated wholesale electricity markets, where revenues are closely tied to wholesale electricity prices. Maintaining the existing nuclear fleet in the United States is expected to provide local economic benefits and help facilitate the transition to a decarbonized electricity system (J. Bistline 2021).

To mitigate the further retirement of existing nuclear power plants, state and federal governments have enacted policies to credit nuclear power for its zero-emission generation (NGA 2019). The *Inflation Reduction Act* (U.S. Congress 2022) *(IRA)* introduced a nuclear power production tax credit (PTC) for plants that are in operation in 2024 (Section 45U), which provides incentive payments through 2032 alongside support for existing nuclear in the *Bipartisan Infrastructure Law*. These recent policy actions have spurred efforts to reverse (or delay) the retirements of additional U.S. nuclear reactors.

The *IRA* also created a new technology-neutral PTC (Section 45Y) and investment tax credit (ITC, Section 48), which are designed to incentivize the deployment of zero-carbon electricity sources. Nuclear power's ability to qualify for these tax credits could help close the gap between current anticipated costs for next-generation nuclear technologies (NREL 2022) and the cost reductions that are likely needed for the deployment of new nuclear capacity (J. Bistline, James, and Sowder 2019). The relatively long duration of these technology-neutral incentives—through 2032 or until the U.S. power sector emits 75% less CO_2 emissions than 2022 levels, whichever is *later*—could be critical for ensuring incentives are still available when next-generation nuclear technologies have moved closer to cost competitiveness.

The existing literature contains a wide array of decarbonization studies for the U.S. electricity supply (Sepulveda et al. 2018; Tapia-Ahumada et al. 2019; Brown and Botterud 2021; Abdulla et al. 2019; Clack et al. 2021; Clune et al. 2020; de Sisternes, Jenkins, and Botterud 2016; Mileva et al. 2016; Motalebi et al. 2022; Sepulveda et al. 2021). Many of these studies have shown that having a firm capacity resource can significantly lower the cost of decarbonization (Sepulveda et al. 2018), but there isn't yet a zero-carbon technology ready to fill this role (Mai et al. 2022). Nuclear power is a familiar technology for many grid operators and utilities, and the widespread adoption of new nuclear power could facilitate an energy transition that requires fewer system changes (compared to a transition that relies almost exclusively on variable renewable energy resources). However, U.S. nuclear plant costs have historically exceeded expectations (Eash-Gates et al. 2020), and the extent of future nuclear deployment will likely depend on many factors: its ability to operate flexibly (Tapia-Ahumada et al. 2019; Jenkins et al. 2018); possible constraints on the deployment of variable renewable energy, transmission, and other lowemitting resources (Brown and Botterud 2021; Denholm et al. 2022; Jenkins, Luke, and Thernstrom 2018); and noneconomic factors that will influence the deployment of next-generation nuclear technologies (Abdulla et al. 2019).

This analysis provides new insights into how and when nuclear power could be competitive with other zero-carbon (and especially firm capacity) resources in a decarbonized U.S. electricity system. We perform coordinated scenario analysis in four state-of-the-art U.S. power sector planning (or capacity expansion) models, which run the same scenarios with a common set of input assumptions. Our explored future scenarios highlight impacts from ranges of future costs for next-generation nuclear power plants; costs associated with operating and maintaining existing power plants; and decarbonization policy trajectories for U.S. electricity supply. We further explain the investment and operational trends for nuclear power via the revenue sources and net-value of nuclear power plants with increasingly stringent emissions targets. Insights derived from these diagnostic scenarios are designed to inform discussions regarding the potential for nuclear power to provide firm, zero-carbon electricity in a fully decarbonized U.S. electricity system, within the deep decarbonization context that the *IRA* (U.S. Congress 2022) aims to accelerate.

2 Methods

The analysis presented in this report is rooted in the use of capacity expansion models (CEMs) for the U.S. power and broader energy systems. In general, capacity expansion models represent the balance of options among electricity generation, transmission, and storage assets that can satisfy demand for electricity, operating and planning reserve requirements, and policy measures. These models are typically set up to find the least-cost portfolio of assets that meet specified requirements, based on simultaneous decisions about capacity investments, transmission expansion, dispatch, and retirement of existing resources.

This work employs a model intercomparison approach using four state-of-the-art CEMs that create nation-wide projections for the U.S. electric sector through 2050 (Table 1). The same models have been employed in previous multi-model intercomparison studies focused on variable renewable energy (Cole et al. 2017) and energy storage (J. Bistline et al. 2020) technologies.

To facilitate comparison and to distinguish the relative roles of model structure and input assumptions, we reduced the influence of some impactful model features by harmonizing the following assumptions across all scenarios:

- Fuel Prices: These scenarios use EIA's Annual Energy Outlook 2021 "Reference" fuel prices for natural gas, coal, petroleum, and uranium. Note that natural gas prices in the 2021 "Reference" scenario are lower than current expectations.
- Carbon Removal ("Negative Emission") Technologies: All scenarios assume that bioenergy with carbon capture, direct air capture, and other negative-emission technologies are not included.
- Retirements: All scenarios incorporate a list of announced retirements for all capacity types (e.g., coal, nuclear, and gas), and assume that endogenous economic retirements can occur in any period. Models use an exogenous assumption that all remaining nuclear plants can operate for 80 years if economic (which is represented as an upper bound constraint).

However, each model was run with its own default structure, coverage, and demand assumptions, including the long-term growth of energy services, electricity demand, and hourly load profiles. In turn, some of the observed differences can be attributed to significant variation in demand profiles and other factors.

With these differences in mind, we defined a set of scenarios that were designed to explore potential future roles of existing and new nuclear power plants on the U.S. electric system (Table 1). We pursued scenarios that include both native and harmonized input assumptions; the former help to provide a better understanding of apparent discrepancies across model projections based on differences in input assumptions, while the latter help to isolate the effects of model structure that were hypothesized to significantly influence model decisions related to the retirement of existing nuclear power plants and investment in new nuclear power plants.

The primary dimensions explored in our scenario analysis include policy and technology sensitivities. For the policy sensitivities, each model explored a set of "Current Policies" and "80% by 2050" scenarios for the U.S. power sector. The Current Policies scenarios include state and federal policies and incentives that were on the books as of June 2021; importantly, this is before the enactment of provisions in the *IRA* (U.S. Congress 2022). The four participating models in this study reflect a range of on-the-books state and federal policies and incentives that impact the electric sector and energy system. State-level policies generally include renewable portfolio standards (including technology-specific carveouts for solar), clean electricity standards (with state-specific definitions of qualifying resources), offshore wind mandates, energy storage mandates, Zero-Emissions Credit (ZEC) policies for existing nuclear power plants, constraints on new nuclear capacity, and state-level CO_2 caps in the electric sector and economy-wide (such as California AB32, which is represented as a carbon tax based on projections by the California Air Resources Board). Regional policies generally include the Regional Greenhouse Gas Initiative (RGGI) cap-and-trade system. Federal policies and regulations generally include current Clean Air Act Section 111(b) new source performance standards for power plants, the PTC for solar, the ITC for wind, and 45Q tax credits for CO_2 capture.

The 80% by 2050 scenarios include a national power sector cap that begins at 2020 levels and linearly decreases to meet 80% reductions in power sector CO_2 emissions by 2050 (relative to 2005 levels). Most of the participating CEMs represented this hypothetical power sector policy as a carbon cap with free national trade and no banking, borrowing, or offsets. However, the NEMS model implemented an equivalent carbon tax proxy designed to achieve a similar level of emissions reductions.

The REGEN and ReEDS models further explore a set of "100% by 2050" scenarios for the U.S. power sector, which involve a national power sector cap that begins at 2020 levels and linearly decreases to a carbon-free electricity supply by 2050. The scenarios do not allow for consideration of negative emissions technologies, so the generation mix in 2050 includes only zero-emitting resources (e.g., solar, wind, energy storage, hydrogen-based combustion turbines [using hydrogen produced by electrolysis], nuclear technologies, geothermal, and hydropower).

Each CEM further layered these policy sensitivities with different technology cost assumptions:

- **Native Costs:** each CEM ran with its native cost and performance assumptions for all technologies, which provides a baseline for understanding how all model differences contribute to disparate U.S. electricity supply projections.

- **Harmonized Costs:** each CEM implemented exogenous cost trajectories from NREL's 2020 Annual Technology Baseline (NREL 2020) for all generation technologies. See Figure 1 for a comparison of native and harmonized capital cost assumptions for key technologies.

- **Breakthrough Nuclear Costs:** in addition to the Harmonized Cost and Financing assumptions (previous bullet), all models adopted reduced fixed operation & maintenance (FOM costs for existing nuclear power plants and a very low-cost trajectory for new small modular reactors (SMRs) that are deployed in 2035 and beyond (J. Bistline, James, and Sowder 2019).

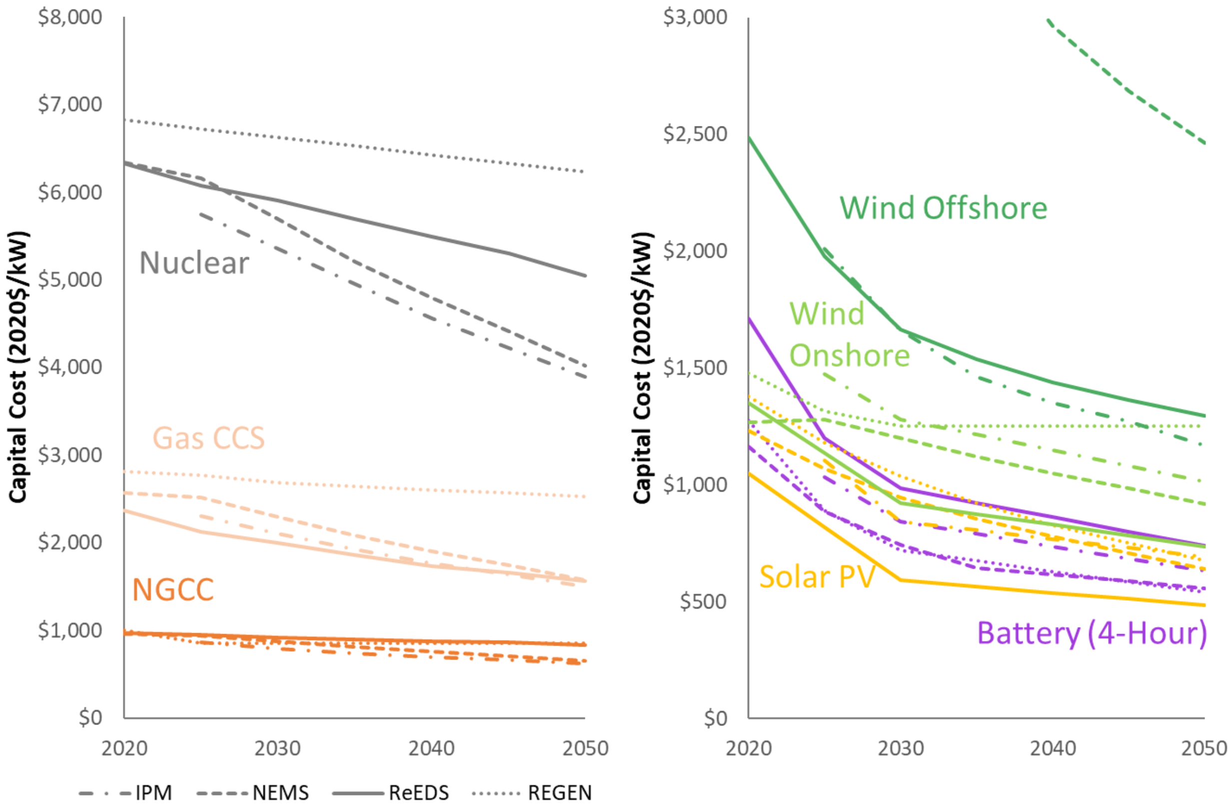

Figure 1. Comparison of native capital cost assumptions by technology and model over time.

The full set of dimensions explored in our scenario analysis is summarized in Table 1. The technology cost assumptions for nuclear technologies in Table 1 represent overnight capital costs, and therefore do not include capitalized financial costs or interest during construction, which can be sizable for the long construction times associated with nuclear power plants. For example, the Annual Technology Baseline (NREL 2020) includes a construction finance multiplier of 17%, which is applied to convert between overnight capital cost (reported in this study) and total capital expenditures. For context, the harmonized overnight capital cost assumptions in this study ($5.6/W in 2035) are on the lower end of recent nuclear power plant projects in North America, South America, and Western Europe but comparable to projected future values (Ernst 2023).

Table 1. Dimensions explored in our scenario analysis

Dimension	Description
Capacity Expansion Models	IPM® (U.S. EPA 2021) is a multi-regional, dynamic, deterministic linear programming model of the contiguous U.S. electric power sector.
	NEMS (U.S. EIA 2019) links the U.S. energy and macro-economy sectors to allow it to evaluate the impact of economic feedback with endogenous energy sector development on the evolution of U.S. energy markets
	REGEN (EPRI 2020) integrates a detailed electric sector capacity planning and dispatch model with an economic model of non-electric sectors capturing end-use technology tradeoffs
	ReEDS (Ho et al. 2021) is an electricity-sector-only model with high spatial resolution, representing wind and solar resources with up to 50,000 individual sites each
Technology Cost Assumptions for Non-Nuclear Technologies	Native: Each model adopts its native assumptions
	Harmonized: All models adopt the same overnight capital and fixed and variable operations and maintenance costs (NREL 2020)
Technology Cost Assumptions for Nuclear Technologies	Native: Each model adopts its native assumptions
	Harmonized: All models adopt overnight capital costs for new nuclear capacity that decline slowly over time, reaching $5.6 per watt in 2035 and $5 per watt in 2050 (NREL 2020) (in 2018$)
	Breakthrough: All models adopt overnight capital costs for new nuclear capacity that drop to $2 per watt in 2035 and beyond (J. Bistline, James, and Sowder 2019) (in 2018$)
Power Sector Decarbonization Assumptions	Existing Policies Only (as of June 2021): This analysis was performed prior to the passing of the Inflation Reduction Act
	80% below 2005 levels by 2050: All models represent emissions targets without negative emissions technologies or end-use electrification
	100% decarbonization by 2050: REGEN and ReEDS represent emissions targets without negative emissions technologies or end-use electrification
Natural Gas Prices	We use the 2021 Annual Energy Outlook's "Reference" fuel price assumptions, which include natural gas price projections that are lower than current expectations

On the other hand, the Breakthrough technology cost assumption for next-generation nuclear technologies ($2/W in 2035 and beyond) is well below empirical data from many countries. Table 2 presents actual and predicted costs for nuclear reactors that were built (or are currently under construction) in North America, South America, and Western Europe over the last 20 years.[1] A review of the data in Table 2 shows that reactors are becoming more expensive (in real dollar terms), and that SMRs currently represent the most expensive projects. The latter is partially explained by the fact that SMRs are an emerging technology.

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[1] For comparison, the default cost assumption used in this study ($5.6/W) represents an overnight capital cost value in 2018$; converting this default cost assumption into the metric and unit used in the final column of Table 2 would correspond to a table entry of $7.1/W (similar to the top row).

Table 2. Actual and predicted costs for nuclear reactors that were built (or began construction) between 2016 and 2020

Country	Reactor	Accumulated Costs (million nominal $)	Cost year	Cost Estimate Type	PPI Inflated Price (2020$)	Power (MWe)	Price per watt capacity (2020$)
USA	Watts Bar 2 part 2 (20% + mods)	$4,700	2016	Actual	$5,398	1165	$7.2
USA	VC Summer 1 (40% completed)[2]	$12,500	2017	Projected (cancelled)	$14,235	0	--
Argentina	CAREM-25	$685	2018	Mid-construction estimate	$743	25	$29.7
Finland	Olkiluoto 3	$12,400	2019	Actual without IDC for overages	$12,749	1600	$8.0
France	Flamanville 3	$22,000	2020	Actual	$22,000	1640	$13.5
USA	Vogtle 3[3]	$15,170	2022	Actual	$12,076	1117	$10.8
UK	Hinkley Point C1[4]	$20,000	2023	Pre-construction price estimate	$15,094	1630	$9.3
USA	NuScale / UAMPS	$9,333	2023	Pre-construction price estimate	$7,160	462	$15.5

That being said, the Breakthrough technology cost assumption for next-generation nuclear technologies is comparable to recent overnight costs in South Korea and to historical costs in the United States and France (Lovering, Yip, and Nordhaus 2016). This very low-cost sensitivity is not meant to be predictive but instead is illustrative of how model responses change across scenarios with different nuclear cost assumptions.

The insights presented in this report focus on capacity, generation, and capacity factors for nuclear technologies, which represent just one of the available firm capacity technology options; indeed, each model is allowed to (and typically does) invest in other firm technology options such as long duration energy storage (e.g., compressed air energy and pumped hydro storage), carbon capture and storage, and new geothermal technologies. While these long-term planning models produce other output metrics of interest, those results are not presented here because they are dominated by scenario definitions. For example, the power sector emissions targets analyzed

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[2] The same values apply to VC Summer 2.

[3] The same values apply to Vogtle 4.

[4] The same values apply to Hinkley Point C2.

in this study define carbon dioxide emissions over time (which are closely related to criteria pollutant emissions). In addition, system costs inherently scale with decarbonization policy, and they are somewhat artificially lowered by assuming significant cost reductions for a zero-emissions generation technology (e.g., our Breakthrough nuclear cost assumptions).

3 Results

3.1 The Future Role of Existing Nuclear Power Plants

We evaluate the future role of existing nuclear power plants based on the potential for economic retirements and more flexible operations. All models assume extensions of nuclear operating licenses, such that existing nuclear power plants can operate for 80 years when economic; however, each model also allows for the retirement of nuclear power plants that cannot achieve sufficient revenues. While the results can help inform discussions related to U.S. energy policy and research and development priorities for nuclear power, they do not represent explicit policy analysis, recommendations, or critiques of ongoing legislative or regulatory discussions.

We observe a wide range of economic nuclear retirements across the models and scenarios explored (Figure 2), which speaks to the cost and policy factors that influence nuclear power plants' ability to achieve sufficient revenues based on simulated energy and capacity prices. In the absence of new power sector emissions targets (left column), the models project between 0 GW and 42 GW of nuclear retirements by 2050. The IRA provides a production tax credit to existing nuclear power plants through 2032, which will help support continued operation of some plants that otherwise may have retired during that time.

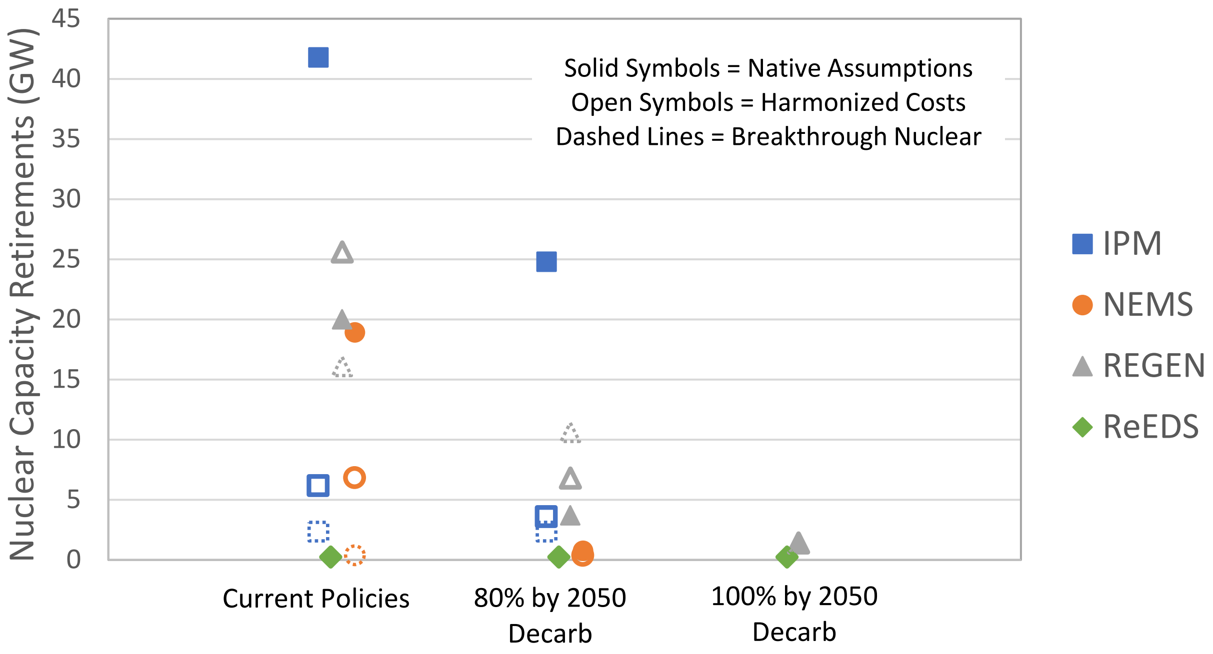

Figure 2. Cumulative projected economic retirements of existing U.S. nuclear power plant capacity by 2050 across all models and scenarios.

REGEN and ReEDS are the only models to explore the 100% decarbonization scenarios.

Harmonizing nuclear FOM costs and capital costs for other generation and storage technologies narrows projected nuclear retirements to be typically less than 7 GW by 2050 (open symbols in Figure 2). Therefore, the range of projected nuclear retirements in the literature likely reflects different cost assumptions, as opposed to fundamental model differences. Increasingly stringent emissions targets also consistently mitigate some nuclear retirements, with a 100% by 2050 decarbonization target mitigating nearly all retirements through 2050.

Each model includes the option to operate nuclear power plants more flexibly if it would lower system costs. With current policies, existing nuclear power plants are consistently operated with high (89%-94%) utilization rates (Figure 3) because they have a lower marginal cost than most other technologies. Increasingly stringent power sector emissions targets have a cascading effect: they drive the widespread deployment of wind and solar, which drives an increase in the frequency of zero- or negative-priced hours, which drives an increase in the value of flexibility. Therefore, decarbonization policies drive the power sector to employ more flexible operations for existing nuclear power plants (i.e., reduced utilization), especially in models with finer temporal resolution (Figure 3).

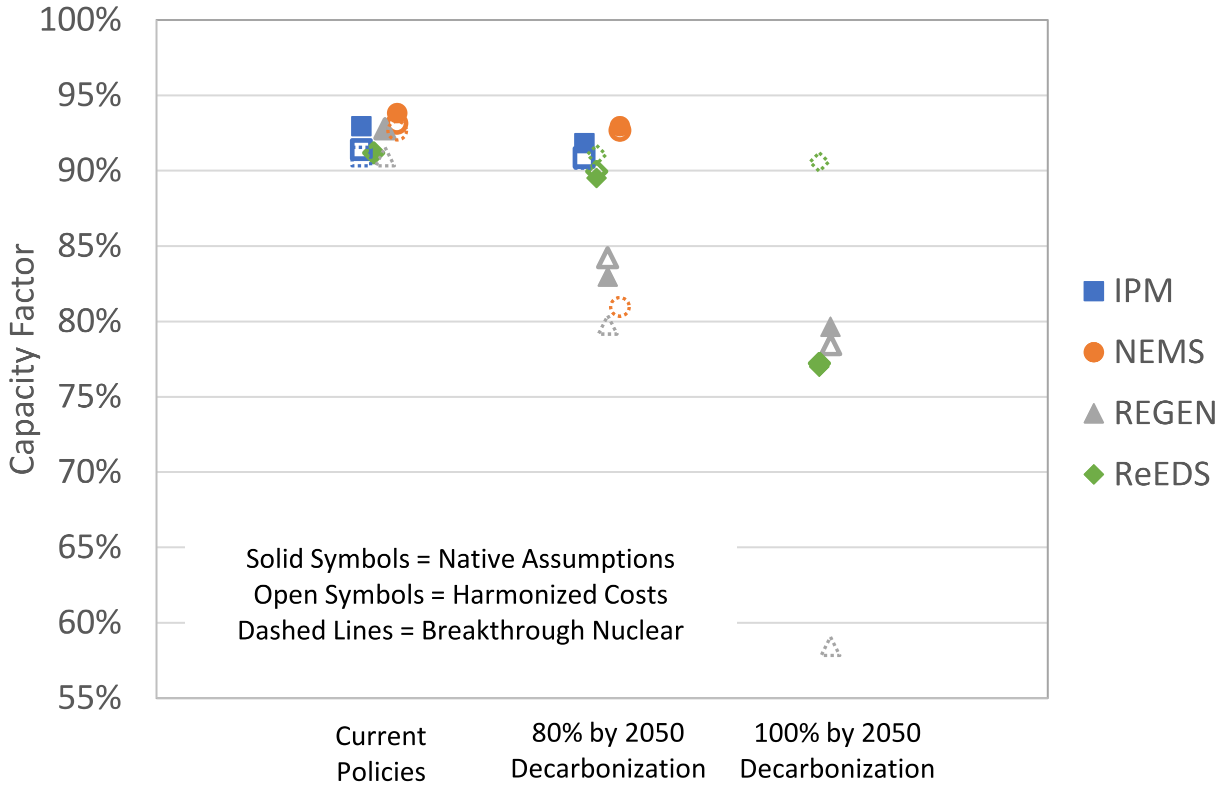

Figure 3. Capacity factors for existing nuclear power plants in 2050 across emissions target (x-axis) and technology assumptions for all participating models (colored symbols).

REGEN and ReEDS are the only models to explore the 100% decarbonization scenarios.

3.2 The Potential for New Nuclear Power Plants

Next-generation nuclear power plants are modeled based on cost and flexibility assumptions that are consistent with anticipated SMR designs. This analysis explores the impacts of two drivers that are expected to be critical for the deployment of SMRs: cost reductions (through technology advancement and/or incentives) and power sector emissions targets. Anticipated cost trajectories for new nuclear power are on the order of $5 to $6 per watt (in terms of overnight capital costs in 2018$), which represents our default assumptions; our Breakthrough nuclear assumptions ($2 per watt in 2035 and beyond) (J. Bistline, James, and Sowder 2019) are ~1/3 of current nuclear power plant costs, including NuScale's stated cost estimate ($89 per megawatt-hour) for the first U.S. power plant based on SMR technology (Ernst 2023).

We find that power sector emissions targets bring new nuclear capacity closer-to-competitiveness (see Appendix A), consistent with other recent studies (Duan et al. 2022; Wesley Cole et al. 2023). However, the power sector CO_2 emissions targets analyzed in this study are typically insufficient to drive the widespread deployment of new nuclear capacity based on anticipated cost trajectories—only modest amounts of new nuclear capacity (up to 5 GW) are deployed during the 2040s (Figure 4), and nuclear power provides less than 17% of total generation in 2050 (see Figure 10, Figure 11, and Figure 12 in Appendix B). Instead, the power sector CO_2 emissions targets are primarily achieved through the widespread deployment of wind, solar, and storage (Figure 5).

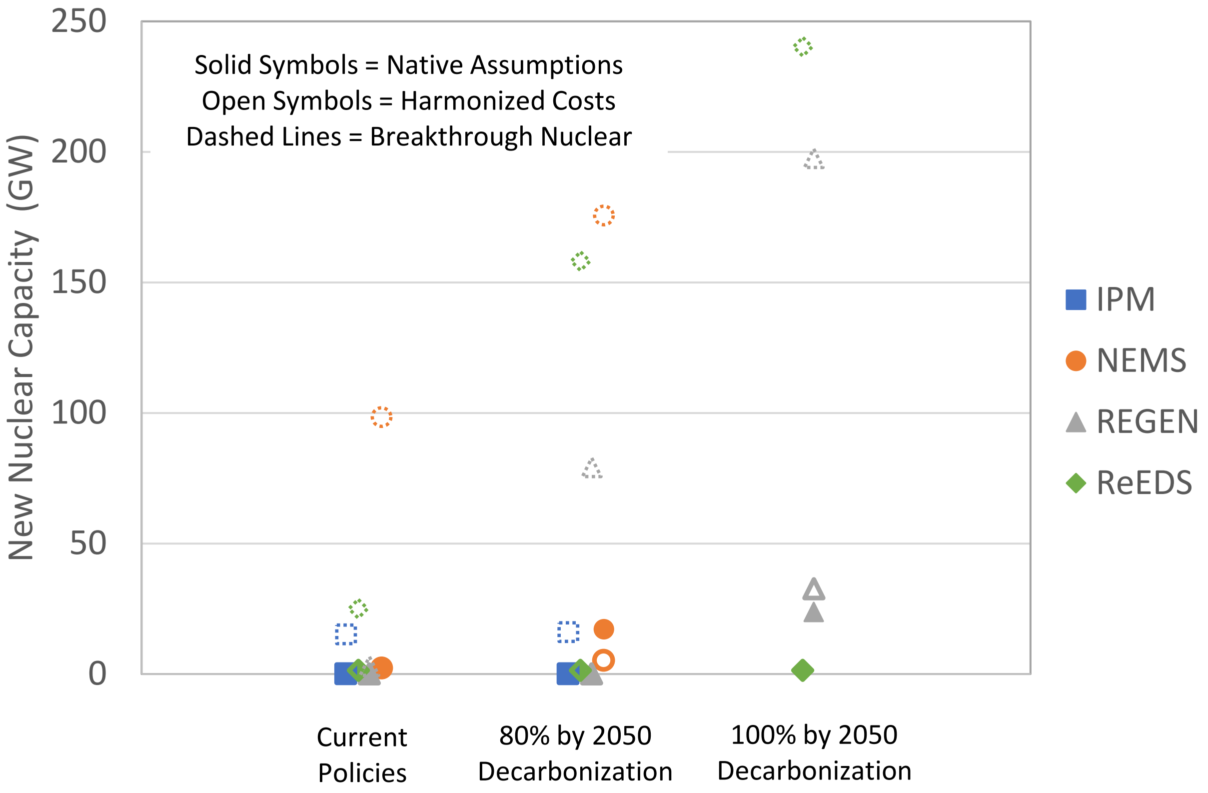

Figure 4. New nuclear capacity results across models and scenarios.

REGEN and ReEDS are the only models to run the 100% decarbonization scenarios.

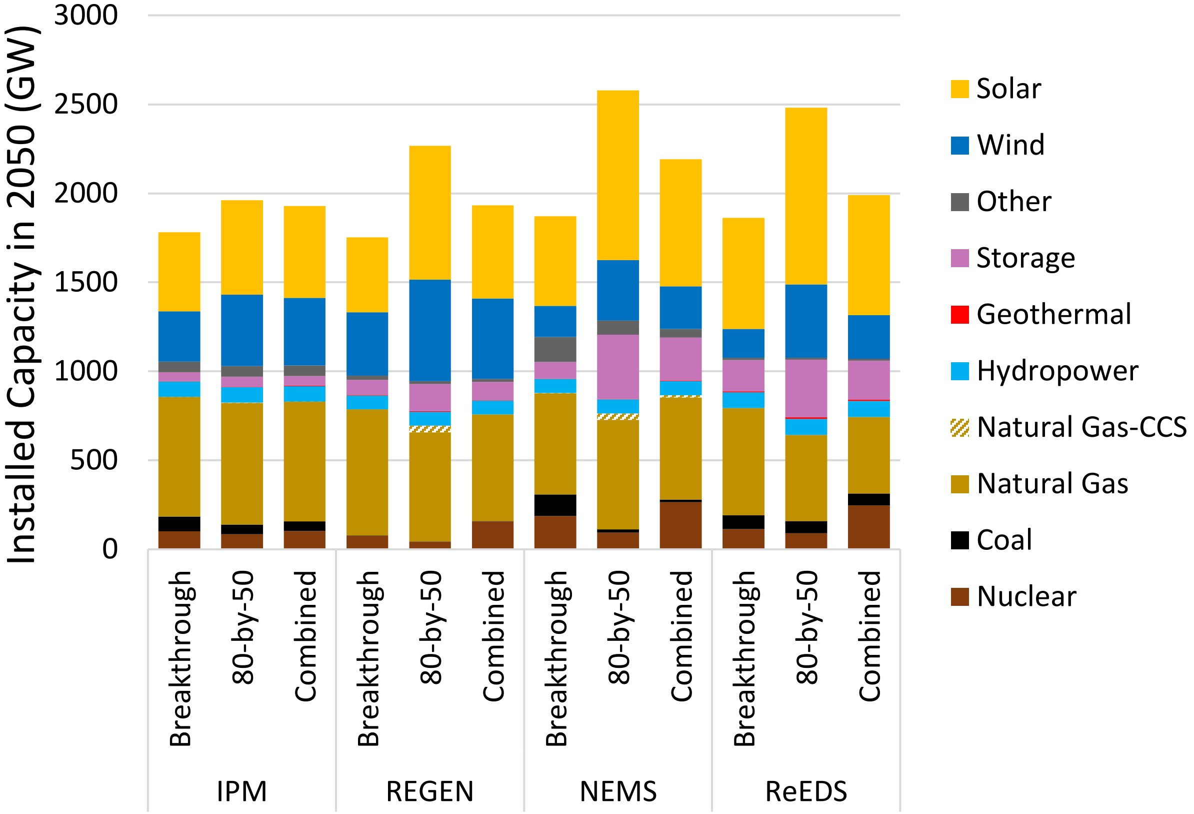

Figure 5. Nuclear deployment under scenarios that combine Breakthrough nuclear cost assumptions with an 80% by 2050 power sector emissions target ("Combined") exceed the individual impacts of each driver ("Breakthrough" and "80-by-50") in each participating model.

Results presented reflect capacity mix in 2050 for scenarios with harmonized cost assumptions for all technologies. Scenario analysis was performed before the *IRA* was signed into law, which dramatically increased the competitiveness of zero-carbon assets.

On its own, the Breakthrough cost assumptions for new nuclear capacity similarly have a modest impact on nuclear deployment: new nuclear capacity is typically below 5 GW (dashed symbols in Figure 4 and "Breakthrough" results in Figure 5), and total nuclear generation remains below 17% in 2050 (see Figure 10 in Appendix B). The select Breakthrough scenarios that include greater deployment of new nuclear capacity (24 GW to 100 GW) reflect a modified representation of the power sector CO_2 emissions policy (in NEMS) or a 100% decarbonization trajectory of new nuclear capacity (Figure 4).

Greater expansion in the role of next-generation nuclear technologies occurs under *both* stringent electric sector decarbonization and Breakthrough nuclear cost assumptions ("Combined" results in Figure 5). Under such conditions, the first nuclear additions occur in 2035 and the ultimate level of nuclear capacity depends strongly on emissions targets. Under Breakthrough cost assumptions for new nuclear power plants, the addition of an 80% by 2050 emissions target drives the incremental deployment of 80 to 130 GW of additional nuclear capacity. For context, total installed capacity is on the order of 2,000 to 2,500 GW in 2050 under the 80% by 2050 scenarios, and it is dominated by additions in wind, solar, and storage (Figure 5). Recall, however, that the Breakthrough nuclear cost assumptions are not meant to be predictive; significant investment and technology gaps would need to be filled for next-generation nuclear technologies to achieve deep technology learning by 2035, as discussed more in the next section.

Increasing the 2050 emissions targets from 80% to 100% decarbonization drives a *further* increase on the order of 100 GW. In other words, a "100% by 2050" emissions target with Breakthrough nuclear cost assumptions drives 200 GW to 240 GW of new nuclear capacity, which provides more than one-third of total generation in 2050 (see Figure 12 in Appendix B). Under these policy conditions, a high-cost sensitivity for new nuclear capacity would offer helpful insights, given that U.S. nuclear plant costs have historically exceeded expectations (Eash-Gates et al. 2020).

For all scenarios, new nuclear power plants are primarily deployed in the Southern and Western United States (see Figure 13 in Appendix B). Nuclear additions in the Southern United States are driven by lower wind and solar resource quality and higher gas prices. In the Western United States, supporting state policies drive the deployment of new nuclear capacity, especially under Breakthrough nuclear cost assumptions. Figure 10, Figure 11, and Figure 12 in Appendix B illustrate the technologies that are displaced by incremental nuclear additions in select scenarios.

The operational characteristics of new nuclear power plants are only modestly sensitive to the presence of power sector emissions targets: new nuclear capacity is typically operated with relatively high capacity factors (84% to 91%), which is consistent with previous studies (Baik et al. 2021). Therefore, even though new nuclear is capable of flexible operations, investment and dispatch economics suggest that these plants are likely to have high-capacity factors (Figure 6) relative to other resources (Table 3). Figure 9 in Appendix B helps to explain the model logic behind the observed decline in nuclear capacity factors with increasing policy stringency by presenting a holistic mix of plant values and costs from a bulk power system perspective.

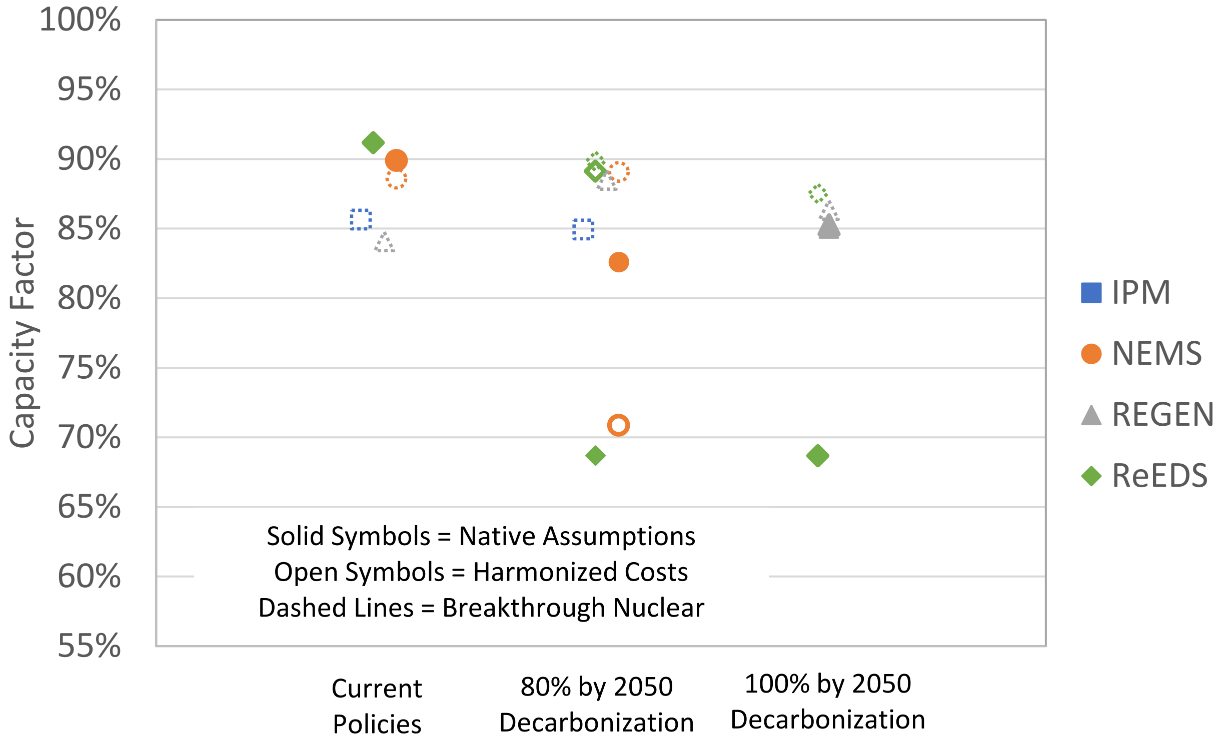

Figure 6. Capacity factors in 2050 for new nuclear power plants across scenarios (x-axis) and models (colored symbols).

Table 3. 2050 annual capacity factor by technology, model, and policy scenario

Policy	Model	Nuclear	NGCC	NGCC-CCS
Reference	IPM	93%	50%	27%
	NEMS	94%	46%	44%
	ReEDS	91%	41%	N/A
	REGEN	93%	61%	N/A
80-by-50	IPM	92%	39%	45%
	NEMS	91%	18%	55%
	ReEDS	89%	14%	N/A
	REGEN	83%	25%	64%
100-by-50	ReEDS	77%	N/A	N/A
	REGEN	81%	N/A	N/A

3.3 Explaining Investment and the Future Role of New Nuclear Power Plants

To explain the investment and operational trends for nuclear technologies, we use one of the participating long-term planning models (ReEDS) to compare the system value and costs associated with various generation and storage technologies. The stacked bars in Figure 7 summarize the sources of revenue in 2050 for key technologies with increasingly stringent emissions targets. The black dots represent a technology's net value in 2050 across increasingly stringent emissions targets—this corresponds to the "required cost" (including capital expenditures and projected fuel and operations and maintenance costs over the economic lifetime of the project) for a technology to be cost competitive.

For all technologies, energy and capacity services are the dominant sources of revenue (as represented by the model). Nuclear, solar, and wind technologies derive most of their value from energy services, whereas natural gas combined cycle, natural gas combustion turbine, and battery technologies derive more value from capacity services (via the planning reserve margin). Under current policies, the net-values (or required costs) of these key technologies in 2050 span a relatively narrow range around $1 per watt.

The revenue sources for next-generation nuclear power plants evolve with the stringency of emissions targets. An "80% by 2050" emissions target (not shown) drives a modest increase in the relative importance of capacity revenue without significantly changing the total value of next-generation nuclear technologies (see Figure 9 in Appendix B). Increasingly stringent (90%) emissions targets first drive an increase in energy revenue, followed by an increase in capacity revenue as the power sector approaches 100% decarbonization. The latter helps explain reductions in nuclear capacity factors in a fully decarbonized electricity system (Figure 3), as a growing share of nuclear revenue is derived from its firm capacity characteristics.

The cost point at which next-generation nuclear power plants become cost competitive is also highly sensitive to the stringency of emissions targets. Under a 90% decarbonization target, new nuclear capacity is competitive at a total cost of $3.2 per watt, or nearly 3x the required costs under current policies. As the power sector approaches full decarbonization, the required cost further increases to $4 per watt; because this number reflects total costs (including capital expenditures and operational costs over the plant's economic lifetime), it is not directly comparable to our assumed overnight capital cost values. Any gaps between anticipated costs for new nuclear technologies and the simulated "required costs" would likely require reductions in capital expenditures, but improvements in financing or operation and maintenance costs could also contribute.

Note that these "required cost" levels are specific to the scenario definitions. Higher natural gas prices, constraints on siting new renewable and transmission projects, and higher-than-anticipated costs associated with capturing and storing power plant CO_2 emissions would all lead to higher required costs (i.e., smaller capital cost reductions) for new nuclear power to be competitive. Conversely, lower natural gas prices and the availability of carbon-negative technologies would likely lead to lower required costs for new nuclear.

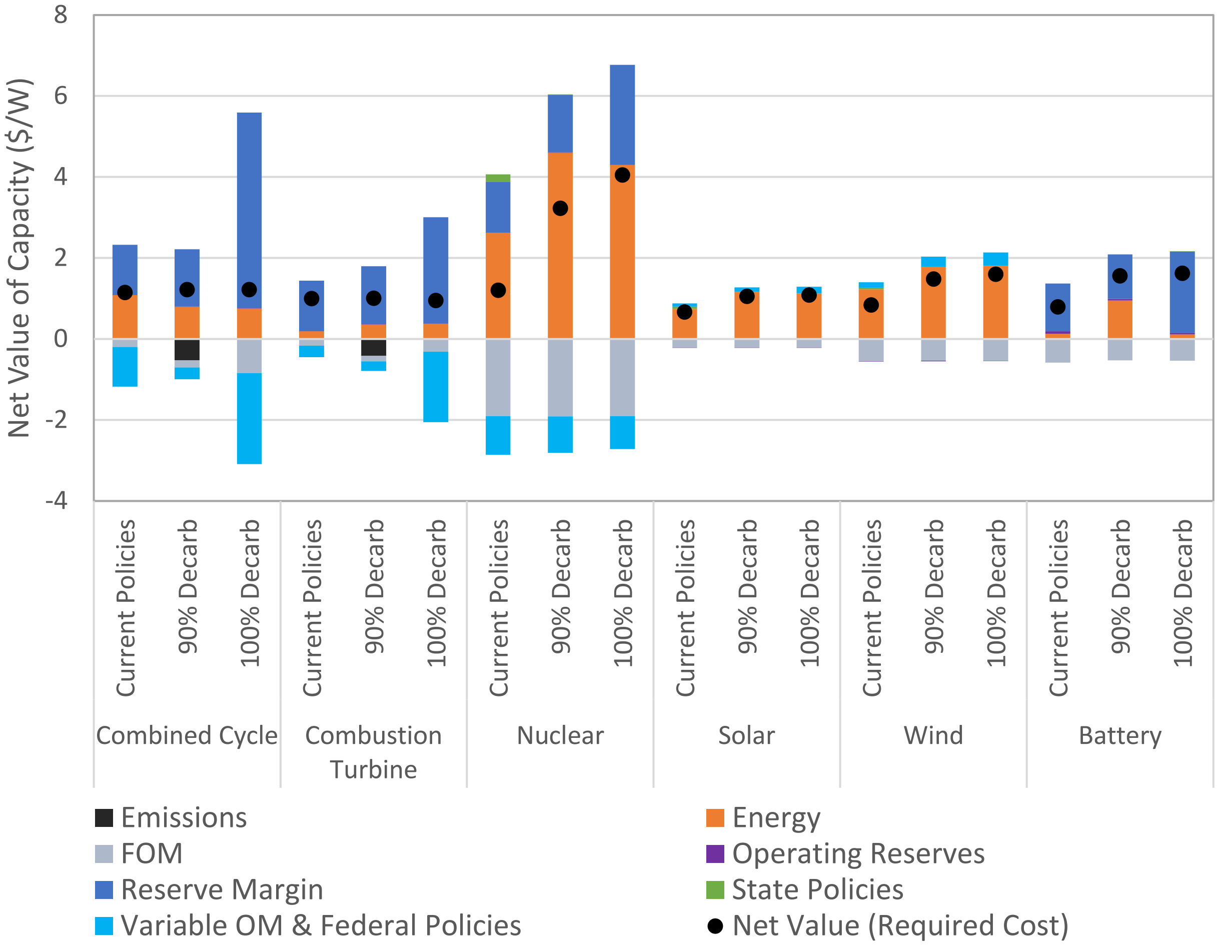

Figure 7. Comparison of value streams for key generation technologies in 2050 with increasingly stringent emissions targets. Under 100% decarbonization scenarios, combined cycle and combustion turbines use hydrogen as fuel.

Black dots indicate net value, or the cost point at which the technology is cost competitive.

4 Discussion

The Results in this report highlight that the future role of nuclear power depends strongly on power sector decarbonization and nuclear cost advances. The most prominent and consistent model response to power sector decarbonization drivers is the widespread deployment of wind, solar, and storage technologies. If nuclear power is going to play a major role in a decarbonized system, our scenario results confirm that the costs will need to come down substantially (J. Bistline, James, and Sowder 2019)—under the explored scenarios, new nuclear capacity only achieves cost competitiveness if it can be deployed for \$2-\$4 per watt.

The pathway for realizing these "required costs" for new nuclear technologies is unclear: empirical data suggest that U.S. nuclear plant costs have historically exceeded expectations (Eash-Gates et al. 2020), and significant gaps remain in terms of the investment and technology advances that would be needed for SMR technologies to undergo deep technology learning by 2035. However, supportive policies could help to shrink or fill these gaps: a recent report found that supportive policies can bring down the effective cost of new nuclear to the point where it is deployed sufficiently to start the technology learning, which will be needed to firm up the supply chain and bring down actual costs (Kim 2022).

Realizing the substantial deployment of new nuclear capacity would also require similar advances in many areas that are beyond the scope of this report (and not directly captured in our cost assumptions). Our analysis does not explicitly consider the uncertainty regarding licensing and permitting of advanced nuclear reactors; supply chain issues associated with a rapid scale-up in the deployment of new nuclear technologies, including reactors and the associated fuels; the evolution of electricity and other energy markets (e.g., nuclear heat generation for industry and hydrogen) (Arent et al. 2021; Frick et al. 2019), which could either enhance or erode the future role of nuclear power; public opposition (Abdulla et al. 2019); or nuclear waste.

A deeper understanding of the impacts of the *IRA* can help improve the analysis community's collective understanding of the future role of nuclear power. The *IRA* represents a significant shift in the future potential of nuclear power in the United States. For existing nuclear power plants, the *IRA* provides a production tax credit through 2032, which will help support continued operation of some plants that may have otherwise retired. However, the new technology-neutral PTC and ITC are expected to incentivize the deployment of technologies that suppress wholesale electricity prices (e.g., solar, wind, and storage) over a similar time period. Therefore, once the near-term tax credit for existing nuclear power plants phases out, a post-policy response that includes additional nuclear retirements could occur (Larsen et al. 2019). Moreover, if new nuclear power plants elect the technology-neutral PTC (as opposed to the ITC), the *IRA* could disincentivize flexible operations, since the level of incentive would scale with total output.

Finally, the results of this report must be interpreted within the context of our analysis limitations. The inclusion of a high-cost scenario for next-generation nuclear power technologies would allow for a more symmetric and meaningful sensitivity analysis, in terms of the knife-edge-like responses that can arise in least-cost capacity expansion models. For most of the scenarios explored, high-cost assumptions for nuclear power would not have a noticeable impact, since new nuclear already plays a modest role in the least-cost solution. However, high-cost nuclear assumptions could offer original insights when combined with the explored decarbonization trajectories for the U.S. power sector (80% and 100% by 2050), since the REGEN and NEMS model solutions include new nuclear capacity under anticipated cost trajectories. In addition, exploring energy sector-wide decarbonization scenarios would offer original insights in terms of the value proposition of new nuclear capacity's ability to provide flexibility and other energy products (e.g., heat and hydrogen) that would be needed to decarbonize non-electric energy demands.

5 Conclusions

This report provides insights for policymakers, electric sector planners, technology developers, investors, and other stakeholders into what drives the greatest differences in projected nuclear retirements and next-generation nuclear additions across a range of technology and decarbonization conditions. We find that the range of projected nuclear retirements in the literature is most closely related to different cost assumptions, which points to the need for better operational cost data for nuclear power plants. We further find that the future role of nuclear is sensitive to the analyzed power sector CO_2 emissions targets, which are expected to mitigate some (or all) nuclear power plant retirements in the near term and drive the nuclear fleet to be operated more flexibly due to the increased value of flexibility. However, the future competitiveness of new nuclear power plants cannot be achieved through flexibility alone; it hinges on significant cost reductions and/or policy support that leads to increased revenue (Buongiorno et al. 2019).

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Appendix A: Nuclear Competitiveness with Increasing Policy Stringency

Power sector decarbonization policies are typically insufficient to drive the economic deployment of new nuclear capacity, based on anticipated cost trajectories for next-generation nuclear power plants and other generation technologies. However, such policies do bring new nuclear capacity closer to being competitive with the least-cost solution (Figure 8), which is an especially important insight for scenarios where new nuclear is not included in the least-cost solution.

The approach employed here is similar to that presented in the body of the report: we explore the system value provided by new nuclear technologies, accounting for a holistic mix of plant values and costs. The approach is applied to scenarios with a range of policy trajectories, but with each scenario requiring the installation of 50 GW of new nuclear capacity. For all policy trajectories, we find a revenue shortfall, which indicates that 50 GW of new nuclear was not included in the least-cost solution.

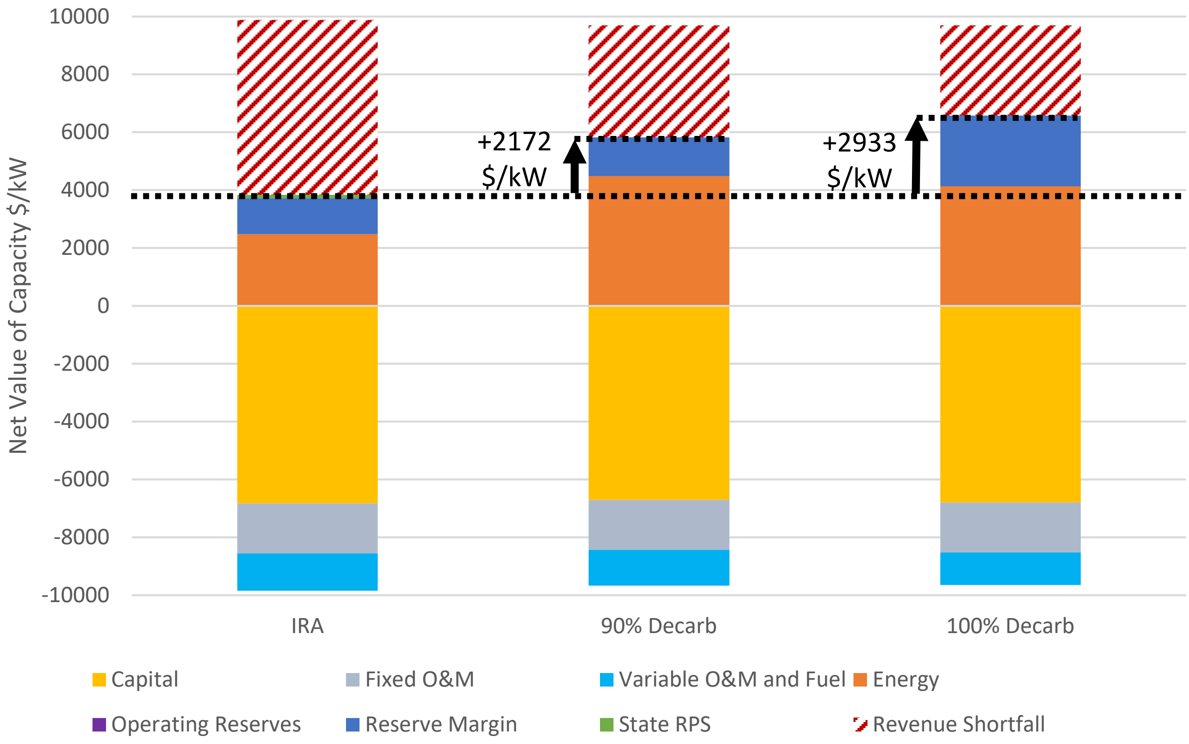

Figure 8. Change in value streams for new nuclear SMRs in 2050 for scenarios that require 50 GW of new nuclear capacity by 2050 with a range of policy trajectories.

This “revenue shortfall” is equivalent to the subsidy that would be needed for that magnitude of new nuclear capacity to be part of the least-cost solution. The shrinking revenue shortfall with increasing policy stringency reveals that power sector decarbonization policy brings new nuclear closer to being cost competitive. Targeted sensitivity analysis indicates that displacing the least-cost generation resources with 50 GW of new nuclear capacity requires a 2%-3% increase in power sector investment and operational expenditures under an 80% by 2050 policy trajectory (compared to a 5%-8% increase under current policy assumptions).

Next, Figure 9 helps to explain the model logic behind the observed decline in nuclear capacity factors with increasing policy stringency by presenting a holistic mix of plant values and costs from a bulk power system perspective. Only subtle changes in revenue (or value) streams are observed as the power sector declines towards 90% emissions reductions: total revenue and net-value remains relatively constant over time (or with increasing policy stringency), but nuclear power plants receive a growing share of their value from capacity services (via the reserve margin constraint).

As the power sector achieves and exceeds 90% emissions reductions, dramatic shifts occur in the nuclear value streams and net value and, in turn, nuclear capacity factors. First, nuclear power plants see a pronounced increase in energy revenue (orange bars at 92% power sector decarbonization) and net value. Then, nuclear power plants see a significant increase in capacity value (dark blue bars at 96% and 100% decarbonization) and net value, with an associated reduction in nuclear capacity factors. These latter two trends are related: nuclear power plants receive a growing share of their value from being *available* to provide energy, and therefore they can achieve comparable (or even greater) revenue with reduced total output or generation.

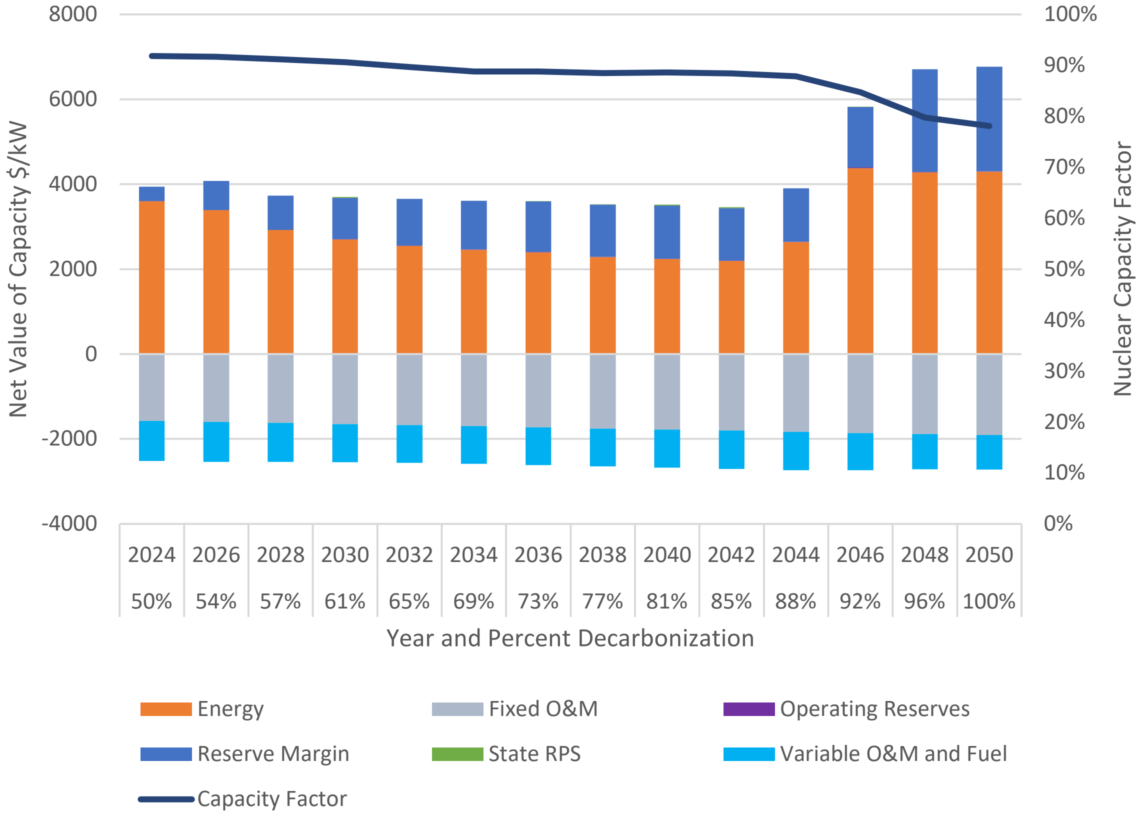

Figure 9. Change in value streams and national annual average capacity factor for nuclear power with a "100% by 2050" electric sector decarbonization policy trajectory.

Appendix B: Additional Results

Figure 10, Figure 11, and Figure 12 present the 2050 capacity and generation mixes under current policies, 80% by 2050, and 100% by 2050 sensitivities (respectively). These results provide context for the body of the report by presenting the nuclear capacities and generation (including existing and new nuclear power plants) alongside results for other key technologies.

There are several common model responses to increasing power sector policy stringency, which generally align with the existing deep decarbonization literature for the U.S. power sector:

1. Avoiding nuclear power plant retirements that were present under the Current Policies scenarios;

2. Retiring a large portion of the existing coal fleet and significantly reducing coal generation; and

3. Increasing deployment of wind, solar, and energy storage (though magnitudes vary across models), which leads to higher installed system capacity.

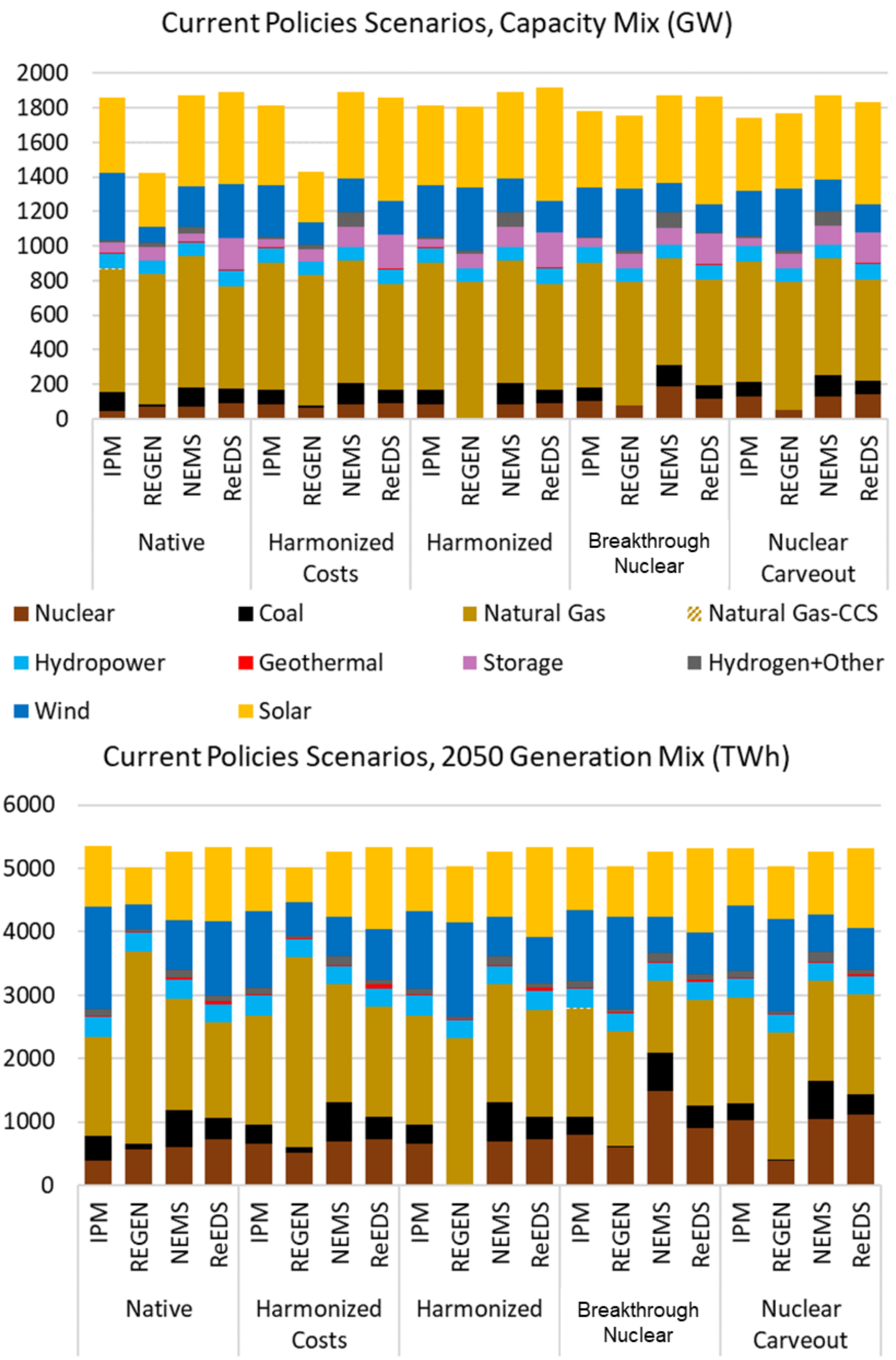

Figure 10. 2050 capacity and generation mixes across the technology sensitivities by model under reference ("current policies") scenarios.

Results presented reflect capacity mix in 2050 for scenarios with harmonized cost assumptions for all technologies. Scenario analysis was performed before the *IRA* was signed into law, which dramatically increased the competitiveness of zero-carbon assets.

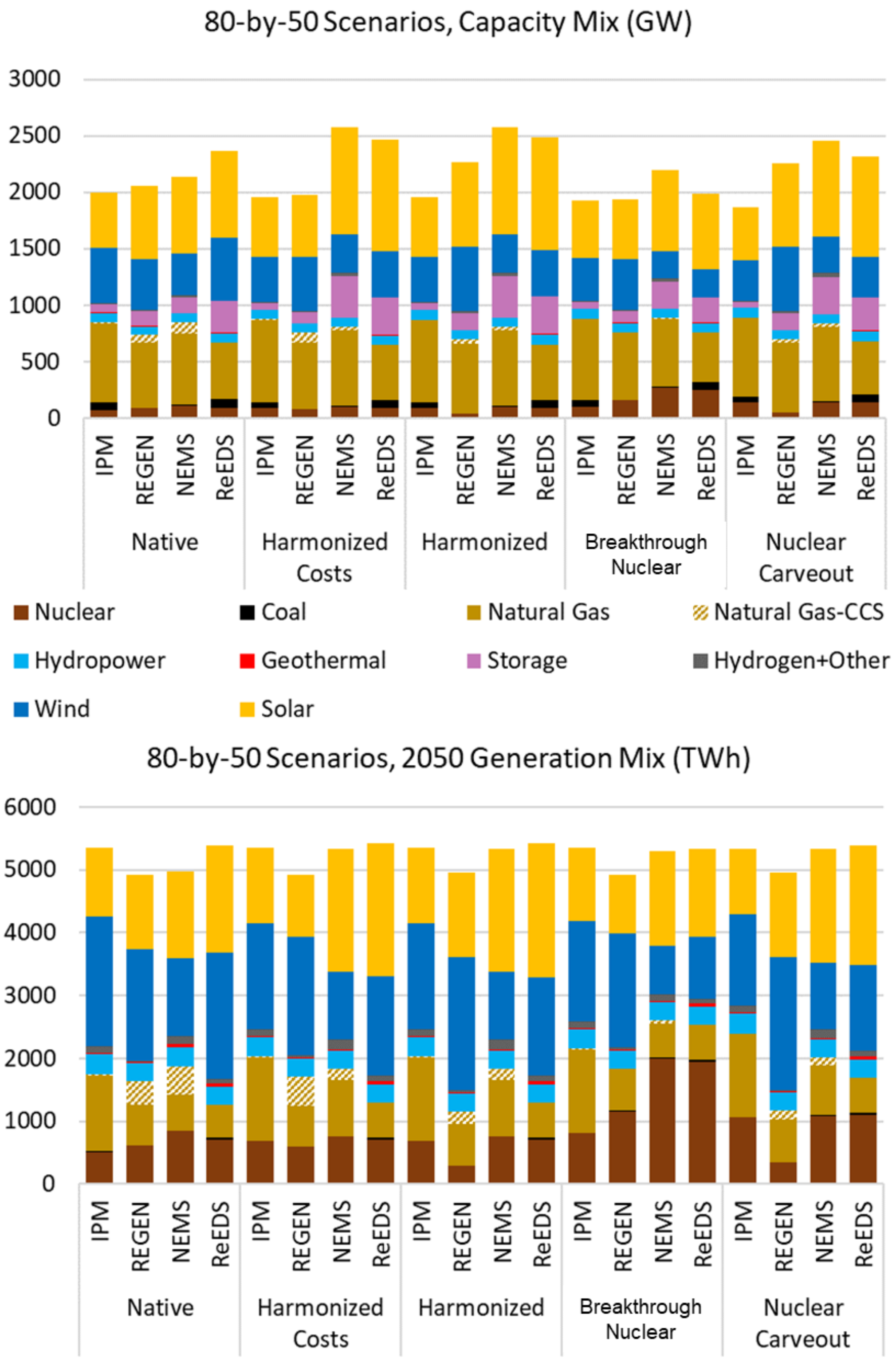

Figure 11. 2050 capacity and generation mixes across the technology sensitivities by model under an 80% by 2050 power sector decarbonization policy.

Results presented reflect capacity mix in 2050 for scenarios with harmonized cost assumptions for all technologies. Scenario analysis was performed before the *IRA* was signed into law, which dramatically increased the competitiveness of zero-carbon assets.

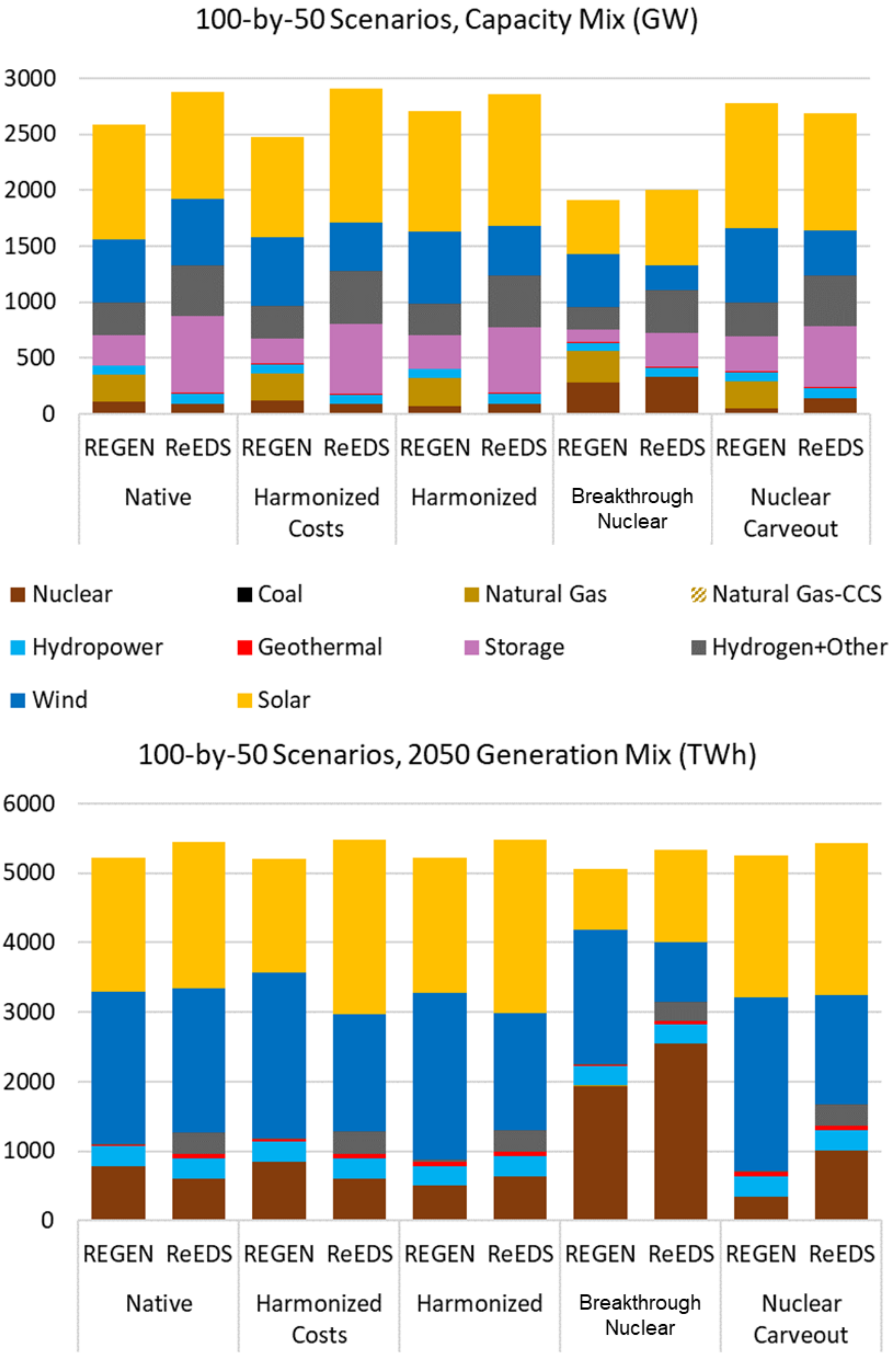

Figure 12. 2050 capacity and generation mixes across the technology sensitivities by model under a 100% by 2050 power sector decarbonization policy.

Results presented reflect capacity mix in 2050 for scenarios with harmonized cost assumptions for all technologies. Scenario analysis was performed before the *IRA* was signed into law, which dramatically increased the competitiveness of zero-carbon assets.

Figure 13 presents a regional breakdown of nuclear power plants across scenarios and models. The four regions correspond to the four main U.S. Census Regions (https://www2.census.gov/geo/pdfs/maps-data/maps/reference/us_regdiv.pdf). Similar regional trends are observed with the "100% by 2050" policy trajectory, but with larger-magnitude additions overall.

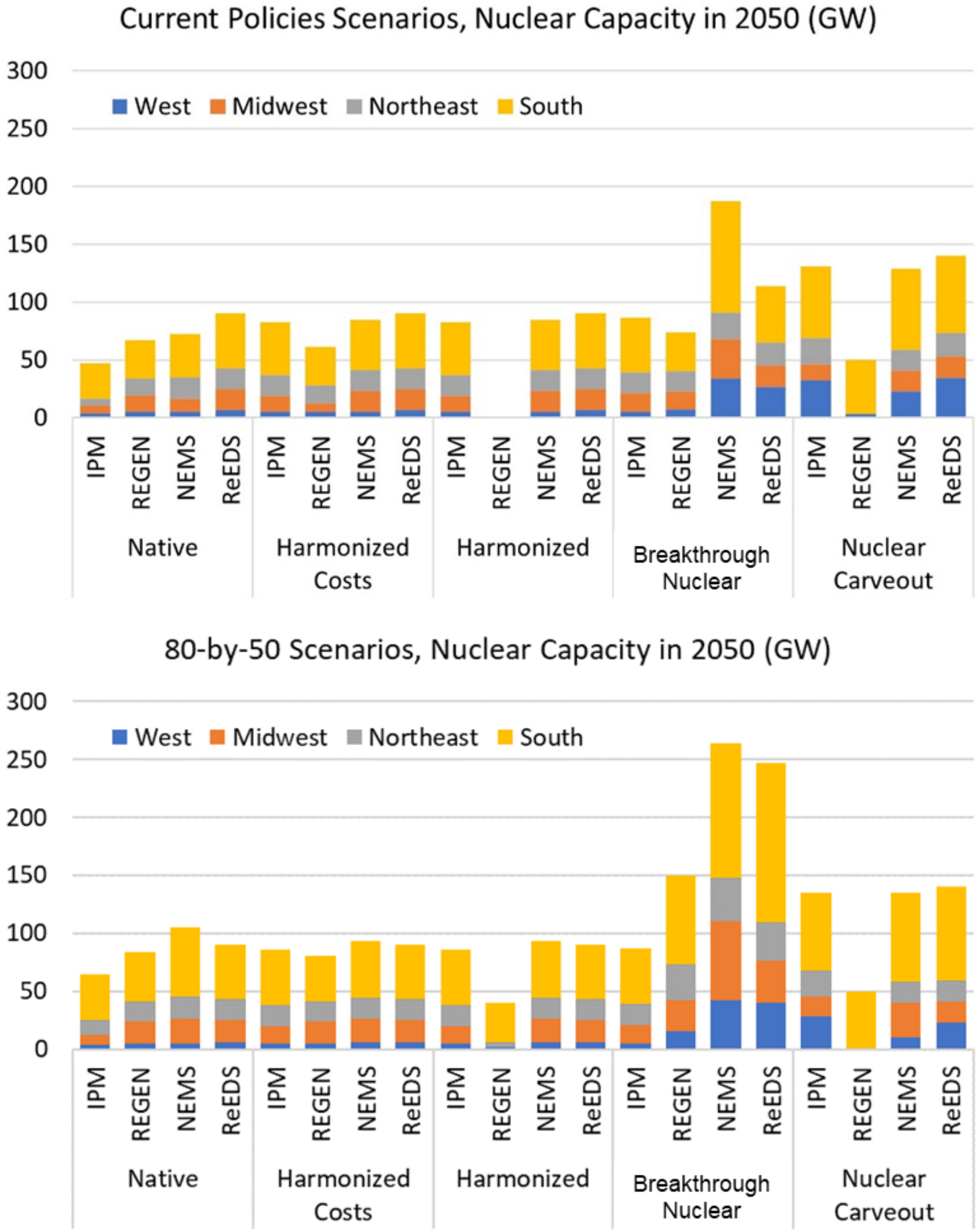

Figure 13. A regional breakdown of nuclear power capacity in 2050 across models and scenarios with current policies only (top) and an "80% by 2050" policy trajectory (bottom).

For all models and scenario definitions, new nuclear power plants are primarily deployed in the Southern and Western United States.