ELECTRIC POWER RESEARCH INSTITUTE

Exploring the Role of Advanced Nuclear in Future Energy Markets

Economic Drivers, Barriers, and Impacts in the United States

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Abstract

This analysis investigates the conditions under which nuclear power could play a role in future markets. This study uses EPRI's U.S. Regional Economy, Greenhouse Gas, and Energy (US-REGEN) energy-economic model to explore tradeoffs across assumptions about technologies, markets, and policies.

Model results suggest that advanced nuclear could be economically competitive across a range of scenarios and that several key drivers may influence deployment:

- **Energy and environmental policies.** Policy and market environments (for example, emissions pricing) may drive nuclear deployment as much as cost targets.
- **Revenue streams.** The extent of advanced nuclear deployment depends **jointly** on changes in costs and market value of different technologies.
- **Regional factors.** Key regional differences (for example, gas pipelines, policies, existing asset mixes, and transmission) make the economic competitiveness of advanced nuclear vary across the country.
- **Capital costs.** Capital cost "sweet spots" for new nuclear investments depend critically on the costs of other technologies and on markets (such as gas prices).

Market opportunities hinge on a combination of these factors, which impact the competitiveness of nuclear relative to other electric sector resources and require modeling to evaluate.

Extensive deployment of advanced nuclear would likely require new policies, innovation in technologies to significantly lower costs, and/or innovation in business models and markets to enable supplemental revenue streams. With policies targeting emissions reductions, the presence of technologies such as advanced nuclear can reduce compliance costs. However, simultaneous cost reductions for other generation options—especially dispatchable low-carbon technologies—create additional economic competition for nuclear deployment.

Keywords

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PRIMARY AUDIENCE: Utilities, technology developers, policymakers, researchers, and other stakeholders who want to understand potential economic drivers, barriers, and impacts for advanced nuclear reactor technologies in future energy markets

SECONDARY AUDIENCE: Other energy sector stakeholders who want to understand tradeoffs between technological options across a range of potential policy, technology, and market uncertainties

KEY RESEARCH QUESTION

In light of the many benefits of and barriers to the deployment of nuclear power, the objective of this energy-economic modeling study is to investigate the conditions under which advanced nuclear technologies (for example, small modular reactors and advanced non-light water reactors) could play a role in future markets. The results of this study are intended to inform nuclear R&D, future modeling research, and technology developers' priorities as well as policy discussions at local, regional, and national levels.

RESEARCH OVERVIEW

EPRI's U.S. Regional Economy, Greenhouse Gas, and Energy (US-REGEN) model is used to compare capacity investment and generation decisions across a wide range of scenarios that examine alternative capital costs of advanced nuclear, market uncertainties (such as natural gas prices), policy environments, and potential additional revenue streams.

KEY FINDINGS

- As shown in Figure ES-1, the analysis identifies many scenarios in which advanced nuclear can play a role in the energy mix, but new deployments in the United States would likely require more compelling technology options with lower costs, a more favorable policy environment that recognizes other attributes of advanced nuclear (for example, carbon pricing), supplemental revenue streams (such as process heat sales), or a combination of these factors.
- In the absence of new policies and in a low natural gas price environment, extensive deployment of nuclear would require some combination of innovation in reactor technologies to significantly lower costs and innovation in business models to enable supplemental revenue streams.
- Policies at the state and/or federal level that encourage CO_2 emissions reductions have significant impacts on the future economic viability of advanced nuclear plants. For instance, new nuclear deployment by 2050 under a $4,000/kW capital cost scenario with a moderate-to-stringent climate policy is comparable to a $2,000/kW capital cost scenario under a reference policy and natural gas price environment.
- The presence of advanced technologies like low-cost advanced nuclear reactors can reduce compliance costs associated with energy and environmental policies like stringent climate targets. However, simultaneous technological progress for other generation options—especially dispatchable low-carbon technologies—creates additional economic competition for advanced nuclear deployment.

- The value of new nuclear investments is subject to considerable uncertainty. Strong policy signals and revenue streams from other products could keep advanced nuclear competitive at higher costs, but scenarios favoring nuclear deployment in this analysis generally include capital cost reductions.

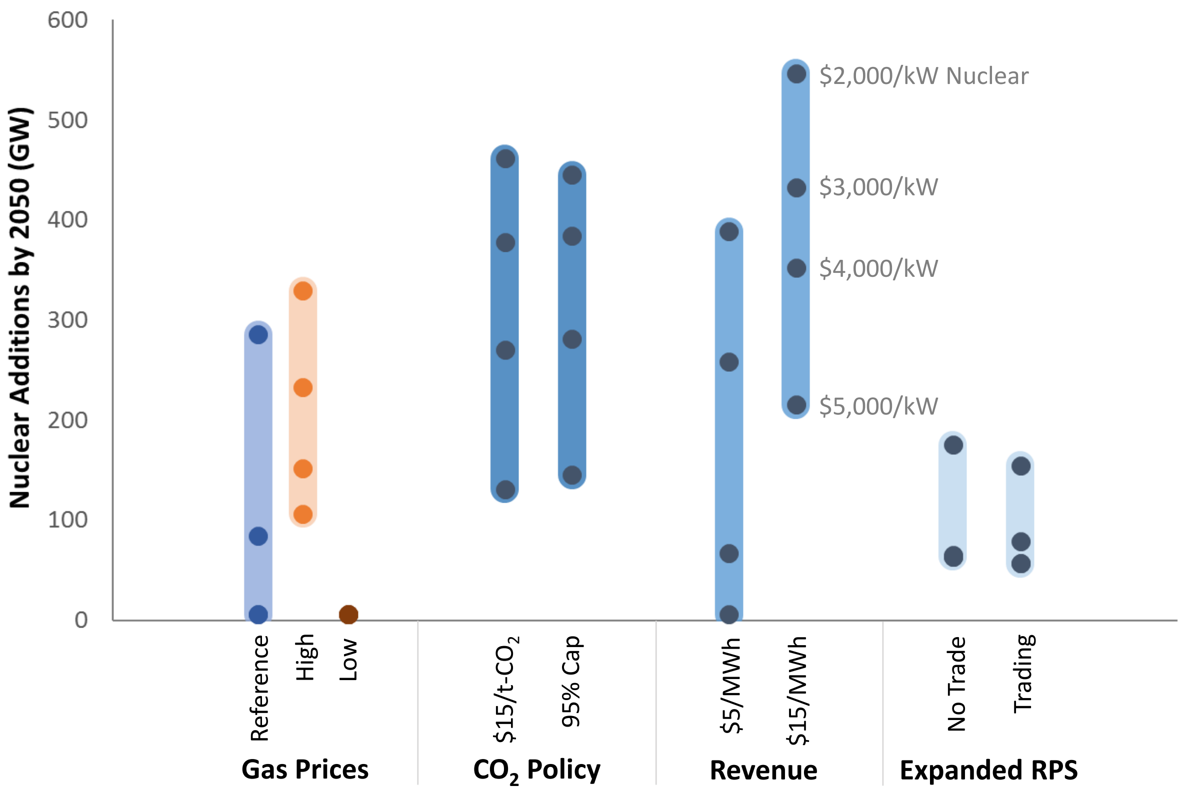

Figure ES-1
Cumulative nuclear additions through 2050 (gigawatts) across a range of sensitivities (horizontal axis) and nuclear capital costs (dots), which increase from top to bottom in each band. (Some higher cost scenarios lead to similar capacity additions, resulting in overlapping dots.)

Model results suggest that advanced nuclear could be economically competitive across a range of scenarios and that several key drivers may influence deployment:

- **Energy and environmental policies.** Policy and market environments may drive advanced nuclear deployment as much as cost targets.
- **Revenue streams.** The extent of advanced nuclear deployment depends jointly on changes in costs and market value of different technologies.
- **Regional factors.** Key regional differences (for example, gas pipelines, policies, renewable resources, existing asset mixes, and transmission) make the economic competitiveness of advanced nuclear vary across the United States.
- **Capital costs.** Capital cost “sweet spots” for new nuclear investments depend critically on the costs of other technologies and on markets (for example, gas prices).

Market opportunities hinge on a combination of these factors, which impact the competitiveness of nuclear relative to other electric sector resources.

EXECUTIVE SUMMARY

WHY THIS MATTERS

As the U.S. and global power sectors continue to evolve and incorporate higher levels of variable renewable energy, demand-side flexibility, and distributed generation, greater emphasis is placed on the dispatchability, flexibility, and reliability of grid resources. Advanced nuclear power technologies offer options that could meet these needs, and the analysis in this report helps readers understand the degree to which advanced nuclear power could provide economically competitive energy services while simultaneously supporting policy objectives. In addition, this research enables technology developers to understand potential cost targets and technical capabilities required for widespread commercialization under different scenarios, including additional revenue streams and market participation.

HOW TO APPLY RESULTS

These results can inform policymakers, potential investors, asset owners, and technology developers in their decisions regarding the development and deployment of advanced nuclear reactors over the next several decades. This analysis explores potential tradeoffs across a range of technological and policy-related assumptions but should not be interpreted as predictions about the future—especially given uncertainties about technologies, markets, and political decisions moving forward. This exploratory scenario analysis is designed to parametrically evaluate the commercial viability of advanced nuclear under a range of assumptions, but the likelihoods of alternative scenarios are not discussed or quantified. In addition, this analysis does not include or quantify other potentially important political, security, or local economic development factors.

Uncertainty abounds in power sector decision making, which makes it critical to examine diverse scenarios and sensitivities to understand the role of specific technologies. The complexity of markets and technological capabilities renders cost-based metrics insufficient for evaluating the economic competitiveness of various technologies. Consequently, energy-economic modeling provides an important input for decision making.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- Technology developers, utility resource planners, researchers, policymakers, and other energy stakeholders will find this report useful in establishing research, asset ownership, and policy positions related to the electric power sector and the role of advanced nuclear.
- EPRI has established an Advanced Reactor Technical Advisory Group (TAG) under the Advanced Nuclear Technology Program to provide a forum for exchanging information and obtaining input on the direction and nature of EPRI's strategic focus on advanced reactor technology.
- Users of this report may be interested in EPRI's Program 201 Project Set C (Emerging Technologies Analysis: Drivers and Impacts), which conducts analysis for its members and the public to understand policy and market drivers for emerging technologies, including energy storage, renewables, nuclear, and carbon capture.

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IMPLEMENTATION CATEGORY: Strategic Long Term

Abbreviations

Abbr.	Definition
AEO	Annual Energy Outlook
ANLWR	Advanced Non-Light Water Reactor
CAA	Clean Air Act
capex	Capital Expenditure
CO_2	Carbon Dioxide
CPP	Clean Power Plan
CWA	Clean Water Act
EPRI	Electric Power Research Institute
GW	Gigawatts
ITC/PTC	Investment Tax Credit and Production Tax Credit
LCOE	Levelized Cost of Electricity
LWR	Light Water Reactor
MATS	Mercury and Air Toxics Standards
NGCC	Natural Gas Combined Cycle
NGGT	Natural Gas Turbine
opex	Operating Expenditure
RGGI	Regional Greenhouse Gas Initiative
REC	Renewable Energy Certificate
RPS	Renewable Portfolio Standard
SMR	Small Modular Reactor
TWh	Terawatt-Hours
US-REGEN	U.S. Regional Economy, Greenhouse Gas, and Energy
VRE	Variable Renewable Energy

Table of Contents

List of Figures

List of Tables

Section 1: Introduction

Background

The economic and policy environment for nuclear power globally and in the United States is complex, with conflicting drivers that impede and support the development and deployment of nuclear technologies for energy systems. Electric power generation from nuclear power plants constitutes 11% of global electricity generation (IEA, 2017), and 19% of U.S. generation (EIA, 2017a). By far, the dominant nuclear generation technology is the light water reactor (LWR), typically deployed in units on the order of 1,000 megawatts (MW) of capacity.

Although nuclear plants are large capital-intensive projects, they have remained a significant part of global electricity generation due to several attributes. First among these are the many benefits derived from the extremely high energy density of nuclear fuel compared to other fuels, including multi-year intervals between refueling, relative insensitivity of production costs to fuel prices, small mass of waste produced, and ease of stockpiling fuel reserves. Other key attributes include the long asset lifetime and reliability of nuclear plants. In the United States, many nuclear units are approaching or have surpassed 40 years of operation; most are expected to continue operation to 60 years following license renewal by the U.S. Nuclear Regulatory Commission and assuming continued economic viability. Operation of current nuclear plants beyond the 60-year mark to 80 years is being evaluated by programs sponsored by the U.S. Department of Energy and EPRI to identify technical challenges and solutions (INL, 2013). Concurrent with this longevity, the U.S. nuclear fleet has in aggregate continuously increased its average capacity factor to levels over 90%, and similar trends have been observed globally (EIA, 2017b; IAEA, 2017). Additionally, nuclear reactors contribute to security of electricity supply and resilience of the electricity grid, routinely operating one to two years without refueling. Nuclear reactors also provide inertia to the electric power grid, thus helping to preserve voltage and frequency stability (NERC, 2017). Finally, nuclear power plants generate minimal environmental emissions, especially in terms of greenhouse gases and criteria pollutants.

While these attributes have led to the development of global and U.S. nuclear fleets, nuclear power has experienced sustained opposition in many regions from the public and policymakers. Principal factors contributing to this opposition are concerns about high capital costs and historical cost overruns, long construction and permitting timelines which create policymaker and investor uncertainty, long-term management of spent fuel from nuclear reactors, potential linkage between the commercial nuclear power and military applications, and potential adverse public health and environmental effects due to severe accidents.

Nuclear has remained a large and important component of the global and U.S. power sectors. However, the anticipated growth of nuclear power in the form of large LWRs has shifted from the West, where efforts have largely stalled in the U.S. and Western Europe, to the East, where construction programs in China, Russia, and India continue at a robust pace (WNA, 2018). Furthermore, a number of countries that current do not have operating nuclear power plants are either constructing new capacity, notably the United Arab Emirates and Belarus, or are actively considering new construction.

There are robust global and U.S. nuclear power generation fleets, which have driven improvements in nuclear plant performance, longevity, availability, and reliability. However, new nuclear deployment has been limited in the West. Absent significant changes in the economic or policy environment, existing nuclear fleets in North America and Europe could begin to shrink in the face of growing economic headwinds leading to early retirements and replacement with non-nuclear generation.

Advanced Reactor Technologies

Interest and investment in advanced reactor technologies are growing globally, and the new features and attributes offered by small modular reactors (SMRs) and advanced non-LWRs (ANLWRs) employing new coolants and fuels are believed to provide new opportunities for nuclear to contribute to global electricity and energy generation in future markets. While most of these so-called advanced technologies are not new and many have been demonstrated and operated commercially, they have not seen broad commercial adoption.

In North America, the landscape of advanced nuclear development is marked by private ventures, including a large number of small entrepreneurs. Third Way, in its latest review of the advanced nuclear landscape, identifies 56 companies and research organizations developing advanced reactor concepts. Worldwide, the tally exceeds 80 entities in 20 countries (Third Way, 2017).

While these advanced concepts promise many benefits on paper, the economic and business case for advanced nuclear largely remains unproven and will likely hinge on these technologies providing utilities and other owner-operators providing compelling advantages over existing, proven nuclear technologies and other generation options.

Key Issues Impacting Nuclear Technology Development and Deployment

A core issue strongly affecting the future role for nuclear power is an economic and policy environment which almost entirely focuses on the near-term cost of bulk electricity generation. Typically, as with other generation technologies, the option to generate electricity via nuclear power is framed (in terms of public and policy debates) in terms of capital cost (e.g., dollars per unit of capacity) and bulk energy cost (e.g., dollars per unit of generated electricity).

Although upfront capital investment costs are critical components of any private or public investment decision, the economic competitiveness and system value of different electricity generation technologies is a complex function of several attributes addressing requirements for an economically, environmentally, and technologically sustainable energy system. Historically, these ancillary objectives have been achieved either by government policies or have been assumed to be met as a by-product of minimizing electricity production cost. In the U.S., for example, the levels of economic activity, electricity consumption, and relatively large margins in power generation and transmission capacity historically assured that grid reliability, security, and resilience needs were met despite the relative absence of explicit policies or regulations addressing these issues.

The U.S. is an important and interesting case study for power sector transformations, since recent drivers have created uncertainty about whether some grid services will be met in the future without policy interventions. Notable trends include electricity market restructuring, changes in the economy, a long period of relative under-investment in the electric power system, and technology-specific federal- and state-level policies and subsidies. Additionally, attribute valuation has been an active area of interest in market design (e.g., DOE, 2017a).

To date, nuclear projects have fundamentally been viewed in the contexts of investment options for electricity generation, differentiated mainly by the cost factors mentioned above. Until recently, U.S. electricity markets and regulations have done little to monetize factors like environmental impact, or contributions to grid reliability and resiliency. Some limited federal policies have been implemented to support nuclear power development (e.g., federal loan guarantees, investment tax credits), but these policies have had little impact on the margin.

Many plants in the existing U.S. nuclear fleet have experienced profitability challenges from wholesale power price suppression largely due to natural gas price declines (DOE, 2017b). As these nuclear plants have been retired or planned for closure, frequently in advance of their license expiration dates, the importance of the various attributes of nuclear plants have become more apparent:

- Many U.S. states have either explicit goals to reduce greenhouse gas emissions from electric power generation, or renewable portfolio standards (RPS) requiring increased deployment of renewable energy technologies. Nuclear plants are generally excluded from policies designed to promote deployment of eligible non-emitting resources. However, the premature retirement of nuclear power plants would adversely impact emissions (Roth and Jaramillo, 2017).
- As the U.S. power system has continued to experience significant weather events leading to interruptions of electricity supply, nuclear plants have played an important role in preserving power supply and providing a foundation for grid recovery.

- Nuclear power plants have long asset lifetimes and require highly skilled workforces, which make nuclear plants drivers of economic growth and job creation in their local economies, both during construction and operation.[1]

Select U.S. states have responded to the prospect of premature retirements of nuclear reactors by instituting policies to value unpriced attributes. New York and Illinois implemented policies assigning zero emissions credits to nuclear plants, while Connecticut is enabling its nuclear plant to enter into long-term power purchase agreements. Other states (e.g., Pennsylvania, New Jersey) are examining potential policy measures. These actions collectively suggest a growing recognition that attributes beyond energy cost are not adequately reflected under current economic and policy conditions.

Assessing the Future Role of Advanced Nuclear Technologies

In light of the benefits and barriers characterizing nuclear power, many stakeholders are interested in assessing the potential value and role of advanced nuclear power technologies. While a complex array of technical, policy, and economic factors affects this future, a fundamental question is the extent to which there are plausible and robust scenarios where advanced nuclear power could play a significant role. The focus of this study is to identify the primary factors defining such scenarios if they exist, which could provide a foundation for future efforts to examine key drivers in greater depth. To answer these questions, the analysis has been structured to systematically explore different combinations of technological costs, policies, and additional sources of revenue beyond power sales, which are discussed in Section 2.

Given high upfront capital costs, many studies have focused on examining the economic viability of nuclear plants and other generation options by comparing capital costs or metrics like the levelized cost of electricity (LCOE). Most recently, the Energy Innovation Reform Project published a report examining the potential cost of different advanced reactor technologies (EIRP, 2017).

While the EIRP study and others like it provide valuable perspectives and convenient summary statistics, levelized cost metrics alone are insufficient for evaluating the economic competitiveness of different technologies, as they do not incorporate the market value or benefits of alternatives nor do they capture additional system costs. These considerations become increasingly important as revenue streams come from multiple markets, comparisons are made across technologies with different levels of dispatchability and flexibility (in terms of construction, siting, and operations), and comparisons are made on the margin as different levels of capacity are installed. The future economic viability of a nuclear power plant (or another generation technology) is a function of costs, potential revenue streams, and policies.

[1] For a list of studies, see: https://www.nei.org/Issues-Policy/Economics/Cost-Benefits-Analyses/Economic-Benefits-Studies

EPRI's in-house electric sector model (**US-REGEN**) represents technological tradeoffs for long-run investment and dispatch.

Energy-economic models are important for simultaneously comparing system costs and market values at the margin to develop a consistent least-cost equilibrium. The Electric Power Research Institute (EPRI) has a well-developed and vetted energy-economic model called US-REGEN, which is ideally suited for this problem (see Section 2 or EPRI, 2017). US-REGEN permits simultaneous treatment of costs, revenue streams, existing and potential new policies, while allowing a fully regionalized treatment of the U.S. power system (e.g., transmission interconnections, policies, distribution of renewable resources, fuel costs, labor costs). US-REGEN is an electric sector capacity planning and dispatch model that facilitates detailed explorations of the sensitivity of future nuclear technology deployment to alternate assumptions about policy, markets, and technologies.

The REGEN platform has been applied to other country contexts, and EPRI also develops and applies the global Model for Estimating the Regional and Global Effects of Greenhouse Gas Reductions (MERGE). Although this report uses the US-REGEN model to assess the economic competitiveness of advanced nuclear in the U.S., EPRI's additional modeling capabilities can be applied in future work to examine potential roles of advanced nuclear in international contexts.

Study Objectives and Scope

The objective of this study is to identify economic and policy conditions under which advanced nuclear technologies could be economically viable. Through design and analysis of a structured set of scenarios, this study seeks to (a) assess what conditions are necessary for economic viability of advanced nuclear power technologies, and (b) the relative importance of different cost, revenue, and policy factors to future deployment. This exploratory scenario analysis is designed to parametrically evaluate the commercial viability of advanced nuclear under a range of assumptions, but the likelihoods of alternate scenarios is not discussed or quantified.

Previous research suggests that in addition to assumptions about capital cost, other key factors include future natural gas prices, potential revenue from sources in addition to electricity sales, and the presence/absence of policies designed to reduce greenhouse gas emissions. Understanding the relative impact of these factors on future advanced nuclear power plant economic viability will inform several key questions:

- To what degree is there a dominant driver of future advanced nuclear plant deployment (e.g., under what conditions is a future climate policy more impactful for advanced nuclear investments than lower capital costs)?
- How important are attributes capable of generating additional revenues (e.g., process heat)?
- How broad is the array of conditions under which advanced nuclear plant deployment is economically viable?

- How important are state and federal policies to the future economic competitiveness of advanced nuclear plants?

An overarching question is how regional differences in the existing generation portfolio, policies, transmission and gas pipeline network characteristics, and electricity demand impact future advanced nuclear plant economic viability.

In addition to informing our understanding of the above questions, this study will also guide further research examining the impact of key differences between different advanced nuclear reactor technologies.

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Section 2: Analysis Framework and Scenarios

Overview

This study investigates the combined impact of cost, revenue, and policy on the future economic viability of advanced nuclear power generation technologies. While several advanced nuclear technologies exist in various stages of development and have different capabilities (e.g., EPRI, 2016), this study models a stylized reactor technology within an energy-economic model to understand the role of advanced nuclear alongside other electric sector resources under a range of assumptions about cost improvements, additional revenue generation, and changes to policy conditions. Some incentives for deployment investigated here relate to advanced nuclear technologies themselves (e.g., cost declines or additional revenue streams), while others relate to the system within which technological options compete (e.g., gas prices, carbon pricing policies). Ultimately, all factors impact net revenues of advanced nuclear and determine its extent of deployment alongside other options.

Scenario Structure

Scenarios for this analysis focus on particular drivers of advanced nuclear and magnitude of their effect on future deployment across a range of technology, cost, and market assumptions. Integration of results facilitates an understanding of what combinations of factors have the strongest impact, or conversely, areas where technology and cost improvements are likely to yield the greatest benefit.

Scenarios examine nuclear deployment across a range of technology, market, and policy assumptions.

The analysis is principally organized around a range of advanced nuclear reactor capital costs and future natural gas price trajectories, as shown in Figure 2-1. The scenario matrix in Figure 2-1 shows the core scenarios of the report, but additional sensitivities (e.g., joint scenario analysis, higher nuclear capital cost sensitivities, lower renewable cost sensitivities) are also explored in later sections.

Market and Policy Sensitivities			Technology Sensitivities: Nuclear Capital Cost Scenarios ($/kW in 2030)			
			$5,000	$4,000	$3,000	$2,000
Reference Natural Gas Prices						
	Electric Sector CO_2 Policy	$15/t-$CO_2$ Tax @ 5%				
		95% Cap				
	Additional Revenue Streams	$5/MWh				
		$15/MWh				
	RPS with New Nuclear	50% by 2050, No Trading				
		50% by 2050, Trading				
High Natural Gas Prices						
Low Natural Gas Prices						

Figure 2-1
Scenario matrix

The choice of these two parameters is based on two key factors:

- Natural gas combined cycle (NGCC) units have the lowest capital costs (by a significant margin) of the major dispatchable assets (gas, coal, nuclear). Electricity production costs from NGCC units are particularly sensitive to fuel costs. Consequently, many analyses have shown that the composition of the electricity generation portfolio is very sensitive to natural gas prices. This study looks at high and reference natural gas price trajectories based on the U.S. Energy Information Administration's *Annual Energy Outlook 2017* (EIA, 2017) and also considers a low natural gas price trajectory. Figure 2-2 shows the three natural gas price trajectories considered.
- The advanced nuclear capital cost scenarios are important for understanding the value of innovation to reduce capital investment requirements.[2] The study considers a range of values to identify capital cost targets necessary for the economic viability of advanced reactors under different investment environments. These values represent capital investment costs including overnight construction costs, capitalized financial costs, and interest during construction.[3] Four assumed advanced reactor capital costs are examined ($5,000/kW, $4,000/kW, $3,000/kW, and $2,000/kW) and vary after 2030. The high end of the range is slightly lower than estimates for large-scale light water reactor designs (see Figure 6-3 in Appendix A). The lower end of this range represents significant cost reductions relative to current projects, including countries like South Korea that have exhibited declining nuclear construction costs (Lovering, et al., 2016). Given historical cost overruns, higher cost sensitivities up to $8,000/kW are included to bracket the deployment envelope for select scenarios where advanced nuclear is deployed at $5,000/kW in this analysis.

Capital investment costs are the sum overnight capital costs, capitalized financial costs, and interest during construction.

[2] Nuclear cost sensitivities vary only the capital costs of advanced nuclear and hold all other costs (e.g., fixed and variable operations and maintenance) constant. It could be the case, however, that lowering capital costs will simultaneously change operations and maintenance costs.

[3] Hence, differences across "capital cost" scenarios may represent alternative assumptions about a range of factors (e.g., lower overnight costs, shorter construction duration leading to lower financing costs, loan guarantees).

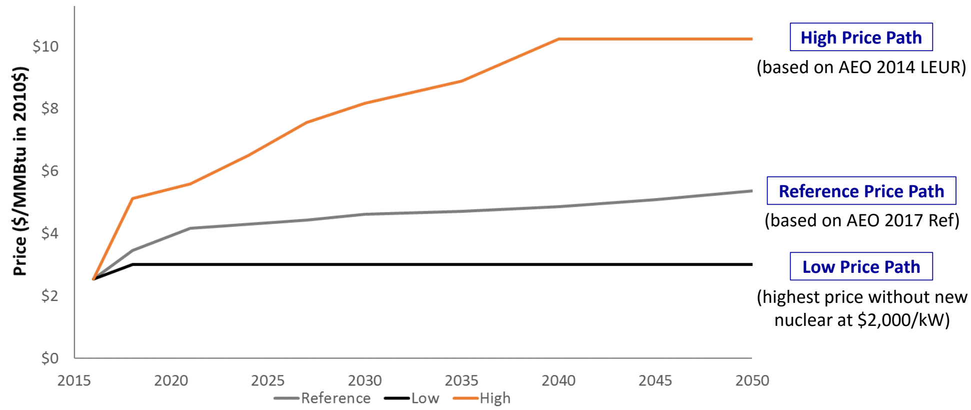

Figure 2-2
Electric sector delivered natural gas price trajectories (2010$ per MMBtu)

To establish a baseline, a reference scenario is included with business-as-usual policy assumptions (i.e., assuming on-the-book state and federal regulations) and reference natural gas prices. Outcomes across the sensitivities are compared with this reference to evaluate changes to the power sector and role of advanced nuclear deployment. <u>This reference scenario is not a forecast of the future</u> but functions as a counterfactual for comparisons. Key assumptions for the reference scenario are summarized in the next section.

The study looks at two other factors potentially affecting future investment in advanced reactors: carbon pricing policies, and potential additional sources of revenue beyond electricity sales. The climate policy sensitivity investigates two market-based alternatives:

- A carbon tax applied to the power sector that starts at $15 per ton CO_2 in 2025, escalating at the model's discount rate (5%), which is similar in timing and stringency to proposed state and federal carbon pricing policies (McFarland, et al., 2018).
- An electric sector CO_2 cap designed to achieve a 95% reduction of national CO_2 emissions below 2005 levels by 2050, which is consistent with reaching an 80% economy-wide reduction (e.g., similar to the June 2013 White House Climate Action Plan).

The sensitivity to additional revenue streams includes two scenarios: one with $5/MWh revenue and another with $15/MWh. The latter value is comparable in magnitude to zero-emissions credits implemented in some states or to the current nuclear production tax credit. Additional sources of revenue for advanced nuclear plants could come from a range of possible sources, broadly either due to policy or due to production of primary energy or other products:

- Policy sources including production tax credits from federal policies, or zero emissions credits from state policies like those recently implemented in New York and Illinois.

- Other revenue-generating products like process heat, energy storage and fuel synthesis (e.g., hydrogen production), district heating, fresh water via desalination, or other opportunities.
- Power purchase agreements for highly resilient facilities or green tariffs for electricity customers willing to pay a premium for zero-carbon power.
- Revenue from electricity markets due the provision of grid services (e.g., voltage/frequency control, resilience) or flexible operations.

While separate treatment of all possible added revenue streams is beyond the scope of this study, the stylized revenue stream represented in the scenarios serves as a proxy for a combination of revenues from sources beyond electricity sales.[4] While some sources may be more applicable to particular advanced reactor technologies, this initial analysis explores the magnitude of additional revenues necessary to affect future advanced nuclear deployment. This scenario provides a basis for future research to differentiate between advanced reactor technologies in terms of operational capabilities and revenue streams.

A final policy proposal modeled here is an expanded, more aggressive renewable portfolio standards (RPS) that includes new nuclear technologies (but not existing nuclear units) as an eligible resource due their non-emitting attributes and anticipated technological change.[5] This scenario assumes RPS programs are expanded to all regions of the U.S. and their stringency is increased over time from 30% of total generation in 2030 to 50% by 2050. One sensitivity analysis considers whether trading of renewable energy certificates (RECs) can contribute to RPS compliance, or whether a region complies only with in-state actions and no inter-regional REC trade. Note that all scenarios capture detailed provisions of existing state RPS requirements, resource eligibility, and technology-specific carve-outs, which reflect current law and scheduled changes over time.

Overview of EPRI's US-REGEN Energy-Economic Model

This analysis uses the electric sector only version of US-REGEN for detailed, state-level analysis of investments and dispatch.

Analysis of the multiple policies, technologies, and economic factors described above was performed using EPRI's in-house U.S. Regional Economy, GHG, and Energy (US-REGEN) model. US-REGEN is a detailed capacity planning and dispatch model of the electric sector that simultaneously determines investment and operational decisions. The model is solved as an intertemporal optimization through 2050 with five-year time steps with the intention of simulating a competitive equilibrium under alternative scenarios. It provides

[4] The stylized revenue stream in this analysis is presented as an equivalent average revenue, though market-clearing prices and the unit's production profile in non-electricity markets likely vary over time. Future work should pursue more detailed structural modeling of these markets and operational dynamics.

[5] This policy sensitivity differs from proposed clean energy standards (CES) in its trading provisions and eligible technologies (e.g., natural-gas-fired generators are often awarded credits under a CES). Blanford, et al. (2014) provide a detailed analysis of a CES using the US-REGEN model.

customizable state or regional resolution, allowing treatment of regional differences in policy, transmission interconnection, and demand.

Joint variability in load, wind, and solar across regions is captured through the selection of so-called "representative hours" using an approach described in Blanford, et al. (2018). This novel feature more accurately captures the spatial and temporal variability of power systems, which is critical for evaluating asset investments and operations.

Appendix A and EPRI (2017) contain greater detail about the US-REGEN model structure and assumptions.

US-REGEN has been used for several similar analyses to investigate a range of power sector and energy questions, notably analyses of the potential impact of national CO_2 policy and of the impact of significantly increased flexible operations in the U.S. generation fleet (e.g., Bistline, 2017; Bistline, et al., 2017; James, et al., 2015; Blanford, et al., 2014).

Models like US-REGEN are valuable not as predictive tools, but rather as tools to explore sensitivities and the inter-dependence of technology, economics, and policy factors. Long-term forecasts require knowledge about technological trends, political decisions, and market prices with high confidence. Since these parameters are fundamentally uncertain, a key use of models like US-REGEN is to compare different scenario results and to identify key sensitivities and technology deployment results which appear robust across a wide range of possible scenarios.

Key Scenario Assumptions

The analysis makes several important assumptions about technologies, policies, and fuel costs. Key assumptions are similar to other US-REGEN analysis (documented in EPRI, 2017 and Appendix A) and include:

- Reference load growth and fuel price assumptions come from the EIA's *Annual Energy Outlook 2017* (EIA, 2017), apart from the natural gas price sensitivities described above.
- Except for announced retirements, US-REGEN does not require existing coal units to retire at specific age limits. Rather, the model implicitly weighs the net present value costs of operating and maintaining existing units versus those of making new investments or changing dispatch of other resources. When the former costs are higher, US-REGEN will retire existing coal units endogenously. [6] The model treats the capital costs of existing units as sunk,

[6] US-REGEN incorporates all announced retirements of existing coal units. The remaining plants tend to have lower short-run marginal costs and, except for the lowest gas price scenarios, are among the lowest-cost dispatchable generators in many regions, especially for mine-mouth plants. US-REGEN refurbishment costs were recently updated for different classes of coal units based on observed costs. In practice, key components are often replaced on an ongoing basis and smoothed over time in the capital budgeting process, especially given the scarcity rents associated with the Clean Air Act § 111(b) constraint on new coal additions without carbon capture.

which gives them an inherent cost advantage over new units. The units remaining after announced retirements typically are more efficient and continue to be dispatched in many scenarios, perhaps at lower capacity factors.

- Existing nuclear unit lifetimes are limited to 60 to 80 years based on EPRI Nuclear assessments of likelihoods of license extensions for specific units, though plants can retire early under unfavorable economic conditions when the net present value of going-forward costs exceed anticipated revenues.
- Technology-specific economic lifetimes are assumed for investment decisions (e.g., 60 years for advanced nuclear).
- Technology cost and performance assumptions are based on EPRI's Generation Technology Options report (EPRI, 2013) but have been updated on an annual basis for rapidly changing technologies like wind and solar. Reference technological costs are shown in Figure 6-3 in Appendix A.
- Existing policies include state renewable portfolio standards (RPSs), the Regional Greenhouse Gas Initiative (RGGI), California's AB 32, and recent (2015) federal extensions of the production tax credit for wind and investment tax credit for solar. No additional environmental regulatory costs (e.g., Clean Power Plan) are included.

There are also several assumptions specific to the representation of advanced nuclear worth noting when interpreting the results. Outputs in subsequent sections are predicated on these assumptions, and specific values in the analysis could change under alternate inputs:

- No explicit differentiation between different advanced nuclear technologies (as described in greater detail in the next section).
- 60-year economic lifetime for new investments in advanced nuclear technologies.
- Advanced nuclear reactors are capable of flexible operations (e.g., adjusting output on an hourly basis given market conditions), unlike existing reactors (which are assumed to be "must run").
- Advanced nuclear technologies are assumed to be available only after 2030. Alternate commercialization timeframes would alter the pace of deployment and are left for future analysis.
- New U.S. nuclear builds include the four units under construction when the modeling was initiated in 2017. Plant Vogtle Units 3 and 4 in Georgia are still under construction; however, construction of V.C. Summer Units 2 and 3 in South Carolina was terminated by the time of publication. These assumptions do not materially alter results and insights drawn from this analysis.
- Existing state policies that establish moratoria on new nuclear builds (e.g., California) are assumed to remain in place.
- No annual build limits on new nuclear or other generation technologies are assumed after 2030. Although this omission does not alter results for most

scenarios with modest advanced nuclear investments, rapid capacity build-outs under the very low cost and CO_2 cap scenarios could be limited, at least initially, by practical constraints related to supply chains, workforce, regulations, financing, and other factors. The absence of annual build rates means that market signals and potential growth opportunities for different technologies are not masked by the important but distinct influence of constructability issues or other ad-hoc modeling constraints. Therefore, all results should be interpreted with caution in light of past experience and expectations of future performance.

Caveats

Caveat 1: Modeling for Insights, Not Numbers

Model results should not be interpreted as forecasts but are useful to explore uncertainties and to identify robust insights across scenarios.

Many caveats about the uses and limitations of economic models should be kept in mind when interpreting analysis results. Models like US-REGEN are by necessity numerical abstractions of the complex and uncertain economic and energy systems they represent. As such, they may contain approximation errors, incomplete system dynamics, and data quality issues. When viewing results, it is important to keep in mind that insights come from running a variety of scenarios, comparing the results, and asking "what-if" questions. Relative changes in values across scenarios offer more meaningful insights than absolute values of particular metrics.[7] Model results should not be interpreted or used as forecasts, but are useful for exploratory analysis to map the uncertainty space and to derive insights that are robust across possible futures.

Caveat 2: Unmodeled Power System Dynamics

There are several power system dynamics omitted in US-REGEN's scope that are relevant for advanced nuclear and other technologies:

- **No subhourly impacts or chronology:** The US-REGEN electric sector model incorporates a simple model of dispatch that excludes several operational costs, constraints, and unit-level detail due to the high computational cost of including such features in a multi-decadal, intertemporal optimization model. To better understand the short-run costs and technical challenges of operating different capacity mixes from the dynamic model, a standalone unit commitment version of US-REGEN was developed (EPRI, 2015). A static version of US-REGEN that focuses on investments in a single year is used for more detailed assessments of hourly system operations and impacts of energy storage investments (Blanford, 2015).
- **No markets for balancing services:** Existing and advanced nuclear plants (along with other grid resources) provide voltage and frequency stability benefits to the grid. They also, by virtue of only requiring refueling on a

[7] For instance, the total market size for new capacity in the power sector will be influenced by macroeconomic trends, electrification, rate of retirement for the existing fleet (including the existing nuclear fleet), and other factors.

multi-year basis, play a key role in grid resiliency in the event of interruption of supply from other sources. These attributes are not represented in US-REGEN.

- **Changes in criteria pollutant emissions not monetized:** US-REGEN is a least-cost optimization model of the power sector subject to technological and policy constraints. It does not account for positive or negative externalities, including pollution from fossil fuel resource extraction, fuel handling, combustion, or waste disposal (Muller, et al., 2011).

Caveat 3: Unmodeled Advanced Nuclear Attributes

There are several attributes unique to advanced nuclear technologies that are not incorporated in the modeling and are left for future work:

- **Siting and operational flexibility:** Some advanced nuclear technologies (e.g., small modular reactors) may offer uniquely valuable siting and operational flexibility capabilities.
- **Financing and learning-by-doing benefits of smaller-capacity technologies:** The potential value to project feasibility, technological change (e.g., learning spillovers within and across countries to lower costs), and financing of the ability to deploy in smaller capacity increments (e.g., small modular reactors) is also not represented in US-REGEN. The systems perspective embodied in the model's optimization formulation also means that the financial risk associated with investments from individual company perspectives is not captured.
- **Energy extraction from spent fuel:** Some advanced reactor types may be able to extract energy from spent LWR fuel, which would positively affect overall reactor economics.
- **National security and global leadership:** While very difficult to monetize, U.S leadership in commercial nuclear power has historically been important in maintaining credibility and advancing foreign policy goals related to non-proliferation (EFI, 2017). This analysis does not attempt to quantify potential diplomatic, security, or local economic development benefits of nuclear.

Caveat 4: Not Differentiating Between Specific Advanced Nuclear Technologies

The objective of this study is to understand the role of advanced nuclear in future energy markets and not necessarily to look at the specific role of different varieties of advanced nuclear like small modular reactors (SMRs) or advanced non-light water reactors (ANLWRs). The report addresses different sensitivities (e.g., additional revenues, discount rate, and cost reductions) deemed appropriate for advanced nuclear reactors based on expectations of additional cost and revenue benefits. Future work can differentiate across technologies and identify drivers of each, but such work likely requires expert elicitations and other evaluations to assess ranges of assumptions about costs, availability, performance, and additional revenues.

Caveat 5: Not Assessing R&D Costs or First-of-a-Kind Project Financing

This study is focused on the long-term economic viability of advanced nuclear reactors. Consequently, costs and revenues modeled here are intended to represent those associated with the "n^{th}-of-a-kind" deployments of advanced reactors. Added costs and challenges associated with demonstration and deployment of first-of-a-kind units are not modeled here (e.g., higher than expected construction costs or schedule delays associated with resolution of licensing challenges unique to advanced reactors). The opportunity for long-term deployment of advanced reactors based on the results of this study will help inform assessment of risks and benefits of investment in demonstration and first-of-a-kind units. Production tax credits and other federal programs are available to help address first-of-a-kind costs.

Caveat 6: Uncertainty

US-REGEN is a deterministic model that provides least-cost investment and dispatch equilibria given assumptions about future technologies, markets, and policies. Given the many uncertainties in the decision-making environment, deterministic models like US-REGEN employ approaches like sensitivity and scenario analysis to understand how alternate inputs relate to outputs of interest and to develop insights about the range of possible futures that can develop.[8] However, such approaches do not provide near-term hedging strategies (e.g., given uncertainty about future climate policy or gas price volatility) or allow for option value analysis under uncertainty like more formal stochastic models. This exploratory scenario analysis is designed to parametrically explore the commercial viability of advanced nuclear. Probabilities associated with alternate states-of-the-world are not discussed or quantified in this work.

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[8] The scenario design reflects different sources of uncertainty including intrinsic bounds on the predictability of complex systems (e.g., the political economy constraints on carbon pricing), diverse stakeholder beliefs (e.g., natural gas prices), and dynamic processes associated with complex systems (e.g., technological change and cost reductions).

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Section 3: Natural Gas Price Sensitivity Results

Natural gas price trajectories are influential parameters in energy system decisions but are fundamentally uncertain, especially over multi-decadal planning horizons. Since prices depend on many supply- and demand-side unknowns, this analysis represents natural gas uncertainty through three pathways (Figure 2-2).[9]

The reference gas price is based on the Energy Information Administration's Annual Energy Outlook (AEO) 2017 reference scenario (without the Clean Power Plan). The high-price path is based on the AEO 2014 Low Estimated Ultimate Recovery (LEUR) scenario. The low-price path is a flat $3/MMBtu price and represents the highest natural gas price at which no new nuclear additions occur in modeling of the reference policy case at $2,000/kW costs.[10] The three natural gas price trajectories are shown in Figure 2-2.

Reference Gas Prices

With low gas prices and no additional policies, new natural gas and renewable capacity is built in many regions of the U.S.

Figure 3-1 shows electricity generation by technology across the U.S. with reference gas prices, no additional energy/environmental policies, and $5,000/kW nuclear costs. Without additional state or federal policies, retirements of existing capacity and rising load are met predominantly by generation from new natural gas combined cycle (NGCC) units and renewables in many regions of the U.S.[11]

[9] Note that Figure 2-2 shows national average prices, but basis differentials are included for model regions.

[10] These scenarios should not be interpreted as forecasts or as likely developments but instead as possible future states-of-the-world that may be relevant for stakeholders.

[11] Although investments in renewables are supported by policies under some conditions (e.g., California solar through the state's RPS), many wind and solar capacity additions are economic without policy support, especially after 2030. The slowdowns in wind and solar additions between 2020 and 2030 are due to a combination of the phasedown of tax incentives, limited incremental RPS demand, and low gas prices.

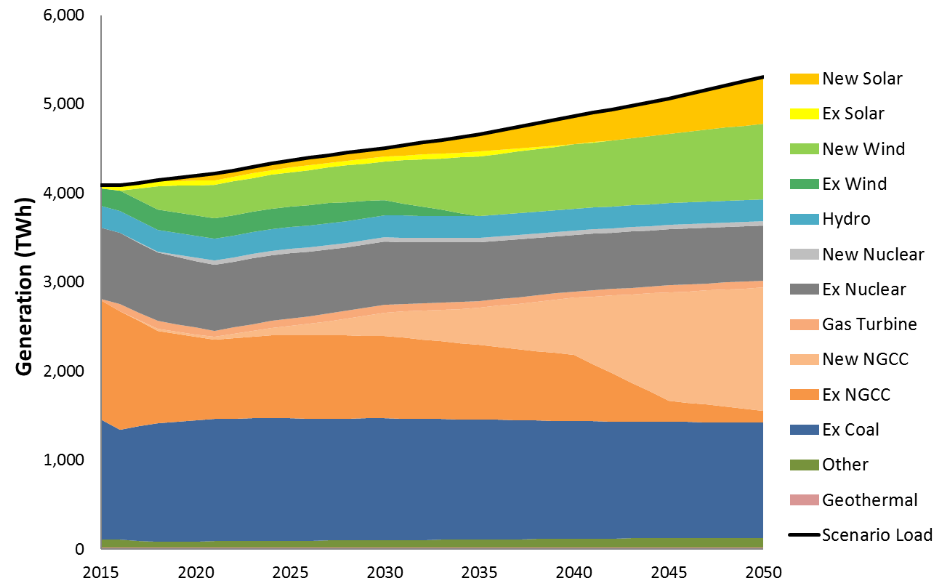

Figure 3-1
Electric generation (TWh) over time under the reference policy and gas price scenario with $5,000/kW nuclear costs

Although new nuclear investments are not in the money with higher costs, Figure 3-2 shows how the national generation mix by 2050 could change when advanced nuclear capital costs decrease. Lower total capital investment costs (including overnight construction costs, capitalized financial costs, and interest during construction) encourage advanced nuclear investment but require costs to be lower than $4,000/kW.

The economic drivers of nuclear power under these scenarios are its dispatchability, lower capital costs, and long lifetime (assumed to be 60 years), which mean that advanced nuclear at $2,000/kW would likely displace new NGCC capacity under reference policy conditions (see Appendix B, Figure B-4). The low variable costs of nuclear lead to high capacity factors across many of these scenarios (Figure B-5), but investment and dispatch characteristics depend heavily on scenario- and region-specific considerations.

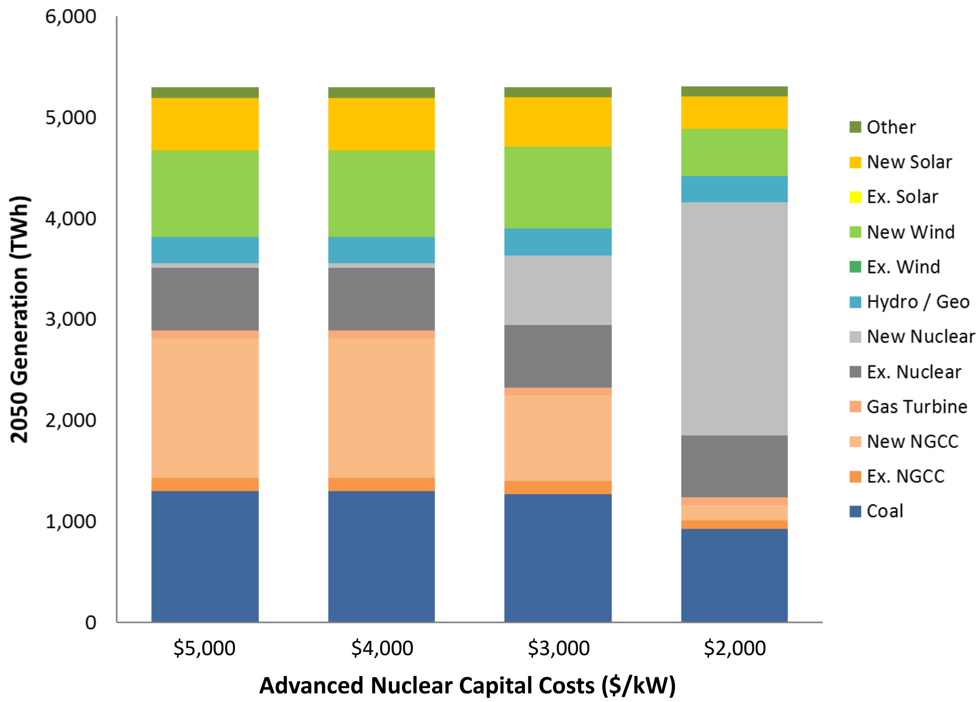

Figure 3-2
Sensitivity of the electric generation mix in 2050 to the assumed capital cost of advanced nuclear with reference policies and gas prices

Sensitivity to Alternate Gas Price Trajectories

Without carbon pricing or other policies, nuclear costs below $4,000/kW would be required for new investments.

With higher natural gas prices, the economics of electric sector investments and dispatch shift significantly. Before 2030, deployment of wind generation is accelerated to take advantage of expiring production tax credits, and higher gas prices simultaneously lower the capacity factors of existing NGCC plants. After 2030, new wind and solar are more competitive with NGCC under higher gas prices especially as costs decline (Figure A-3 in Appendix A), and new nuclear becomes economic in some regions even with higher capital costs (Figure 3-3). New nuclear construction is concentrated in Southern and Eastern regions due to higher gas prices and lower-quality wind resources, as demonstrated in Figure 3-7.

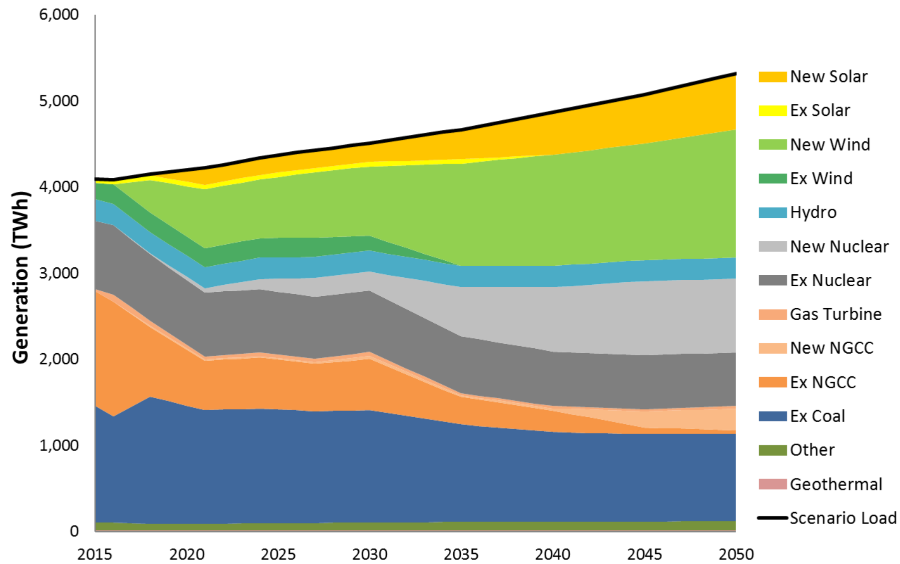

Figure 3-3
Electric generation (TWh) with reference policies, high gas prices, and $5,000/kW nuclear costs

The combination of higher gas prices and lower nuclear capital costs results in more substantial deployment nationally by 2050. Figure 3-4 illustrates how declining costs for nuclear power in a high gas price investment environment could curtail wind and solar investments unless installation costs for those technologies fall more sharply than shown in Figure A-3 in Appendix A.

Capital cost "sweet spots" for new nuclear investments depend critically on the costs of other technologies and on markets, especially gas prices.

The bottom row in Figure 3-4 underscores the considerable barriers to economic competitiveness of non-gas assets when natural gas prices remain low. Without additional climate policies and with flat $3/MMBtu gas prices, both nuclear and renewables would likely face investment headwinds. Uncertainty, hedging, unexpected technological progress, and policy changes may make this equilibrium unlikely, but these results highlight the compelling economics of NGCC assets for sustained low natural gas prices.

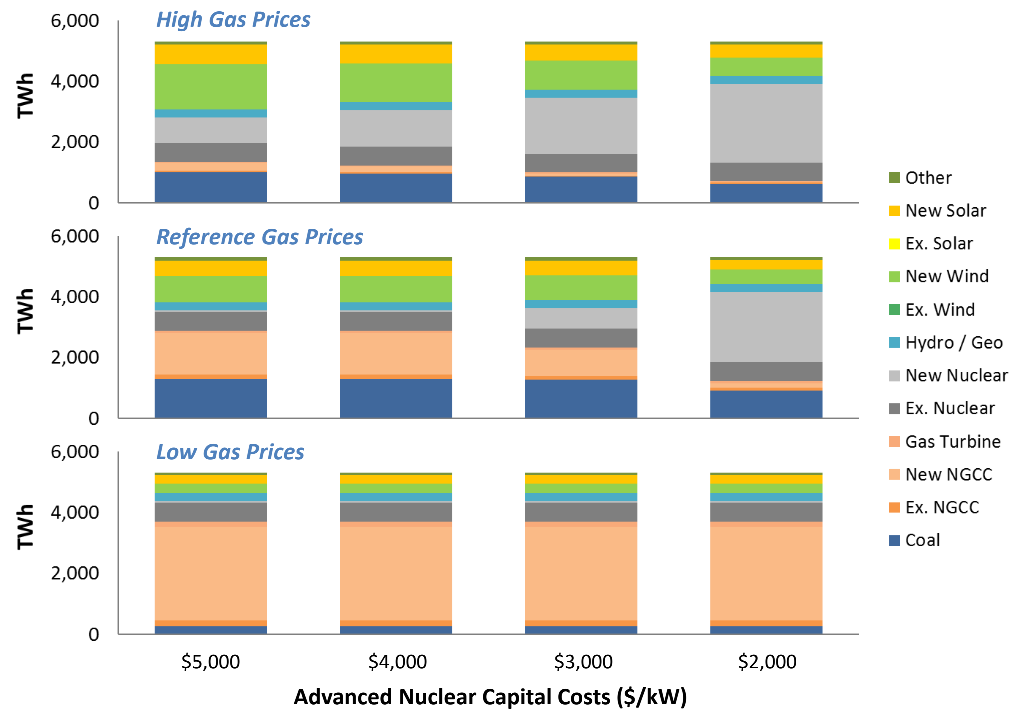

Figure 3-4
Sensitivity of the 2050 generation mix to the assumed capital cost of nuclear (columns) and gas prices (rows) under reference policies

Figure 3-5 extends the range of advanced nuclear capital costs to demonstrate the sensitivity of the national capacity mix to these higher values.[12] Although modeling indicates extensive advanced nuclear deployment at capital costs lower than $5,000/kW, higher costs result in limited deployment. At these higher costs for new additions, the nuclear fleet consists primarily of currently operating plants with license extensions. Note that for scenarios where new nuclear deployment is limited and wind and solar are competitive, total installed capacity of all technologies is higher due to the lower capacity factors of variable renewable energy.

[12] "Nuclear" capacity in Figure 3-5 includes both existing plants and advanced reactors.

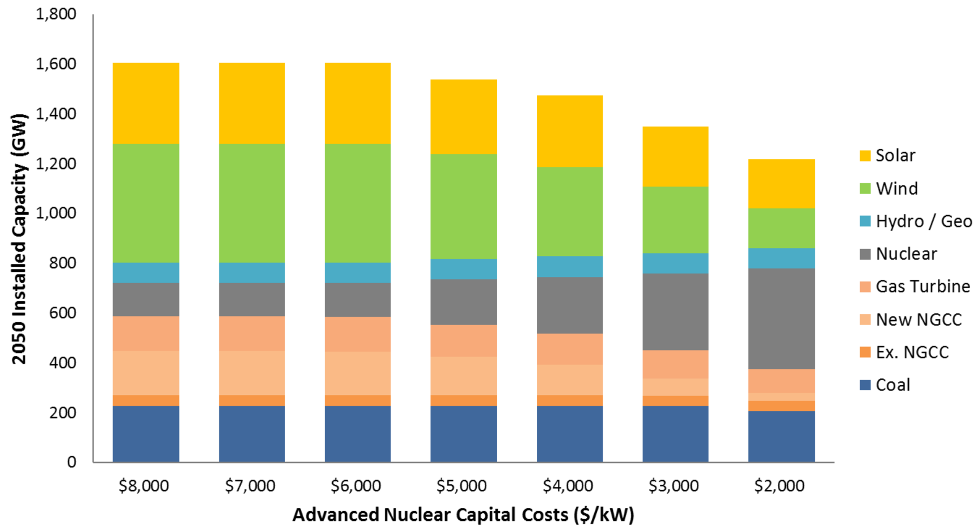

Figure 3-5
Installed capacity by technology in 2050 for alternate nuclear cost scenarios (with reference policies and high gas prices)

Sensitivity to Discount Rates

Nuclear power – like renewables, transmission, and energy storage – is a high-capital-cost but low-variable-cost resource, which means that assumptions about project finance and time preference (i.e., comparing current costs and revenues vis-à-vis future ones) are important for deployment. US-REGEN typically assumes a five percent discount rate in its intertemporal optimization formulation, but reasonable alternatives are also possible given uncertainty about future macroeconomic parameters and incentives for different decision-makers.[13]

[13] Another important financing assumption is the economic lifetime of different assets. US-REGEN assumes a 60-year lifetime for advanced nuclear investments. Since the anticipated lifetimes of advanced reactor designs may be longer or shorter, a methodological review and sensitivity around this parameter are left for future work.

Figure 3-6
Sensitivity of the electric generation mix in 2050 by technology across different discount rates (bars) and nuclear capital costs (panels)

Assumptions about the discount rate materially impact planning decisions for nuclear and other technologies.

Figure 3-6 shows a sensitivity where the real discount rate is varied between 3%, 5% (reference for all other runs in this report), and 7%. The assumed discount rate has significant impacts on the split between higher fixed cost technologies (e.g., wind, solar, nuclear) and higher operating cost ones (e.g., natural gas) under all conditions. All else being equal, lower discount rates provide more favorable investment environments for renewables and nuclear, while higher rates favor NGCC. Differences in cumulative capacity additions for individual technologies can vary by hundreds of GW between the 3% and 7% scenarios (e.g., wind additions decrease from 396 GW to 277 GW, respectively).

Under reference policy assumptions, the high-capex but low-opex cost profile of nuclear has the largest impact for nuclear capital costs of $3,000/kW. Cumulative nuclear additions through 2050 for the 3%, 5%, and 7% discount rates are 145 GW, 85 GW, and 6 GW, respectively. At higher costs ($5,000/kW), deployment of advanced nuclear is not sensitive to the discount rate, since it is out of the money without additional policies or revenues. At very low costs ($2,000/kW), deployment of advanced nuclear also is not sensitive to the discount rate.

Discount rates and financing assumptions will likely vary for different advanced nuclear technologies. For instance, project size and risk influence the cost of capital and will differ significantly among SMR and ANLWR concepts.

Regional Market Results

Earlier results focus on national electric sector outcomes across different possible gas price and nuclear cost outcomes. Across many scenarios, there are important regional differences (e.g., natural gas pipelines, policies, renewable resources, existing asset mix, transmission) that will make the economic competitiveness of advanced nuclear generation vary across the U.S.

For instance, Figure 3-7 and Figure 3-8 show generation by region under two different scenarios.[14] Figure 3-7 shows how 7 of 15 regions build new nuclear with high gas prices even with $5,000/kW nuclear costs. More broadly, these scenarios demonstrate how specific technologies can play a significant role in some regions despite smaller generation shares nationally. Nuclear builds are more attractive in Southern and Eastern regions with higher gas prices and lower-quality wind resources. Figure 3-8 indicates that lower capital costs for nuclear could create broader market opportunities for commercial deployment relative to the high-gas-price scenario.

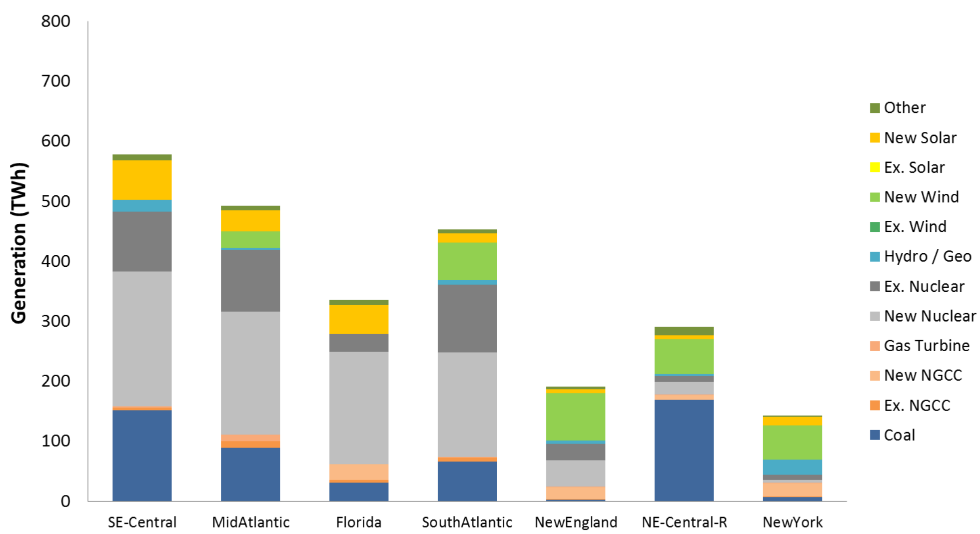

Figure 3-7
2050 generation by technology in model regions building new nuclear under the high-gas-price scenario with $5,000/kW nuclear

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[14] The mapping between US-REGEN model regions and states is shown in Figure A-1.

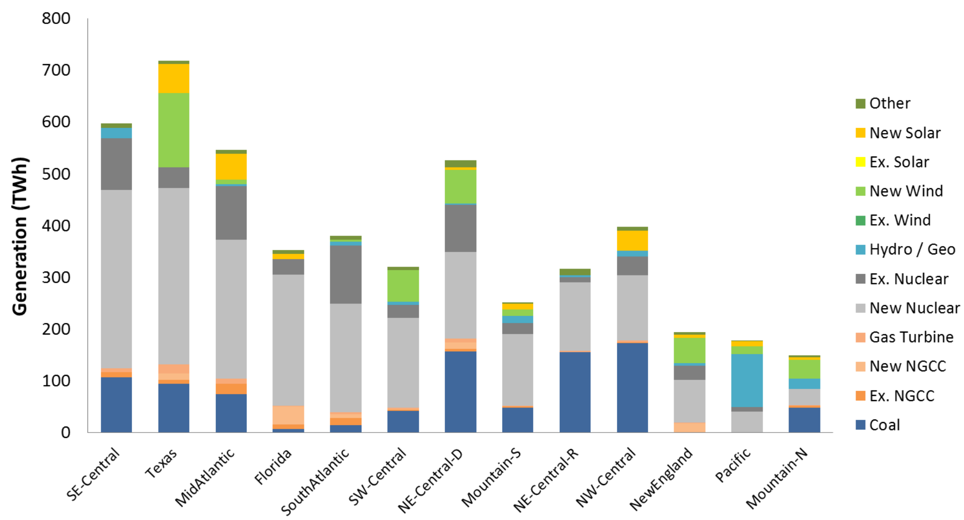

Figure 3-8
2050 generation by technology in model regions building new nuclear under reference gas prices with $2,000/kW nuclear

Summary of Insights

- Capital cost "sweet spots" for new nuclear investments depend critically on the costs of other technologies and on markets, and natural gas prices shape tradeoffs between nuclear and other generation options.
- Without carbon pricing or other policies, capital costs of nuclear below $4,000/kW would be required for new nuclear investments under reference gas prices, but nuclear could be in the money at $5,000/kW under high gas prices. Investments in nuclear and renewables potentially hedge against natural gas price volatility, though these dynamics of decision-making under uncertainty are not explored in this analysis. Under low gas prices, NGCC investments crowd out other technologies unless other policies are enacted.
- Absent additional policies or revenues, the economic proposition for advanced nuclear in these scenarios are a combination of significantly lower capital costs, dispatchability, and long asset lifetimes. If advanced reactors designs do not exhibit these attributes or if alternate technologies are able to exceed these cost or performance levels, then the market for advanced nuclear may be more limited.
- Assumptions about financing and the discount rate materially impact planning decisions moving forward. For instance, under a reference policy scenario with $3,000/kW nuclear costs, moving from a 7% discount rate to 3% increases advanced nuclear additions through 2050 from 6 GW to 145 GW.
- Key regional differences (e.g., gas pipelines, policies, existing asset mix, transmission) make the economic competitiveness of advanced nuclear vary across the U.S. Nuclear builds are more attractive in Southern and Eastern regions characterized by higher gas prices and lower-quality wind resources.

Section 4: Energy and Environmental Policy Sensitivity Results

Analysis in Section 3 indicates that nuclear power's total capital investment costs are an important driver of deployment in a world without supporting policies or supplemental market opportunities. Nuclear deployment would require aggressive cost declines (and associated technological change) and even more so if natural gas prices are low. This section investigates the potential impact of energy and environment policies on nuclear deployment.

CO_2 Tax

The CO_2 Tax sensitivity looks at a national power sector carbon price of $15/t-$CO_2$ that starts in 2025 and escalates annually at the model's discount rate of five percent (reaching over $50/t-$CO_2$ by 2050).[15] Figure 4-1 shows cumulative nuclear deployment by 2050 under the CO_2 Tax and other analysis sensitivities.

Policy and market environments may drive advanced nuclear deployment as much as cost targets.

Nuclear additions depend jointly on capital costs and market value. The CO_2 tax raises wholesale power prices, especially as plants with higher emissions intensities retire, which increases potential revenues to low-CO_2 technologies like nuclear.[16] As a result, nuclear additions are appreciable when carbon taxes are in place, even with higher capital costs (e.g., 131 GW by 2050 with $5,000/kW nuclear costs, as shown in Figure 4-1). For the range of nuclear costs studied here, the $15/t-$CO_2$ tax provides a greater incentive for deployment than higher gas prices. Lower capital costs increase advanced nuclear deployment, though the total market share depends heavily on technological progress for other low-carbon technologies.[17]

[15] This scenario represents a stylized carbon pricing policy and is not designed to mimic the timing or stringency of any state or federal proposals.

[16] All carbon pricing scenarios implicitly assume that the CO_2 price is reflected by generators in their dispatch offers based on the carbon intensity of their output.

[17] A caveat with Figure 4-1 is that it aggregates important dynamics associated with regional impacts, the time profiles of investment, and sensitivities to other market drivers (which are addressed in other sections of the report).

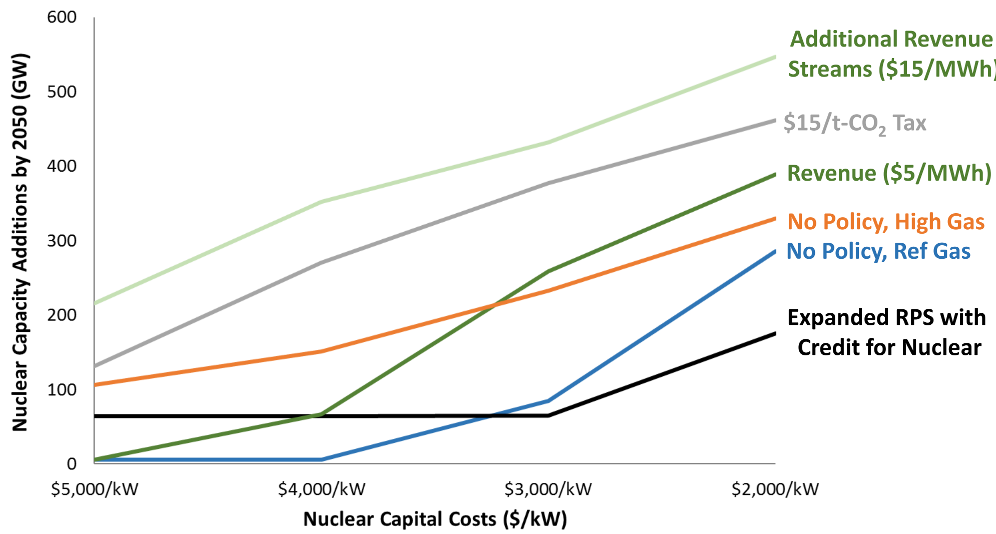

Figure 4-1
Cumulative nuclear capacity additions through 2050 (GW) across different nuclear capital costs ($/kW) and scenarios

Note that cumulative nuclear additions are roughly similar between the scenario with $2,000/kW costs without policy and $4,000/kW with a $15/t-$CO_2$ tax. This result reinforces that deployment varies based on a combination of both technological changes in nuclear technologies and the policy landscape.

95% Cap

Another form of emissions pricing entails implementation of a quantity-based cap-and-trade system, which imposes fixed annual emissions caps and requires covered entities to submit allowances equal to their emissions during a compliance period. To reach an 80% economy-wide reduction in CO_2 emissions relative to 2005 levels (e.g., similar to the June 2013 White House Climate Action Plan), power sector reductions would likely be larger due to the sector's comparatively low marginal abatement costs and the important role of electrification in reducing emissions in other sectors (Bistline and de la Chesnaye, 2017; Clarke, et al., 2014).

To reflect these goals in a stylized manner (acknowledging many uncertainties in policy design and timing), this scenario examines the impacts of a cap-and-trade policy with electric sector emissions consistent with the Clean Power Plan through 2030 (reaching 32% below 2005 levels by 2030) and then straight-line reductions to 95% reductions by 2050.

Figure 4-2 shows the generation transformation to reach the 95% target. With higher nuclear costs ($5,000/kW), new investments include a range of low-carbon technologies, including wind, nuclear, solar, and gas (largely NGCCs with and without carbon capture). Lower nuclear costs ($2,000/kW) incent greater nuclear deployment. All 95% cap scenarios entail coal phaseouts before 2050.

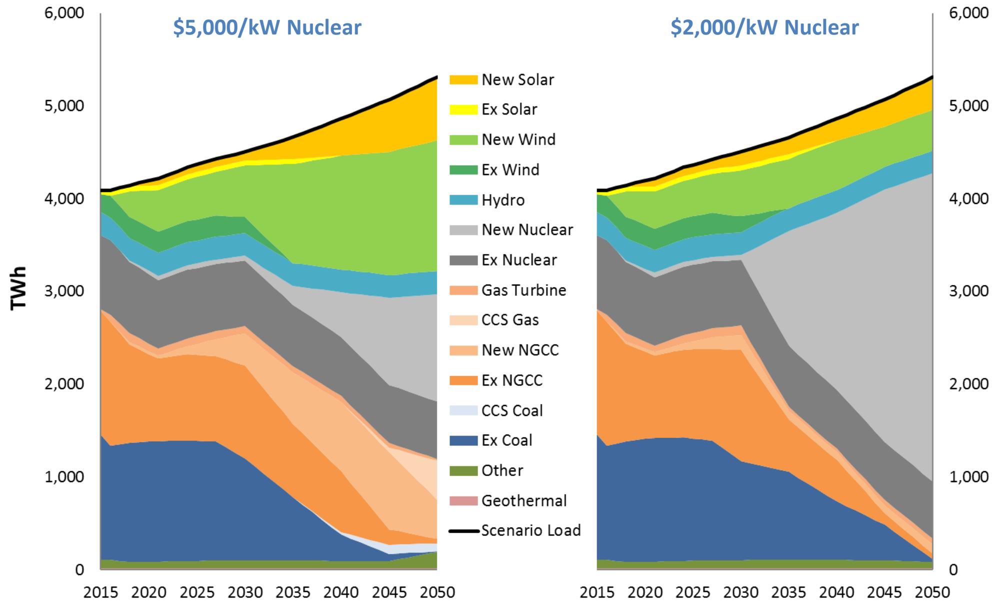

Figure 4-2
Electric generation (TWh) over time under the 95% Cap scenario and reference gas prices under two nuclear capital cost scenarios

Figure 4-3 demonstrates changes in the national capacity mix under the 95% cap scenario across an expanded range of advanced nuclear capital costs. As nuclear costs decrease, deployment decreases for CCS-equipped gas, new NGCC units without CCS, and variable renewable energy.

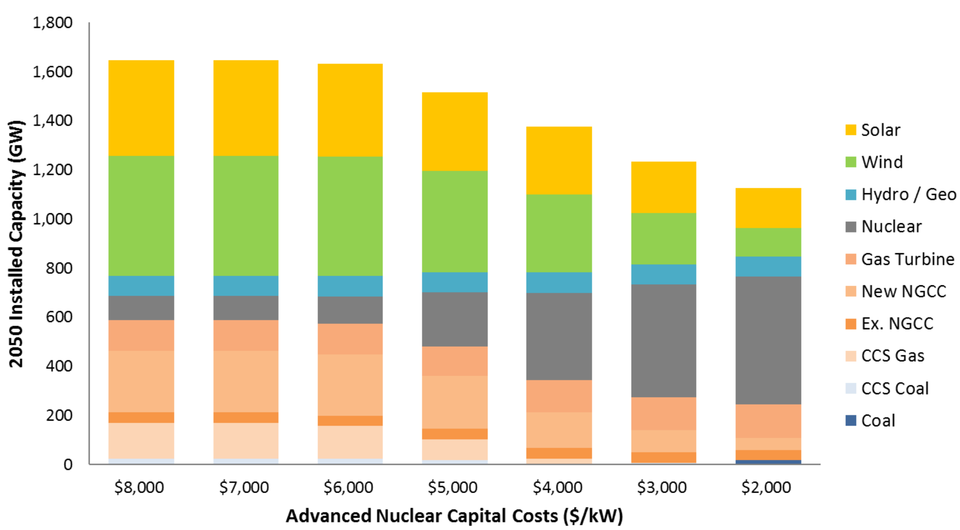

Figure 4-3
Installed capacity by technology in 2050 for alternate nuclear cost scenarios under the 95% Cap scenario (with reference gas prices)

2050 allowance prices (which are outputs of optimization models like US-REGEN and provide one metric for assessing the relative costs of policies like emissions caps) vary from \$36/t-CO_2 with low (\$2,000/kW) nuclear capital costs to \$76/t-CO_2 with high (\$5,000/kW) nuclear costs, as shown in Figure 4-4. Similarly, the incremental electric sector costs[18] of the 95% cap policy decrease from about \$260 billion with high nuclear costs to \$110 billion with low costs (Figure B-8 in Appendix B).

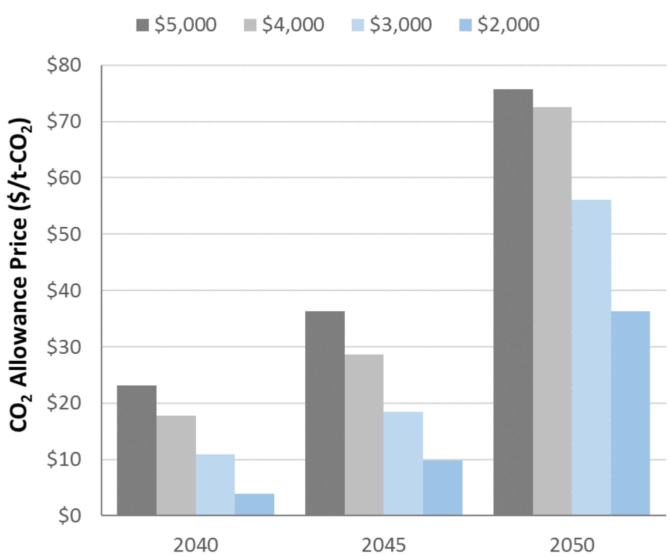

Figure 4-4
CO_2 allowance prices for the 95% cap policy (\$/t-CO_2) by year under different nuclear capital costs

Lower nuclear costs under the 95% cap scenario increase generation in new nuclear relative to the higher-cost scenario and displace generation from wind and gas (both with and without carbon capture), as shown in Figure B-4 (Appendix B). Under the reference policy, lower-cost nuclear competes with new NGCC generation along with coal and wind in some regions. Figure B-4 underscores how the market opportunities and competition for low-cost nuclear depends on the CO_2 policy scenario.

For emissions reductions policies, the presence of technologies like advanced nuclear can lower compliance costs.

When gas prices are low, capture-equipped NGCC capacity challenges nuclear's competitiveness as a low-cost, low-CO_2 dispatchable generator. Gas prices can alter power sector outcomes across a range of scenarios, even without significant progress in the capital costs or assumed efficiencies of NGCC units. With higher nuclear costs, emissions pricing may not be enough to encourage widespread nuclear deployment with low gas prices (Figure B-6 in Appendix B).

[18] Policy costs are incremental relative to the reference (i.e., no policy) scenario. These costs are the net present value of total electric sector costs between 2016 and 2050, including capital costs, fixed and variable operations and maintenance costs, fuel costs, transmission-related costs, and regulatory costs.

Overall, these results underscore how dispatchable low-carbon resources like advanced nuclear and CCS reduce the costs and technical challenges of deep decarbonization.

Expanded RPS with New Nuclear

Another potential avenue for policy support is to expand state renewable portfolio standards (RPS) to include advanced nuclear as an eligible technology. RPSs require firms in a jurisdiction to supply a minimum fraction of retail load from eligible resources and have been used by states to achieve a variety of goals including emissions reductions, job creation, and innovation for clean technologies. Although RPS eligibility requirements differ across states, new nuclear is not included in current RPSs, though it has been discussed as part of broader Clean Energy Standards at state and federal levels (Blanford, et al., 2014).[19]

This sensitivity examines the impact of including advanced nuclear as an eligible technology in expanded RPS requirements. This expanded RPS scenario increases each region's RPS to 50% by 2050.

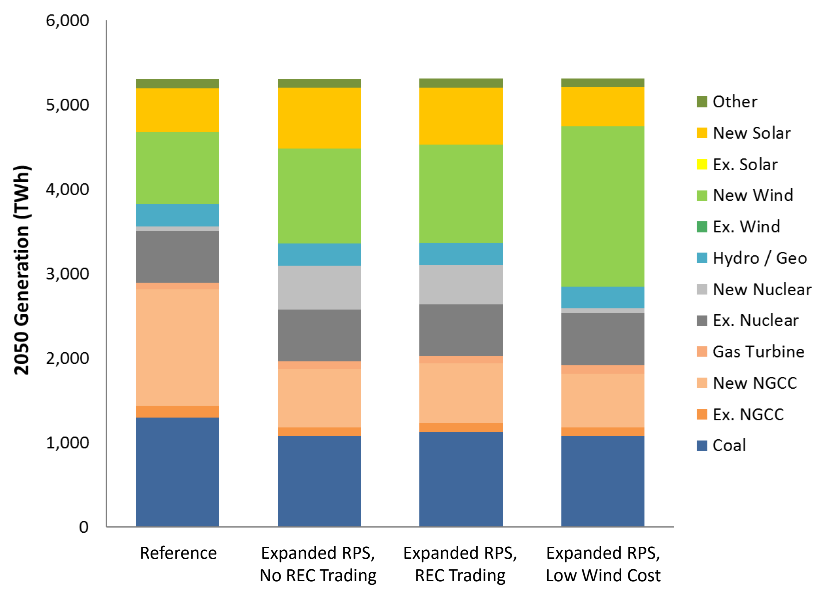

Figure 4-5
Sensitivity of the electric generation mix in 2050 (assuming $5,000/kW nuclear capital costs) to "Expanded RPS" scenarios where new nuclear is an eligible technology and targets reach 50% by 2050

Figure 4-5 compares the 2050 generation mix across the reference and three expanded RPS scenarios. Even with higher capital costs ($5,000/kW), advanced

[19] Note that regulatory approaches to energy and environmental policy (e.g., technology mandates and subsidies like the RPSs studied here) differ from market-based approaches (e.g., carbon pricing in previous sections) in their technology-specific impacts (Fawcett, et al., 2014; Fischer and Newell, 2008).

nuclear enters the generation mix, as electricity market revenues are supplemented by renewable energy certificate (REC) sales that make new nuclear investments profitable.

Although these scenarios illustrate how revenue from zero-emissions attributes can help technologies like nuclear under some conditions, Figure 4-5 also shows how policy provisions and technology competition make these revenues uncertain. For instance, allowing REC trading across regions allows low-cost wind in Texas and the Great Plains regions to increase supply in REC markets, which puts downward pressure on REC prices and revenues received by nuclear and other eligible technologies. Revenues from these markets drop even more when unexpected technological breakthroughs occur, and lower-cost project development depress REC prices. Figure 4-5 presents a sensitivity with wind capital costs dropping by 44% by 2030 relative to current levels.[20] This scenario entails significantly more wind in the generation mix, which decreases solar deployment and crowds out advanced nuclear deployment.

REC prices (in $ per MWh terms) are shown in Table B-1 in Appendix B across scenarios and regions. REC trading raises prices in some states (e.g., Texas) and lowers prices in others (e.g., SE-Central). Lower wind cost decreases REC prices from $9.60/MWh to $2.90/MWh, which would impact new investments in eligible clean generation resources that receive a greater fraction of their revenue from REC sales.

Overall, these scenarios highlight uncertainty associated with relying on REC markets for all eligible generators (not only nuclear). There are many uncertainties moving forward about factors like:

- **Exposure to external forces:** The timing and stringency of RPSs are uncertain and may change abruptly based on a variety of political economy factors. These scenarios illustrate that significant increases in stringency would be required to incent new nuclear at higher costs.
- **REC market depth and liquidity:** Unexpected cost reductions for individual technologies could depress market prices. Additionally, assumptions about interregional trade could also impact REC prices (either increasing or decreasing prices depending on a region's net trade position).
- **Volatility:** A variety of trading assumptions and market expectation may impact RPS-related revenues. These sensitivities examined a limited number of scenarios to examine potential impacts of an expanded RPS on new nuclear investments, but many other states-of-the-world are possible.

Summary of Insights

- Policy and market environments may drive advanced nuclear deployment as much as cost targets. More generally, specific policy goals and assumptions

[20] These reductions come from the "low scenario" from recent expert elicitations in Wiser, et al. (2016), "Expert Elicitation Survey on Future Wind Energy Costs," *Nature Energy*.

about available technologies moving forward jointly determine the generation mix.

- Under stringent CO_2 emissions reduction targets, supply-curve-like dynamics (e.g., decreasing returns to renewable energy, biomass supply curves), sunk costs (e.g., the existing generation mix), and functional attributes (e.g., energy, capacity, flexibility) drive portfolio diversity. There are unmodeled drivers of diversification like uncertainty and public acceptance that also could alter the mix.
- Although nuclear (and other low-carbon technologies like wind, solar, biomass, CCS-equipped generation) may be desirable from an environmental perspective, the economic prospects of new additions require these attributes to be reflected in the investment context through a policy-induced price signal.
- The presence of advanced technologies like low-cost nuclear can reduce compliance costs associated with energy and environmental policies like stringent climate targets. However, simultaneous technological progress for other generation options, especially dispatchable low-carbon technologies, poses risks to nuclear deployment.

References

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Section 5: Additional Revenue Stream Sensitivity Results

Results in previous sections assumed that revenues for new nuclear come only from participation in electricity markets and environmental compliance markets when available (e.g., the expanded RPS scenarios in Section 4). This section examines a sensitivity where nuclear energy systems also receive additional revenue streams.

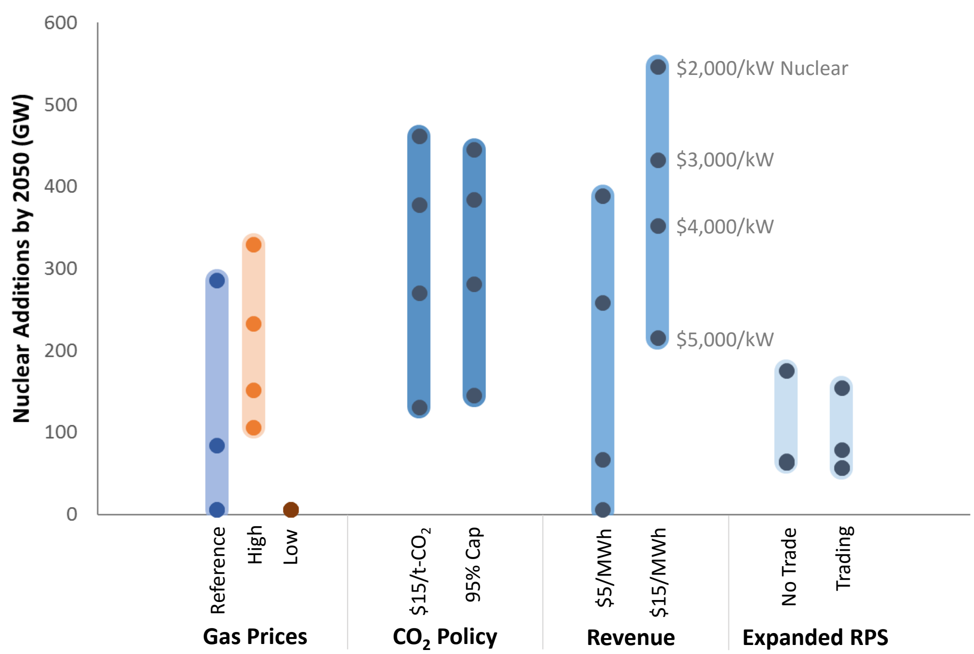

Figure 5-1
Cumulative nuclear additions through 2050 (GW) across all sensitivities (horizontal axis) and nuclear capital costs (dots[21])

As a proxy for potential sales of other products like primary heat and desalination, production tax credits, green tariffs, or power purchase agreements for highly resilient facilities, the additional revenue stream is modeled as a

[21] Certain sensitivities entail similar nuclear additions at different capital costs. Overlapping dots in Figure 5-1 occur for sensitivities with fewer than four dots at the lowest deployment level.

stylized equivalent average revenue of $5/MWh or $15/MWh and is assumed to apply only to new nuclear. Such additional revenues may be more accessible to advanced reactor technologies given their technical capabilities than to conventional light water reactors. These revenues beyond power sales are akin to revenue stacking for energy storage, where projects may clear investment hurdles by serving multiple applications and combining a variety of revenue streams.[22]

Additional revenue streams improve the value prospects of advanced reactors.

Figure 5-1 shows the cumulative nuclear additions through 2050 across the scenarios in this study and nuclear capital costs. Even with a modest $5/MWh revenue stream (and without other supporting policies), nuclear additions are higher for all capital cost sensitivities. The higher $15/MWh revenue sensitivity (which is slightly lower than the current production tax credit and similar in magnitude to proposed Zero Emissions Credits) incentivizes considerably more nuclear capacity than a counterfactual with revenues from electricity markets only, which is up to 200 GW higher by 2050. Wholesale electricity prices in the reference (i.e., no policy) scenario with reference gas prices are typically between $30 and $50/MWh for regions over time, as shown in Figure B-3 in Appendix B. Therefore, supplemental revenues of $15/MWh represent between a 30 to 50 percent increase in revenue per unit generation. Comparing across all scenarios suggests that additional revenue streams of about $15/MWh would be most impactful in encouraging deployment. Otherwise, a carbon pricing policy appears to be the most influential factor in advanced nuclear additions.

Additionally, the current and future emphasis on capacity provision to meet peak residual load means that flexibility is essential to navigate future power systems, though the timescales and degree of flexibility required will depend on system configurations and technological characteristics.

Additional revenue streams (e.g., production tax credits, primary heat sales) provide different varieties of investment uncertainty in comparison to the various forms of regulatory support examined in Section 4. Carbon pricing through a CO_2 tax or cap offer relatively predictable ways to value the emissions reduction benefits of nuclear, but their technology-neutral structures also help other low-carbon substitutes as well (e.g., wind, solar, CCS), which makes evaluations of competitiveness difficult a decade or more in advance. The "Expanded RPS" with new nuclear offers an additional revenue stream, but as Section 4 illustrated, there is uncertainty associated with relying on REC markets given how these revenues are exposed to external forces, questions about market liquidity and depth, and technological progress for wind and solar eroding prices.

Summary of Insights

- The extent of advanced nuclear deployment depends jointly on changes in costs and benefits (i.e., market value) of different technologies at the margin. For example, new nuclear deployment by 2050 at $5,000/kW capital cost

[22] The stylized revenue stream in this analysis is presented as an equivalent average revenue, though market-clearing prices and the unit's production profile in non-electricity markets likely vary over time. Future work should pursue more detailed structural modeling of these markets and operational dynamics.

with additional revenue streams ($15/MWh on average) is comparable that of a reference policy at $2,000/kW (and 95% CO_2 cap at $4,000/kW), as shown in Figure 5-1.

- Non-electricity revenues and the policy environment could drive advanced nuclear deployment as much as capital cost targets but entail different uncertainties that may be less controllable by technology developers.

Section 6: Conclusions and Future Work

Summary of Key Findings and Recommendations

This study evaluated the economic viability of advanced nuclear across a range of scenarios representing different combinations of technology, economic, and policy conditions. These scenarios allowed an assessment of the relative importance of different cost, revenue, and policy factors to future deployment of advanced nuclear reactors.

The analysis suggested that it is unlikely that a single dominant factor will determine future deployment of advanced nuclear (e.g., capital cost). A combination of reduced capital costs, favorable policy conditions (e.g., climate policy), and additional revenue streams for other services and products is more likely to create conditions under which significant new deployment of advanced nuclear reactor technology will occur.

An important corollary is that advanced reactors could need to obtain additional revenue beyond that received from bulk energy sales, for example from process heat, energy storage and fuel synthesis (e.g., hydrogen production), district heating, or other opportunities. Therefore, without new policies or innovation to significantly drive down costs, future nuclear reactors will need to be developed and sited to facilitate the provision of multiple services and products.

Model results suggest that advanced nuclear could be economically viable across a range of scenarios. In addition, substantial variation in the existing regional generation portfolios leads to economic viability for advanced nuclear power in some regions, even under scenarios where national deployment is not widespread.

Several detailed insights from this study underlie the above high-level conclusions:

Capital Cost Insights

- Capital cost “sweet spots” for new nuclear investments depend critically on the costs of other technologies and on markets, and natural gas prices shape tradeoffs between nuclear and other generation options.
- Without carbon pricing or other policies, capital costs of nuclear below $4,000/kW would be required for new nuclear investments under reference gas prices, but nuclear could also be competitive at $5,000/kW under high gas prices.

- Under low gas prices, NGCC investments crowd out nuclear investments, even at $2,000/kW, unless other policies are enacted. The capital cost sensitivities under different alternate gas scenarios underscore the importance of assuring economically robust generation portfolios considering uncertainty in the long-term trajectory for fuels prices and technological costs.

Energy and Environmental Policy Insights

- Policy and market environments may drive advanced nuclear deployment as much as cost targets. More generally, specific policy goals and assumptions about available technologies jointly determine the future generation mix.
- Policies at the state and/or federal level that encourage CO_2 emissions reductions are important to the future economic viability of advanced nuclear plants. New nuclear deployment by 2050 under a $4,000/kW capital cost scenario with a moderate to stringent climate policy is comparable to a $2,000/kW capital cost scenario under reference policies and natural gas prices.
- The presence of advanced technologies like low-cost nuclear can reduce compliance costs associated with energy and environmental policies like stringent climate targets. However, advanced nuclear technologies must compete with any other technology that can deliver lower compliance costs through technological progress.
- Expanded RPS policies as modeled in this study would likely result in new nuclear deployment, but uncertainty about market depth and cost reductions of other technologies make the effectiveness of such policies in encouraging new nuclear deployment uncertain.

Additional Revenue Stream Conclusions

- The extent of advanced nuclear deployment is strongly influenced by revenue sources beyond electricity sales, if they are available.
- Non-electricity revenues and the policy environment drive advanced nuclear deployment as much as cost targets but entail different uncertainties that may be less controllable by project and technology developers.

In summary, the degree to which advanced nuclear reactor technologies can more successfully achieve lower capital costs, **and** provide additional value through products and operational capabilities will play a strong role in the extent and speed of their future deployment.

Insights for Modeling and Analysis

This analysis suggests a few key insights for economic modeling of advanced nuclear and other low-carbon technologies.

Uncertainty abounds in power sector decision-making, which makes it critical to examine diverse scenarios and sensitivities to understand the role of a specific technology. This report conducted a range of sensitivities tailored to advanced nuclear reactors and indicated that, in addition to customary CO_2 policy and gas price scenarios, model outputs are dependent on the magnitudes of additional revenue streams. Additionally, the complexity of markets and technological capabilities mean that cost-based metrics alone are increasingly insufficient for evaluating the economic competitiveness of various technologies, which makes energy-economic modeling an important input to decision-making processes.

Model results also highlight the importance of discount rate and financing assumptions. Nuclear plants are large capital-intensive projects, which means that the cost of capital can materially impact planning decisions (Rothwell, 2016). For instance, under a reference policy scenario with $3,000/kW nuclear costs, this analysis showed that moving from a 7% discount rate to 3% increases advanced nuclear additions through 2050 from 6 GW to 145 GW. Therefore, analysis should investigate how alternate financing assumptions impact model conclusions. Comparisons across models can be challenging, however, given how financing assumptions vary with model structure (Cole, et al., 2017). Likewise, a model's treatment of end effects is important given the long-lived nature of nuclear investments, which means that the asset's lifetime will extend well beyond the model's time horizon.

A model intercomparison project on advanced nuclear could quantify how differences across models (e.g., treatment of end effects, financing assumptions, revenue streams, cost assumptions) give rise to alternate valuations of low-carbon technologies.

Future Work

This analysis also suggested areas for future work. Explicit modeling of different advanced nuclear technologies would be desirable to understand tradeoffs between different advanced nuclear designs. Expert elicitations for advanced nuclear are a useful complement to such analysis to understand expectations about different costs, revenue streams, and capabilities of unique configurations.

Other areas for future research include:

- **Modeling additional product markets:** Since advanced nuclear deployment is sensitive to additional revenue streams (as shown in Section 5), future work should include more detailed structural modeling of these opportunities and qualitative assessments of factors that could influence market participation (e.g., required regulatory changes).
- **Investments under uncertainty:** US-REGEN is a deterministic model, but using a stochastic modeling framework could provide near-term hedging strategies or allow for analysis of real options associated with nuclear RD&D (and other technologies).
- **Global analysis:** The current analysis focuses on a U.S. context, but global demand for advanced nuclear is expected to exceed domestic markets. Some issues and insights in this report may be applicable to nuclear's competitiveness in some contexts but not all. A global framework would also be better suited for evaluating international technology spillovers.

- **Sensitivity to operations and maintenance costs:** Cost sensitivities in this analysis vary only the capital costs of advanced nuclear and hold all other costs (e.g., fixed and variable operations and maintenance) constant. Future work should investigate the impacts of simultaneous changes in operations and maintenance costs on the competitiveness of advanced nuclear.
- **Extended operation of existing nuclear:** Extensions of operation could provide strategic bridges to advanced deployment, but this report does not explicitly assess the sensitivity of results to the economics of the existing fleet in detail.
- **Energy storage:** This analysis does not include endogenous investments in energy storage technologies, though the impact of this omission is unclear.
- **Alternate commercialization timeframes:** Advanced nuclear technologies are assumed to be available only after 2030 in this analysis. Future work could examine impacts of earlier or later advanced nuclear availability.

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Appendix A: US-REGEN Model Description and Assumptions

The U.S. Regional Economy, Greenhouse Gas, and Energy (**US-REGEN**) model was developed by the Electric Power Research Institute. The model combines detailed capacity planning and dispatch of the power sector for the Lower 48 U.S. states with a dynamic computable general equilibrium (CGE) model of the economy and detailed end-use model.[23] The models are solved iteratively to allow policy impacts on the electric sector to account for economic responses (and vice versa), which allow US-REGEN to assess a wide range of energy and environmental policies.

Additional detail can be found in the updated documentation (EPRI, 2017), which is available online along with recent applications of US-REGEN: http://eea.epri.com/models.html

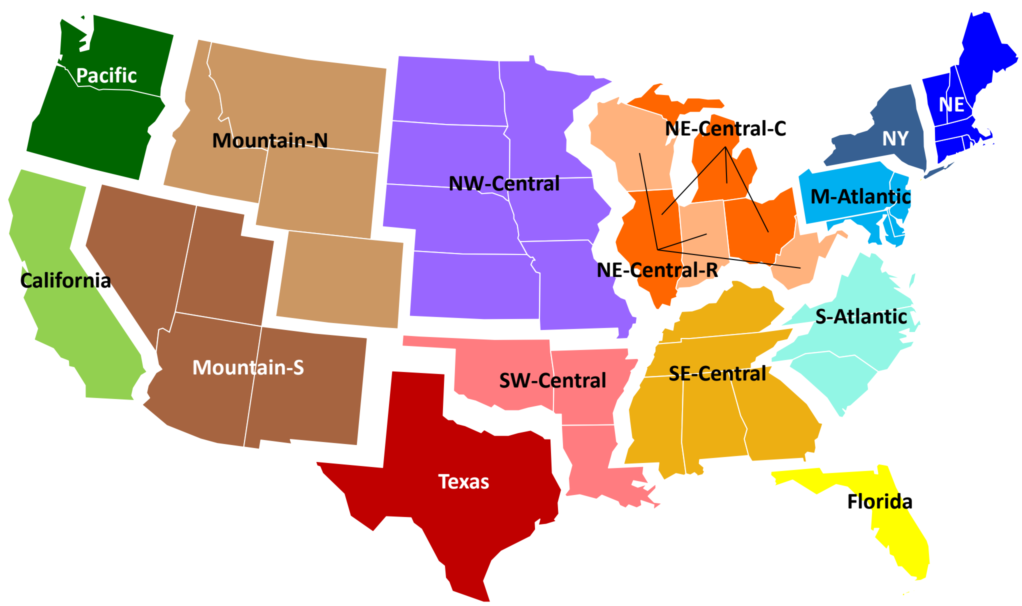

Figure A-1
Regional structure of the US-REGEN model

[23] The CGE and end-use models include representations of the residential, commercial, industrial, transportation, and fuels processing sectors.

US-REGEN has a national scope with flexible regional disaggregation based on state- or sub-state-level data. For this analysis, states are aggregated into the 15 regions shown in Figure A-1.

This uses the electric-sector model to analyze the potential role of advanced nuclear in future energy systems. The forward-looking, long-term capacity planning (including co-optimized transmission) and dispatch model optimizes investments through 2050. The model simultaneously determines a cost-minimizing solution for all model regions subject to technical and policy-related constraints. Each customizable-length (typically five-year) time step includes capacity investment, retrofit, and retirement decisions as well as dispatch for installed capacity over representative intra-annual hours.

US-REGEN employs an innovative algorithm to capture the hourly joint variability of load, wind, and solar profiles in a multi-decadal planning model. Using a novel "extreme hour" selection and clustering approach (Blanford, et al., 2018), this algorithm selects "representative hours" to preserve key distributional requirements for regional time-series data with a two-orders-of-magnitude reduction in dimensionality. This procedure provides approximately 100 intra-annual segments for system dispatch and load balancing. This approach significantly outperforms simple heuristic selection procedures that focus on representing the load duration curve at the expense of other time-series data. Figure A-2 shows how US-REGEN's "representative hour" approach compares to the "seasonal average" approach (Blanford, et al., 2018).

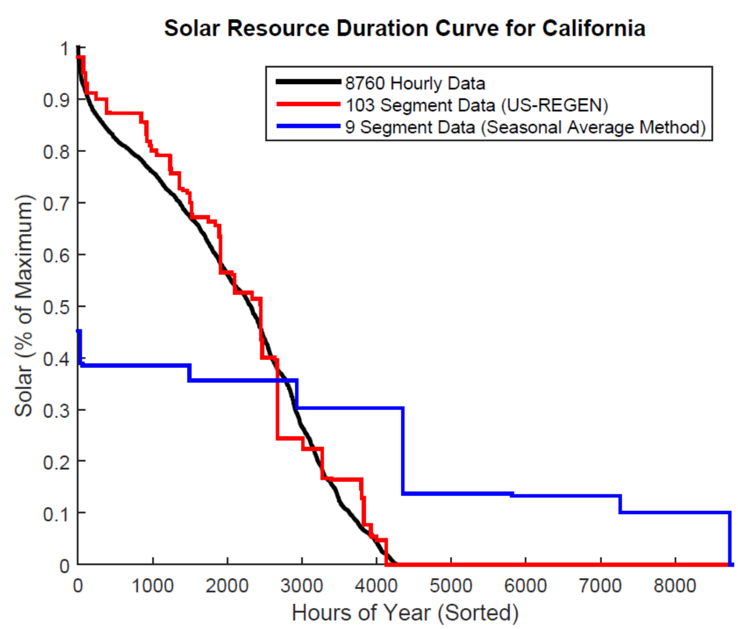

Figure A-2
Comparison of US-REGEN's representative-hour algorithm output for a solar resource duration curve in Texas with the underlying hourly data (black) and the seasonal-average approach (blue)

US-REGEN uses a bottom-up representation of capacity grouped into technology blocks within a region based on heat rates and dispatches these blocks across a range of intra-annual time segments. The electric sector model's optimization formulation is a straightforward minimization of total electric sector costs summed across regions and time periods discounted to present value, which is subject to power system constraints including electricity market clearing conditions. The requirement that demand is met in each intra-annual time segment simulates the clearance of both an energy *and* capacity market.[24] The model's intertemporal optimization means that full revenue sufficiency will be achieved for new investments, including an approach to mitigate end effects that accounts for assets with lifetimes longer than model's planning horizon (e.g., advanced nuclear technologies).

Many long-term capacity planning models have trade-based grid representations where segment-level cross-border transactions are bounded by installed transmission capacity (Santen, et al., 2017). US-REGEN adopts this approach to transmission capacity between regions (zonal) and allow for endogenous transmission investments.

Technology cost and performance assumptions come from the most recent EPRI Integrated Generation Technology Options report, and solar and wind costs are updated more regularly. Capital costs are shown in Figure A-3. Capital costs for onshore wind include a one-time $450 per kW charge to reflect incremental intra-regional transmission investment, and utility-scale solar PV capital costs include the same one-time hookup and network changes. Transmission between regions can be added at a cost of $3.85 million per mile for a notional high-voltage line (e.g., 500 kV AC or 800 kV DC) to transfer 6,400 MW of capacity.

[24] US-REGEN does not currently consider capacity costs above those necessary to meet peak demand.

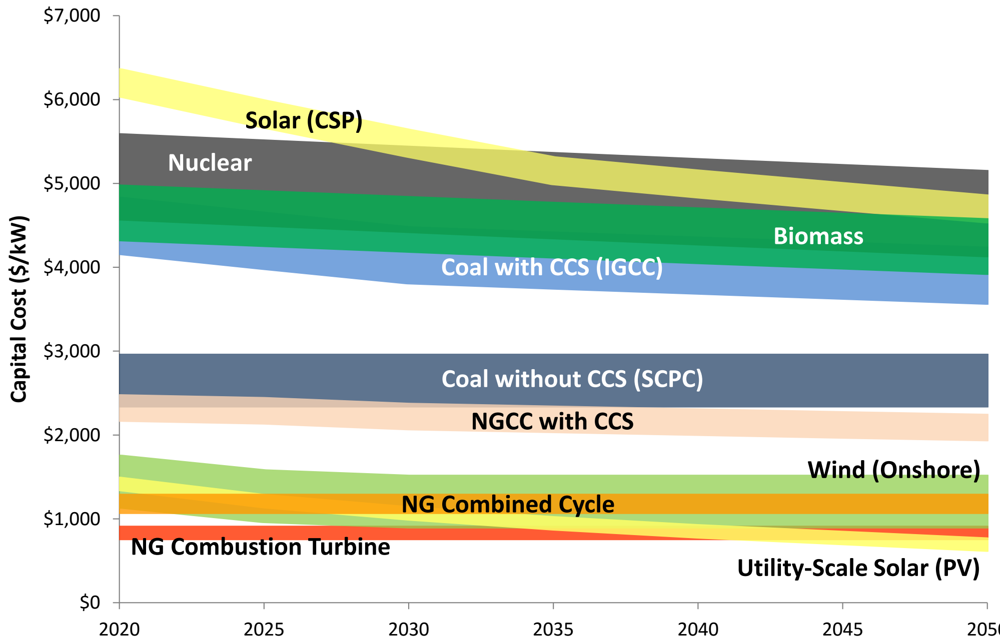

Figure A-3
US-REGEN capital cost trajectories (bands represent regional differences)

Fuel price trajectories generally come from the EIA's *Annual Energy Outlook 2017* reference scenario without the Clean Power Plan unless otherwise noted. Fuel prices are not responsive to changes in demand for these runs, though such feedbacks are possible using the integrated version of US-REGEN. Natural gas prices and sensitivities are discussed in Section 2. Delivered gas prices in the model include region-specific adders, which are calibrated to observed 2016 values and assumed to decline over time.

The reference (i.e., business-as-usual) scenario includes most existing and known future state and federal policies and regulations. Updated state renewable portfolio standards (RPSs) are included[25] along with federal policies like Mercury and Air Toxics Standards (MATS) and Clean Water Act (CWA) § 316(b). Other state policies include California's AB 32 and the Regional Greenhouse Gas Initiative (RGGI) for eastern states. The Clean Air Act § 111(b) CO_2 performance standards are included in the analysis but not the Clean Power Plan. Federal 2015 tax extenders adopted by Congress for wind or solar are also included.

The cost metric most commonly used in this report is the net present value (NPV) of total electric sector costs across the modeling horizon (i.e., between 2016 and 2050). These cost comparisons include the following discounted electric-sector cost categories:

[25] US-REGEN captures existing state RPS requirements, resource eligibility, and technology-specific carve-outs, which reflect current law and scheduled changes.

- Capital costs associated with new investments
- Fixed and variable operation and maintenance costs
- Fuel costs
- Cost of new transmission plus maintenance, which are assumed to be split equally across connected regions
- Regulatory costs (e.g., alternative compliance payments for renewable portfolio standards)

These costs are typically expressed as *incremental* costs relative to the reference scenario.

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Appendix B: Additional Results

This appendix presents additional US-REGEN model results.

Natural Gas Price Sensitivities

Figure B-1 shows the capacity mix by technology over time under reference gas and policy assumptions. This capacity mix underlies the generation portfolio shown in Figure 3-1. Annual peak national load is shown in black.

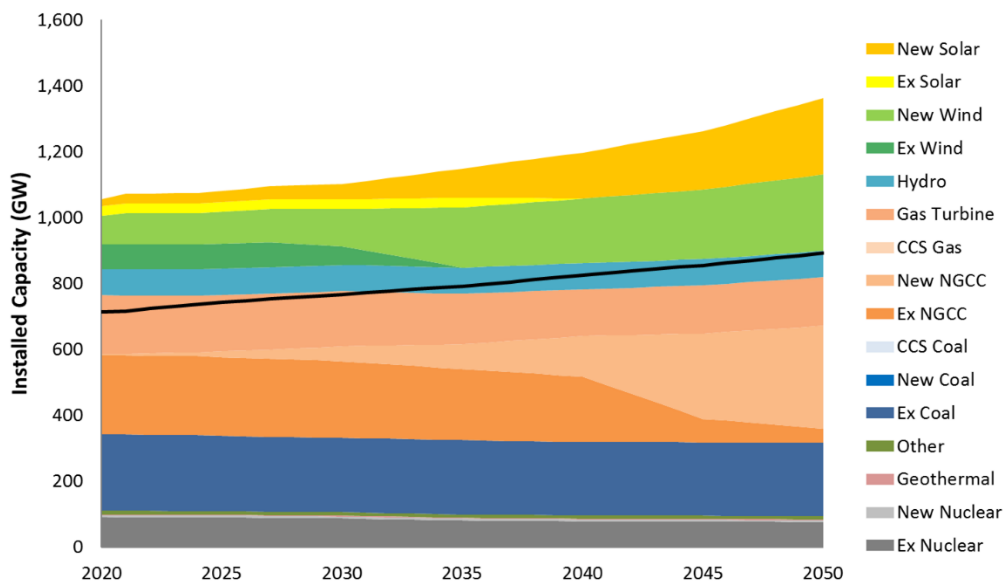

Figure B-1
Capacity (GW) by technology over time under the reference policy and gas price scenario and $5,000/kW nuclear costs

CO_2 emissions trajectories in the reference scenarios vary based on the assumed nuclear capital costs (Figure B-2). CO_2 emissions are nearly 800 million metric tons lower by 2050 when nuclear costs are $2,000/kW, as emissions-free nuclear replaces a combination of new NGCC generation, coal, and wind (Figure B-3). However, emissions trajectories are significantly higher than the 95% cap trajectory beginning in 2030.

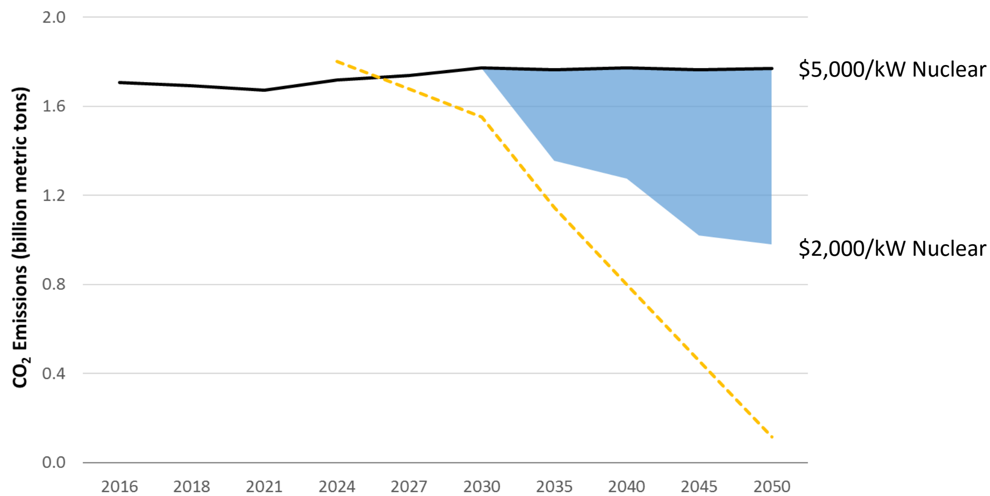

Figure B-2
CO_2 emissions over time for reference gas prices across nuclear capital cost scenarios (blue) compared with the 95% cap trajectory

Figure B-3 shows wholesale electricity prices over time by region and natural gas price scenario. Section 5 illustrates the effects of additional revenue streams $5 and $15/MWh on advanced nuclear deployment. The significance of these revenues is suggested by their magnitudes relative to electricity market revenues shown in Figure B-3, which vary considerably across scenarios.

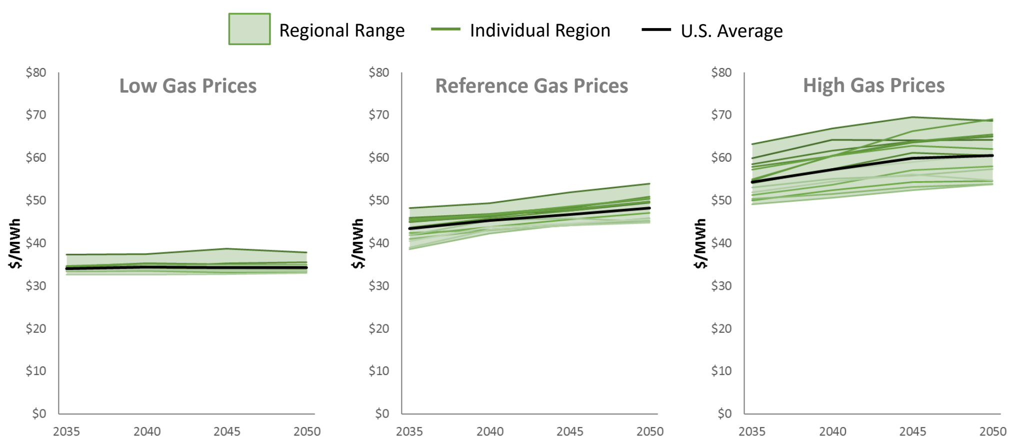

Figure B-3
Wholesale electricity prices ($/MWh) across low, reference, and high gas prices across regions

Energy and Environmental Policy Sensitivities

Figure B-4 illustrates which technologies are displaced by low-cost nuclear under the reference and stringent policy cases. Note that the high capacity factor of nuclear plants means that the displaced capacity is even larger, which is why policy cost reductions are substantial with low-cost nuclear (as discussed in

Section 4). Under the reference policy, advanced nuclear primarily displaces gas generation (especially from new NGCC units) as well as coal and renewables. Under the 95% cap, advanced nuclear displaces a portfolio of lower-emitting generators like gas, renewables, and CCS-equipped coal and gas. Since the emissions cap is binding and early nuclear deployment displaces higher-emitting generation, this emissions headroom is consumed by the lowest-cost resource, which is existing coal under these conditions.

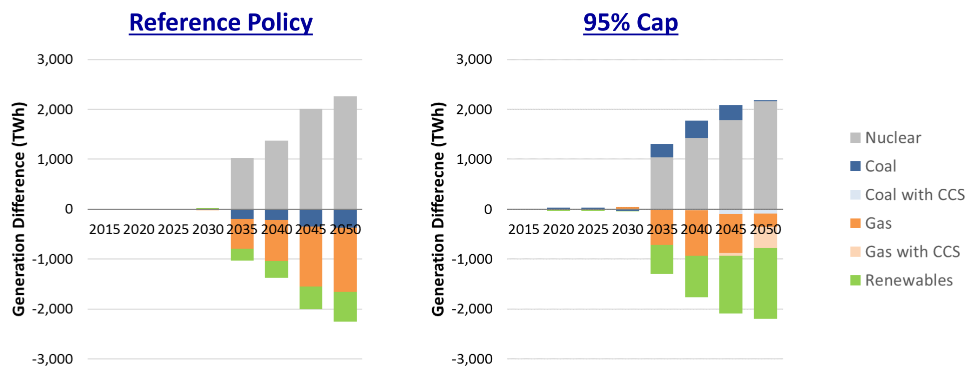

Figure B-4
Generation difference (TWh) between scenarios with $2,000/kW nuclear capital costs and $5,000/kW costs under the reference (left) and 95% policy (right) environments

Figure B-5 shows regional capacity factors for new nuclear in 2050. There is considerable variation across scenarios and scenarios, but nuclear's low short-run marginal costs generally leads to high utilization for new nuclear plants. Scenarios and regions with high variable renewable energy deployment require greater flexible operations, which is reflected in the lower points in Figure B-5. This suggests that added operational flexibility would be an important attribute for advanced nuclear reactors.

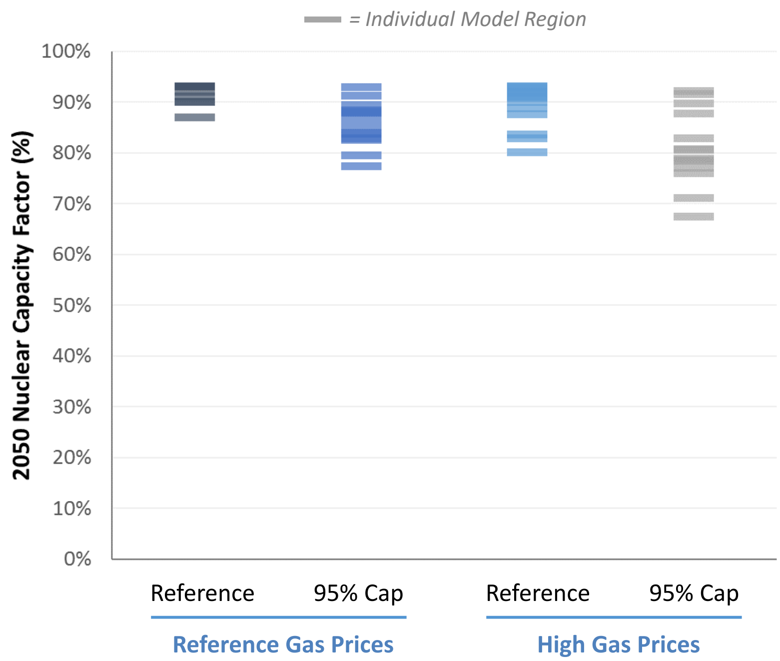

Figure B-5
2050 nuclear capacity factors by region (%) across alternate natural gas and policy sensitivities

The impact of gas prices on the generation mix under the 95% Cap scenario is shown in Figure B-6. With lower gas prices and $5,000/kW nuclear costs, no advanced nuclear capacity additions are made by 2050.

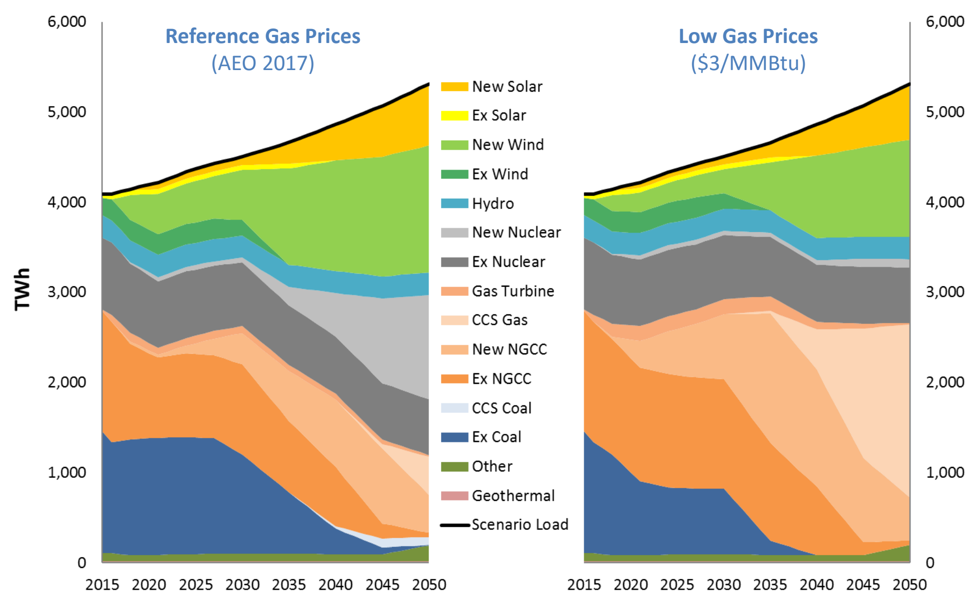

Figure B-6
Electric generation (TWh) over time under the 95% Cap scenario and $5,000/kW nuclear costs under reference and low gas prices

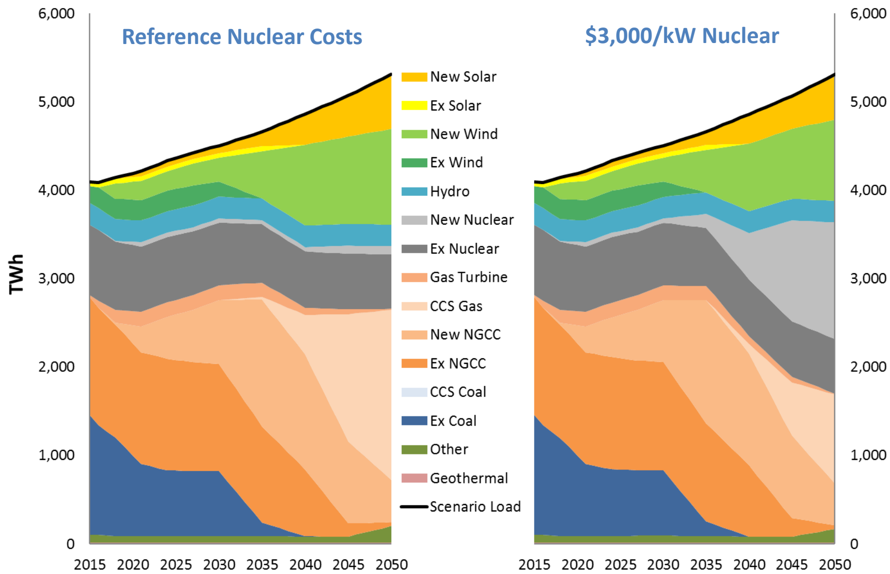

Figure B-7
Electric generation (TWh) over time under the 95% Cap scenario and low gas prices under $5,000/kW nuclear (left) and $3,000/kW (right)

With low enough capital costs, advanced nuclear can compete with CCS-equipped gas under the stringent decarbonization scenario even with very low gas prices. Figure B-7 shows the extent of generation from new nuclear with $3,000/kW costs. A broader point is that new nuclear competes with varieties of CCS for the dispatchable low-carbon market share when stringent decarbonization policies are in place. The relative mix between these technologies depends critically on technology and cost advances moving forward, including policy support and R&D.

Figure B-8 compares the incremental electric sector costs associated with the 95% cap policy. As described in Appendix A, these incremental costs include all capital, operating, fuel, and regulatory costs above the reference scenario. Lowering nuclear costs reduce overall policy compliance costs.

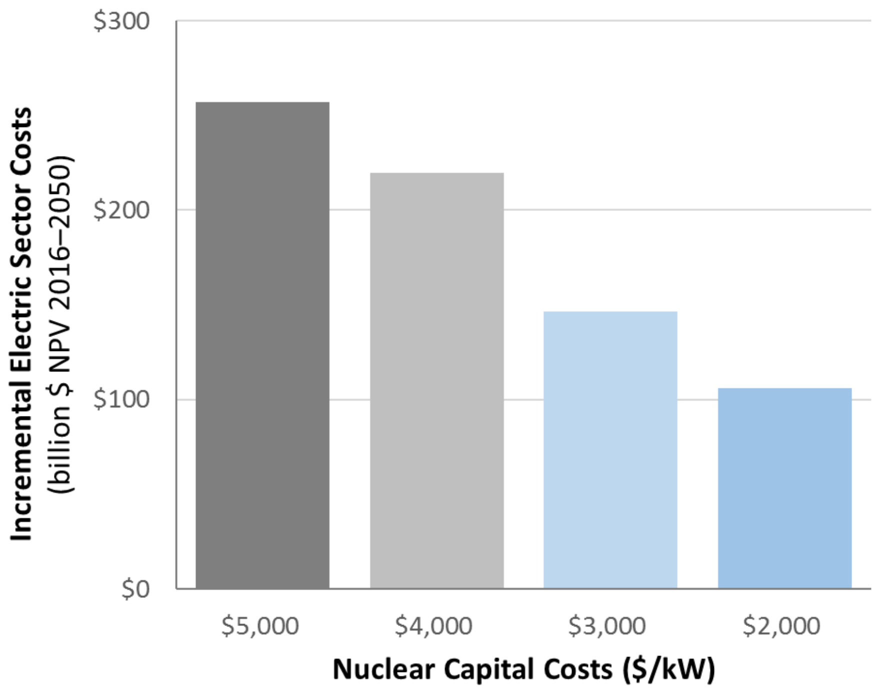

Figure B-8
Incremental electric sector costs for the 95% cap policy (billion $ net present value 2016–2050) under different nuclear capital costs

Under the RPS sensitivities discussed in Section 4, Table B-1 shows renewable energy certificate prices across four different sensitivities.

Table B-1
Renewable Energy Certificate (REC) prices ($/MWh) by region and expanded RPS scenario

	Reference	RPS, No REC Trade	RPS, REC Trade	RPS, Low Wind Cost
New England	$5.06	$7.60	$9.64	$2.86
New York	$9.43	$15.88	$9.64	$2.86
Mid-Atlantic	$8.32	$17.62	$9.64	$2.86
South Atlantic	$0.00	$8.82	$9.64	$2.86
Florida	$0.00	$21.33	$9.64	$2.86
NE-Central-R	$0.00	$16.46	$9.64	$2.86
NE-Central-D	$0.00	$15.52	$9.64	$2.86
SE-Central	$0.00	$9.72	$9.64	$2.86
NW-Central	$0.00	$6.28	$9.64	$2.86
SW-Central	$0.00	$0.31	$9.64	$2.86
Texas	$0.00	$1.92	$9.64	$2.86
Mountain-N	$0.00	$2.77	$9.64	$2.86
Mountain-S	$0.00	$2.13	$9.64	$2.86
Pacific	$3.79	$12.50	$9.64	$2.86
California	$3.16	$6.42	$9.64	$2.86

Program:

Technology Innovation

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