National Renewable Energy Laboratory: Nuclear Energy With Flexible Operation, High VRE, and Emission-Constrained Scenarios

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Renewable energy includes a broad range of technologies, including hydropower, bioenergy, geothermal, marine, wind, and solar. These technologies have seen significant improvements in recent years, with wind and solar having achieved uniquely rapid improvements and cost declines (NREL 2019). In the United States, the power generated from nonhydro renewable energy has risen from a total of 167.2 TWh in 2010 to 446 TWh in 2019. For the United States, this results in an increase from 4.05% of total electricity generation in 2010 to 10.9% in 2019 on the utility scale, according to the U.S. Energy Information Administration (EIA 2019). Considering hydropower (6.6%) and nuclear power (19.7%), the United States has reached 37.2% of low-carbon electricity generation.

Renewable energy's increasing competitiveness has led to significant deployment relative to other electric generation sources over the last 5 years (EIA 2019). Nearly all (98.9%) of renewable energy's growth in the United States since 2010 has come from VRE, specifically wind and solar (EIA 2019). Studies have been performed to examine the feasibility of balancing significant percentages of VRE generation with electricity demand in the power system (70% and above, using current technologies) (Brinkman 2015; Novacheck, Brinkman, and Porro 2018). These studies suggest that flexible conventional generation sources can make it easier to integrate increased deployment of VRE resources. Innovative technologies can help compensate for changes to VRE output that are either anticipated (such as predictable daily solar ramping) or uncertain (such as rapid changes in wind speed) (Mai et al. 2012). In addition to electrical flexibility, many nonelectric applications currently do not have cost-competitive sources of renewable energy (applications such as industrial heat and hard-to-electrify sectors such as air travel). Therefore, research institutes such as NREL are actively partnering with INL to explore how nuclear energy can act as a companion to VRE and how nuclear flexibility can be a valuable asset to assist with VRE deployment while increasing economy-wide low-emissions energy supply. The purpose of this chapter is to examine the value of flexible and low-cost nuclear energy coupled with increased renewable energy penetration to the U.S. electrical system. This chapter will first describe NREL software used in evaluating future electricity scenarios, followed by a summary of the analysis performed, results, and conclusions derived from this work.

1.1 Modeling the Future U.S. Electricity System: The Regional Energy Deployment System (ReEDS) Model

Several organizations have created sophisticated models to investigate the evolution of the U.S. electricity system. Of these, capacity expansion modeling is a common approach. Examples of nation-wide U.S. long-term forecasting tools include ReEDS (Brown et al. 2020), EPRI's U.S. Regional Economy, Greenhouse Gas, and Energy (EPRI 2020), and the U.S. Energy Information Administration's National Energy Modeling System (Nalley et al. 2019). Each of these models examine different aspects of the future electricity system and are often used to better understand the impacts of different technology and policy scenarios; previous studies have compared results across models and discussed how structural differences across these models could lead to the differences in results (Cole et al. 2017; Hodson et al. 2018). Generally, these models aim to minimize system costs or maximize social benefits of operations and investment through representation of key time periods (e.g., a "summer peak" or "winter morning"). All models are simplifications, and model results will always reflect the uncertainty inherent in these simplifications and approximations. Still, these assumptions are useful in that they can be varied across scenarios to estimate the impact of cost assumptions, technological characteristics, and policies on future energy portfolios and U.S. emissions reductions. ReEDS has been used for a wide range of analyses examining power sector evolution through 2050 (Cole et al. 2019; Mai, Cole, and Reimers 2019).

The U.S. version of ReEDS consists of 134 regions where the power balance constraint must hold (i.e., generation plus net transmission losses must equal load) and 356 subregions with unique characteristics and supply curves for wind, PV, and CSP capacity. The 134 balancing areas also face system reliability constraints, such as operating reserve and planning reserve requirements to ensure grid reliability and adequate capacity exists to meet peak demand, respectively. Technology-specific curtailment rates are computed in a submodule that accounts for the availability of a resource, and technology-specific capacity credit (the potential contribution to the planning reserve margin) is computed in a submodule that computes a technology's availability in peak net load hours (Zhou, Cole, and Frew 2018). Figure 1 shows the U.S. regions as represented in ReEDS. Another version of ReEDS has been modified to represent India; both the U.S. and India versions are publicly available.[1]

[1] More information can be found here: https://www.nrel.gov/analysis/reeds/.

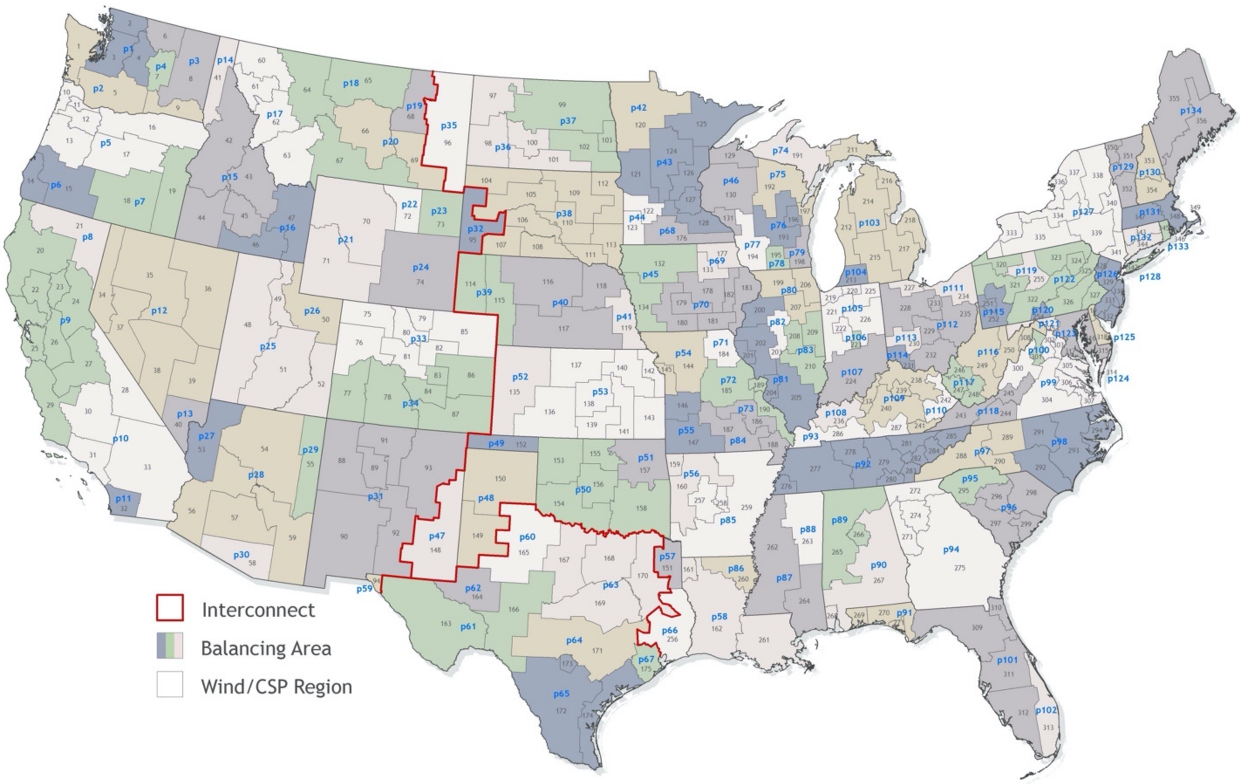

Figure 1. ReEDS map of the United States with balancing area

Source: (Brown et al. 2020)

As previously mentioned, ReEDS minimizes the costs of investment and generation using a mixed-integer linear optimization. This has several implications for the interpretation of ReEDS results. Perhaps most importantly, this implicitly reflects a perfectly competitive market with perfect information resulting in an economically optimized outcome, as opposed to a situation where firms compete strategically. In addition, model results are highly influenced by input assumptions, such as the cost and performance of new generators or the future price of fuel.

When capacity expansion models are used, analysis is typically not just performed for a single scenario, but rather multiple mode runs are performed with different scenarios constructed to help understand the impact of a range of future conditions, such as technology performances, fuel prices, and policies that affect electricity generation. In this way, the value of capacity expansion modeling is not derived from perfectly predicting the future, but rather from better understanding the impact that innovation, price reduction, and technology decisions can have on future generation portfolios. Each year, the ReEDS development team produces several "standard scenarios" important to the U.S. electricity system (Cole et al. 2018; 2019).

Key members of the U.S. nuclear industry, led by the DOE LWR Sustainability program, are researching both technical and economic barriers for existing LWRs to operate beyond their initial 40-year operating licenses. Some reactors have renewed their license to operate up to 60 and 80 years (McCarthy 2017). The baseline scenario for ReEDS incorporates plant-specific and exogenously imposed retirement rates of 60–80 years for nuclear plants, but there is another option for assuming nuclear reactors are allowed to operate up to 80 years. Nuclear reactors can still close for economic reasons—as suggested by ReEDS when endogenous retirements are enabled. Reactors that have announced their closure are forced to close in the ReEDS model. Results from these two scenarios are provided in Table 1. The system levelized cost of energy is the overall system costs divided by total power generated and is expressed in terms of U.S. dollars ($) per unit of energy (MWh).

Table 1. ReEDS Standard Scenario Mid-Scenario 2050 Nuclear Capacity (Cole et al. 2019)

Scenario	System Levelized Cost of Energy ($/MWh)	Nuclear Capacity (GWe) in 2050	Percentage Increase Capacity (GWe) Nuclear Generation Over Base Scenario
Base Scenario (60-Year Nuclear Lifetime)	48.2	47.3	N/A
80-Year Nuclear Lifetime	47.2	89.3	188%

The scenarios summarized in Table 1 are "business-as-usual" type scenarios and, therefore, do not include potential futures such as innovations in nuclear flexibility, the availability of SMRs, the availability of integrated energy systems, or policy changes that might impact nuclear generation. However, the purpose of this example is not to predict the overall nuclear capacity, but rather to set a baseline for examining the value of nuclear flexibility for the power system. In this scenario, the impact of allowing plant life changes from the reference assumptions to 80 years when economically viable as evaluated by ReEDS is significant to overall nuclear generation.

1.2 ReEDS Analysis of Nuclear Flexibility: Description of Scenarios

For the Flexible Nuclear Campaign, NREL used the ReEDS tool to examine some of the effects of nuclear flexibility within the context of the U.S. power system. A main focus of the Campaign is to demonstrate how flexible nuclear energy might complement and enable high contributions of VRE; hence, scenarios were chosen that examine both high VRE and highly flexible nuclear scenarios, and, most importantly, the impact of nuclear flexibility (both existing capabilities and future innovation) on overall deployment. In the following subsections, the cases examined are described in detail. A summary of scenarios explored is also provided in Table 2.

A few caveats are important to note about this ReEDS analysis as uniquely related to nuclear energy. ReEDS is a U.S. focused and entirely economic based optimization and analysis tool (with technology-specific physical constraints)[2]. The costs of nuclear in the U.S. are higher than many other countries (Wittenstein et al. 2015). The costs for this work were chosen to include both

[2] In the context of ReEDS, ReEDS estimates nuclear construction linearly and does not estimate discrete units. This means that ReEDS models SMRs only as a price reduction and possessing increased flexibility. The minimum or discretized capacity of SMRs along with other SMR qualities is not a consideration for ReEDS analysis. Additionally, SMRs are not yet a commercialized technology in the U.S. therefore these parameters are yet to be established beyond projections (Varro et al. 2019).

international experience and some of the costs projected for SMRs, but the analysis is only performed for the U.S. (Wittenstein et al. 2015; MITEI et al. 2018). This implies that cost-barriers in the U.S. are addressed such that U.S. nuclear reactor builds are on-par with the lowest international costs. It is important to also emphasize that nuclear energy can provide value for national security or by providing nonelectric products (such as nuclear produced liquid fuels) that are of high strategic value. ReEDS does not capture these attributes and therefore might not capture some opportunities for nuclear to provide additional value to the energy system.

1.2.1 Base Scenarios

Following the lead of previous work on capacity expansion and nuclear deployment (Bistline, James, and Sowder 2019), the ReEDS analysis first examined base scenarios where the only change with regard to nuclear technology was its capital cost. According to the Annual Technology Baseline, the current capital expenditures overnight capital cost (OCC) for nuclear in the United States is $6200/kW (NREL 2019). OCC is a simplified metric that divides the cost of a system with nameplate capacity. Five additional scenarios were run to show the effect of capital cost on nuclear deployment. These prices take effect in 2025 and are reduced at an annual reduction rate of 1% thereafter. Prices for all other technologies in both the base and counterfactual cases were taken from the Annual Technology Baseline (NREL 2019). Although previously referred to as baseline, hereafter in this paper the 'Base' scenario and all scenarios built on it assume an 80-year nuclear lifetime.

At $3,000/kW and above, the capacity and annual generation of nuclear energy does not change in the ReEDS model. At the lower costs of $2,000/kW and $1,500/kW there is significant buildout of nuclear power. These scenarios will be used to further examine the impact of nuclear innovation, high RE contribution, and emissions policy on nuclear deployment. Note that costs below $3,000/kW are low for the United States but have been achieved in other countries (MITEI et al. 2018). Future work should examine the feasibility of these cost reductions ($6,200/kw down to $3,000/kW and below) in advanced economies (Gogan and Ingersoll 2018; MITEI et al. 2018), and should examine a broader scenario space to identify opportunities for nuclear power to be deployed economically at capital costs higher than those seen here. Table 2 summarizes system parameters of the base scenarios where only the capital cost of nuclear energy is changed and demonstrates how nuclear costs significantly affect the overall electric system. For example, due to nuclear energy's high capacity factor, low-cost nuclear energy reduces the overall system nameplate capacity while maintaining overall energy generation.

For the remainder of the chapter, the costs are binned into four categories: no change ($6,200/kW), baseline ($3,000-$5,000/kW), low-cost ($2,000/kW), and very low-cost ($1,500/kW) to better connect the numerical values with potential future scenarios.

Table 2. Varying Capital Expenditures (CapEx) of Nuclear Energy Within the United States and With an 80-Year Nuclear Lifetime

CapEx of New Nuclear	No Change	Baseline	Low-Cost	Very Low-Cost
2050 Total System Capacity (TWe)	1.75	1.75	1.75[3]	1.71
2050 Total Annual System Demand (TWh)	5.27e3			
2050 Installed Nuclear Capacity (GWe)	89.3		105.2	107.0
2050 Generation (TWh)	713.5		840.2	854.9
Nuclear % of Generating Capacity	5.1%		6.0%	6.3%
Nuclear % of Generation	13.5%		15.9%	16.2%
System Levelized Cost of Energy ($/MWh)	47.2		46.6	46.0
2050 GHG Emissions (Million Metric Ton)	884		891	893[4]

1.2.2 Flexible Nuclear, High VRE Penetration, and Emissions Limits

Using the low-cost and very low-cost CapEx scenarios, other permutations on these CapEx scenarios were developed. These permutations were: the impact of innovations surrounding nuclear flexibility, high VRE contribution, nuclear flexibility coupled with high VRE penetration, and a low-emissions scenario—each explained further in this section.

For the scenario of nuclear flexibility, nuclear energy was allowed to ramp 100% of its output in an hour and had no minimum generation requirement. Additionally, there was no minimum time during ramping that nuclear energy had to stay at a certain power level. This assumes nuclear energy achieves near perfect flexibility yet still not as fast ramping as electronically driven sources such as batteries that can ramp 100% capacity over minutes. This ramping rate is nonphysical, but since ReEDS is an economic rather than physics-based model, this parameter was chosen to place an upper bound on the impact of flexibility on nuclear deployment. A more realistic ramping rate would be close to natural gas which, in ReEDS, can ramp at a rate of ~10% per min (Brown et al. 2020). From this perspective, a physics-based or production cost model would likely produce different results given its further resolution of power system operations.

To simulate high VRE contribution, the Annual Technology Baseline scenario with low VRE prices was used (NREL 2019). Table 3 summarizes some of the OCC of VRE used for this analysis for the base and low cost (high penetration) VRE scenarios. There are additional technologies than

[3] The total system capacity varied by less than 0.005 TWe across these scenarios.

[4] Although counter-intuitive, in the scenarios with low-cost nuclear, emissions increase with increasing nuclear capacity. This is not because nuclear is an emitting resource, but rather because the addition of nuclear in these cases enables an increase in natural gas. The scenarios listed in this case are focused only on nuclear costs and not on increased VRE or decreased emissions. These will be addressed in later scenarios.

those listed in Table 3 and more information can be found in the Annual Technology Baseline; but the technologies listed here are provided for reference. Low VRE costs resulted in significant deployment of VRE capacity and was paired with flexible nuclear innovations to examine how the addition of flexibility would impact the U.S. electricity system under high VRE penetration.

Table 3. Base and Low Overnight Capital Cost for Select VRE Used in ReEDS Analysis (NREL 2019)

	Base 2025 Overnight Capital Cost for VRE ($/kW)	Low 2025 Overnight Capital Cost for VRE ($/kW)
Onshore Wind	$1,360	$1,283
Utility PV	$956	$724
Distributed Solar—Residential	$1,960	$1,510

For a low-emissions scenarios, an emissions cap of 95% reduction by 2050 from 2005 levels was chosen. This forces the model to choose generation sources with low or zero end-use emissions at point of generation. This generally includes technologies with low life cycle emissions (<50 gCO_2/kWh), though life cycle emissions are not included in ReEDS. Technologies that fit this criterion are nuclear, natural gas with carbon capture, select renewable energy (including CSP, geothermal, solar PV, and wind), and battery storage technologies (Schlömer et al. 2014). Although the technologies listed above produce little to no emissions at the point of electricity generation, life cycle emission estimates incorporate all the emissions used to develop, construct, and transport components for these technologies and are, therefore, non-zero.

Integrated energy systems that incorporate multiple generators and multiple energy users were not examined in detail. To adequately analyze integrated energy systems, ReEDS would need to provide compensation as a nuclear reactor's electrical output ramps down. Currently, this is not implemented in ReEDS and was excluded from this work.

The metrics examined in this study were power system capacity (GW) and annual generation (TWh), nuclear capacity (GW) and annual generation (GWh), percentage contribution from nuclear both in capacity and generation, system average cost per MWh (referred to as levelized cost of energy in $/MWh), overall system costs[5] and savings over the base case ($), and 2050 emissions (MMton). A summary of the parameters for the scenarios discussed here is given in Table 4.

[5] In this context, system costs are considered the sum over modeled years of the costs of investment and operations, discounted to 2020 with a 5% discount factor.

Table 4. Summary of Scenarios

Scenario (Label)	Description
Flexible Nuclear (Flex)	Nuclear energy both existing and new is allowed to ramp at 100% per hour with no limitations on minimum generation or hold times.
High VRE Penetration (High VRE)	Beginning in 2025. low VRE costs from the Annual Technology Baseline are used in place of base-scenario VRE costs.
Flexible Nuclear+High VRE (High VRE+Flex)	Both flexible nuclear and low VRE costs are implemented.
Low-Emissions	Neither nuclear flexibility nor VRE costs are changed, but electricity GHG emissions are capped at 5% of 2005 emissions (a 95% emissions reduction).

1.3 Results

The results of the ReEDS simulations are displayed in Table 5 for the scenarios described previously. Where appropriate, comparison values between the scenarios examined here and the base scenarios are included in the table. An important note for the calculation is that the energy system savings are based on a discount rate for a future value. Changing the discount rate or analyzing the value only for 2050 would significantly increase the numerical value of the system cost and system savings. Additionally, for both low emissions scenarios, the Savings over Base Scenario are negative, meaning the emissions cap incurs additional power sector costs when replacing all emitting technologies with non-emitting ones. This calculation ignores any external costs that may be incurred by emissions. Table 5 provides a graphical representation of these results in terms of nuclear electrical generation capacity (GWe) and nuclear annual electricity generation (TWh).

Table 5. 2050 Results for Capacity, Generation, Percentage, and Cost for Nuclear and Renewable Energy

Scenarios	Cost	Flex	High VRE	High VRE+ Flex	Cap
Total System Capacity (TWe)	Low-Cost	1.713	2.032	2.054	2.11
	Very Low-Cost	1.710	2.053	2.044	1.93
Nuclear Capacity (GWe)	Low-Cost	104.8	89.3	89.6	135.2
	Very Low-Cost	107.4	90.6	99.6	214.2
Nuclear Generation (TWh)	Low-Cost	836.9	714.5	708.8	998.2
	Very Low-Cost	857.0	722.9	791.3	1626
Nuclear Capacity %	Low-Cost	6.12	4.39	4.36	6.41
	Very Low-Cost	6.28	4.41	4.87	11.10
Nuclear Generation %	Low-Cost	15.8	13.5	13.4	18.8
	Very Low-Cost	16.2	13.6	14.9	30.7
System Levelized Cost of Energy ($/MWh)	Low-Cost	45.9	43.3	43.0	53.4
	Very Low-Cost	45.8	43.0	42.9	49.0
2050 Annual System[6] Costs (Billion USD)	Low-Cost	243.27	229.49	227.9	283.02
	Very Low-Cost	242.74	227.9	227.37	259.7
2050 Annual Savings Over Base Scenario (Billion USD)	Low-Cost	6.89	20.67	22.26	-32.86
	Very Low-Cost	7.42	22.26	22.79	-9.54
2050 GHG Emissions (Million Metric Ton/yr)	Low-Cost	889	519	501	121
	Very Low-Cost	889	509	506	121

[6] 2050 system costs and savings are the annual system costs and savings for the year 2050, but in 2004 adjusted U.S. dollars based on a 5%–7% adjusted discount rate. For more information, see the ReEDS documentation on how future costs are adjusted (Brown et al. 2020).

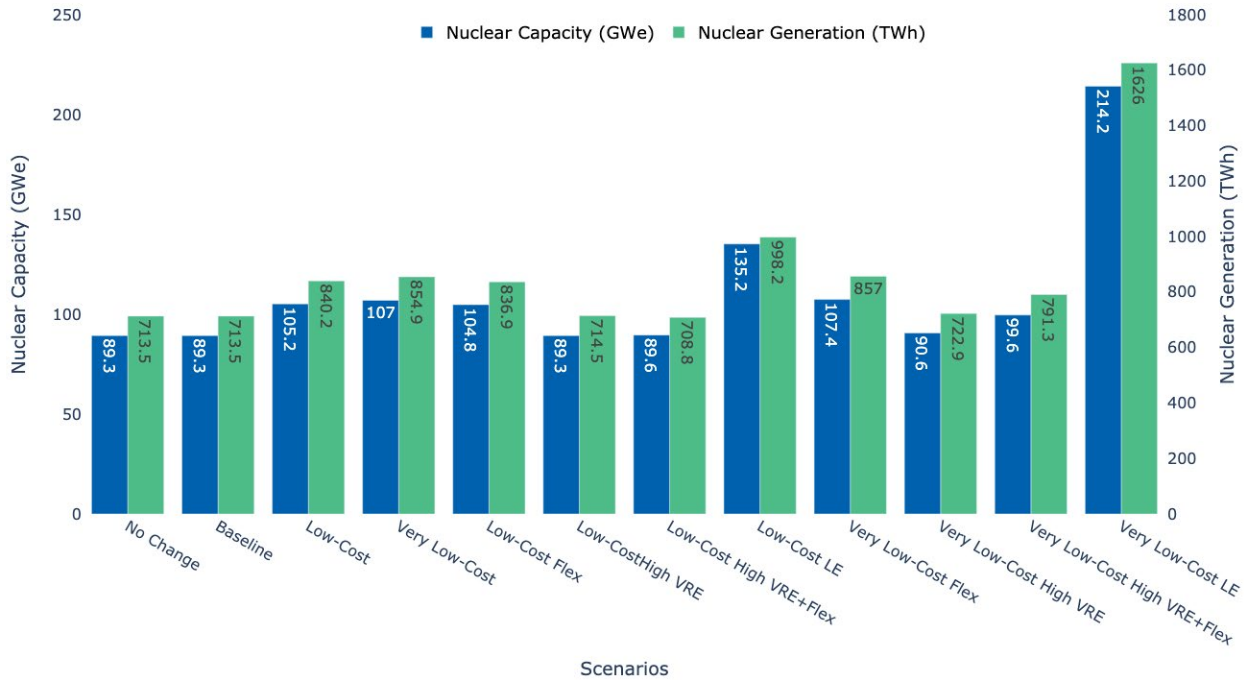

Figure 2. Nuclear capacity calculated with ReEDS in 2050 based on the given scenarios in Table 2 and Table 4

Source: NREL. Used with permissions.

1.4 Discussion

The primary results of this work demonstrate the need for additional research to understand what attributes of nuclear energy are most valuable to the electricity system under a high-VRE scenario and how this value should be measured to produce a forecasted deployment. From these results, additional observations can elucidate the interactions between flexible nuclear energy, VRE, and their combined ability to provide low-cost reliable grid performance.

- In both the low-cost and very low-cost scenarios, the addition of only nuclear flexibility has a nominal effect on the overall deployment of nuclear energy and VRE deployment; however, in both scenarios, the addition of nuclear flexibility over the base scenario reduces the discounted system costs by $6.89 and $7.42 billion with low-cost and very low-cost, respectively, implying that nuclear energy flexibility can prove to be a valuable asset for the electricity system as a backstop for VRE in lieu of some other technology being adopted.

- In the low-emissions scenario, the availability of low-cost nuclear energy significantly decreases the overall electricity cost versus a low-emissions scenario with no low-cost nuclear. The results indicate that an emission-constrained system decreases from an average price of $53.4/MWh down to $49.0/MWh with the addition of nuclear flexibility. While this difference may seem small, when multiplied by the annual generation in TWh, this results in a change in the present value of system cost of $23.32 billion due to the availability of low-cost nuclear. In terms of nuclear capacity, this emission constrained scenario results in an increase in nuclear capacity by 40 GW in the low-cost scenario and approximately 120 GW in the very low-cost scenario. This is also for the baseline VRE costs scenario. This simulation did not include the impact of flexible nuclear energy on top of low-cost nuclear energy; this is a next step for future analysis.

- The availability of low-cost VRE and flexible nuclear energy decreases the overall system cost relative to corresponding scenarios with no flexibility. Said differently, the introduction of low-cost and flexible nuclear energy contributes to the reduction of system costs and increase in VRE capacity more than just low-cost nuclear. In alternative ReEDS scenarios, system flexibility is provided by other energy sources such as natural gas with carbon capture, energy storage, or increased renewable energy curtailments. When nuclear energy reaches this low price point, it begins to replace some of these alternative technologies. The scenarios described in this chapter do not include a robust analysis of alternative sources of flexibility, which should be further investigated.

A goal of the NICE Future initiative and the Flexible Nuclear Campaign is to encourage collaboration between nuclear and renewable communities. The findings in this report, specifically around reduced system costs through the availability of both low-cost VRE and flexible nuclear energy, help to support the themes of the NICE Future initiative. A holistic planning process that considers the benefits of flexible nuclear energy and VRE generation in tandem may support a more sustainable, economic, and reliable U.S. electrical system. This analysis also suggests that future work could be conducted to further quantify these benefits.

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