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Revision 0

Nuclear Energy Model Intercomparison Project

Project Plan

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ABSTRACT

This document summarizes the current status and future plans of the Nuclear Model Intercomparison Project. The objectives of this project are to understand how issues central to nuclear energy are modeled in long-term capacity expansion models, to investigate how model structures and input assumptions impact projections for nuclear's role, to refine model representations of nuclear energy, and to communicate findings to the research community and decision-makers. High-level goals are discussed for each of the four participating model groups: the U.S. Energy Information Administration (EIA), U.S. Environmental Protection Agency (EPA), Electric Power Research Institute (EPRI), and National Renewable Energy Laboratory (NREL). This document summarizes scenarios and assumptions for the model comparison, outcomes from the first workshop, and next steps.

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CONTENTS

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1. Introduction

1.1 Study Background

Capacity expansion models (CEMs) are important tools that inform strategies for meeting future electricity and energy needs under a range of policy scenarios, technology options, and market conditions. However, CEMs vary significantly in their coverage, structure, and input assumptions. As a result, model projections for similar policies differ—sometimes dramatically—especially in relation to nuclear power plant retirement and deployment. Different projections for nuclear energy and other resources may support alternate strategies for research, development, and demonstration (RD&D) investment in order to achieve policy goals.

Understanding model differences and output drivers is important for improving model insights and capabilities, providing context for interpreting results, and, ultimately, better informing RD&D related to existing and advanced nuclear energy technologies as part of a portfolio that supports safe, reliable, affordable, environmentally responsible energy. Working with the teams who own, update, and apply these models—as well as subject matter experts from national laboratories, industry, and the research community—has led to the creation of a forum in which experts can discuss structure/coding assumptions and challenges in order to develop the models for future use.

1.2 Objectives

This study seeks to:

- Provide an understanding of how issues central to nuclear power plant operations and economics are modeled in CEMs
- Investigate how model structures and input assumptions for CEMs can impact projections for existing and new nuclear plants under a range of technology, market, and policy conditions
- Identify and prioritize areas for refining the representation of nuclear energy in CEMs (and, to the extent feasible, implement the changes and run diagnostic tests to understand how these features could impact projections)
- Communicate findings to decision-makers and the research community, helping them improve the representation of nuclear energy in their tools as well as interpret model outputs in light of the models' respective strengths and limitations.

To address these goals, a multi-organization, multi-model study has been initiated. The four models to be evaluated and updated as necessary are:

- The National Energy Modeling System (NEMS) – U.S. Energy Information Administration (EIA)
- Integrated Planning Model (IPM) – U.S. Environmental Protection Agency (EPA)
- Regional Economy, Greenhouse Gas, and Energy (REGEN) model – Electric Power Research Institute (EPRI)
- The Regional Energy Deployment System (ReEDS) – National Renewable Energy Laboratory (NREL)

1.3 **Modeling Team Goals**

In addition to the study objectives listed in the previous subsection, each participating modeling team has their own specific goals.

1.3.1 **U.S. Energy Information Administration (EIA)**

- Understand the state of the art for representing nuclear technologies in national-scale electricity capacity expansion models, and identify modeling best practices and areas of potential improvement for NEMS.

1.3.2 **U.S. Environmental Protection Agency (EPA)**

- Identify opportunities to improve the manner in which a range of model inputs affecting the existing nuclear fleet are represented.
- Develop cost and performance assumptions for new and emerging nuclear technologies.
- Identify policy-relevant insights regarding the value of existing facilities (e.g., grid support, emissions, and retail rates).

1.3.3 **Electric Power Research Institute (EPRI)**

- Incorporate and transfer best practices for data and model representation of nuclear energy in long-term energy-economic models.
- Understand why model results indicate different portfolios of low-carbon technologies, including nuclear technologies in deep decarbonization scenarios (i.e., the relative roles of input assumptions and model structure).
- Understand how technological change for nuclear energy and other resources shape power-sector and energy-system pathways.

1.3.4 **National Renewable Energy Laboratory (NREL)**

- Learn from the nuclear experts involved in the project, especially with regard to the progress being made toward—and the ultimate vision for—advanced nuclear technologies. In particular, NREL wants to better understand the important differences between conventional and emerging nuclear technologies in terms of their expected costs, performance, and outputs (including non-power products and services).
- Improve the ReEDS representation of both conventional and advanced nuclear technologies, based on insights from the participating nuclear experts and modeling teams. Areas to be considered and potentially updated (depending on feedback) include:
    - Ensuring that the treatment of nuclear power plants in our existing state-level policy representations (e.g., zero-emissions credits [ZECs] and clean energy standards) is accurate and up to date
    - Improving our representation of endogenous retirement decisions, based on feedback pertaining to both the representation itself and parameters that inform such decisions in the model

- The magnitude and relative shares of fixed versus variable operations and maintenance (O&M) costs for both existing and new nuclear power plants
    - Adequate representation of the flexibility of existing nuclear power plants via ramp rates, minimum generation levels, etc.
    - Appropriate parameterization of advanced nuclear technologies (e.g., small modular reactors [SMRs] and/or integrated energy systems), including costs, ramp rates, minimum generation levels, construction timelines, finance rates, and additional revenue streams.
- Gain a better understanding of how the ReEDS representation of, and projections for, nuclear power plants compare to those associated with the other participating models. Achieving this goal could take the form of benchmarking the collective teams' projections for nuclear under both "base case" and "decarbonization" scenarios. For the latter scenarios, our goal would be to better understand the role of nuclear power plants under decarbonized futures, including how nuclear's role varies with increasing levels of decarbonization (e.g., 85%, 90%, 95%, and 100%).
- Prioritize scenarios that help us better understand the model outcomes with respect to nuclear power plant retirement and deployment. Considering both intra- and inter-model comparisons, options include our break-even cost analysis, sensitivities related to fixed O&M costs, increasing levels of decarbonization, and market sensitivities.
- Gain a better understanding of the role of nuclear license extensions—both in other models and in the real world—in terms of their costs and impacts on retirement decisions.
- Increase project participants' confidence in the ReEDS model, based on the representation of nuclear and the overarching model architecture and structure.

2. Study Design

The study is patterned after recent collaborations among EIA, EPRI, NREL, and EPA to assess and compare the existing model approaches, structures, and underlying assumptions that impact model outputs for variable renewable energy and energy storage technologies. These studies centered on the following key activities:

- Evaluation of model features and initial modeling scenarios, with feedback from other modeling teams and subject matter experts
- Development of scenarios for multi-model comparisons, intra-model experiments, and model improvement plans
- Conduct of experiments
- Communication of results via a final report, peer-reviewed article(s), presentations, and a public workshop.

The current project focuses on model improvement with respect to technology-specific input assumptions (e.g., cost, performance, and lifetime assumptions), as well as each model's other relevant components that impact projections of nuclear generation (e.g., temporal and spatial resolution, how capacity is valued, and the cost and performance of competing generation resources). This effort will identify how nuclear-related assumptions and data inputs are currently treated in the four models, and will address key model attributes and targeted modifications for improving the representation of nuclear technologies. A greater understanding of model structures, assumptions, parameters, and limitations will likely improve the models' capability to effectively represent market interactions under a variety of market and technology assumptions, enhancing the ability of decision-makers to evaluate the value of new and existing nuclear generation. For issues that cannot be analyzed quantitatively, the comparison would provide qualitative guidance on the expected impacts on electric sector outcomes.

Preliminary scenario descriptions are discussed in Section 3, and a list of proposed intra-model comparisons is provided in Section 5.

3. Preliminary Scenario Definitions

This section summarizes scenarios for *inter*-model comparisons (i.e., multiple models run the same scenarios with a common set of input assumptions) along policy-related and technological dimensions. These comparisons will be complemented by *intra*-model comparisons (i.e., a single model runs a series of diagnostic or scenario-based experiments). The scenarios in Table 1 are designed to span a wide (but incomplete) range of futures to test nuclear energy under different environments. These diagnostic scenarios can inform model understanding, interpretation, and development for a range of stakeholders, though many insights may be able to inform decision-making.

Table *1*. Preliminary scenario matrix for the first round of the nuclear energy modeling intercomparison project. Policy and technology assumptions detailed below.

	Technology Sensitivities				
Policy Sensitivities	**Native**	**Harmonized Costs Only**	**Harmonized**		
			Reference	Low Costs	Carve-Out
Reference ("Current Policies")	**R2.1.0**	R2.1.1	R2.1.2	R2.1.3	R2.1.4
Deep Decarbonization: 80-by-50	**R2.2.0**	R2.2.1	R2.2.2	R2.2.3	R2.2.4
Deep Decarbonization: 100-by-50	**R2.3.0**	R2.3.1	R2.3.2	R2.3.3	R2.3.4

<u>Policy Scenario Specifics</u>

Reference ("Current Policies") Scenario

This scenario reflects all on-the-books state and federal policies and incentives as of January 2021. The goal of this scenario is to estimate how existing and new nuclear technologies (e.g., Gen III+, Gen IV, and SMR designs) will compete on an economic basis.

Potential policies and incentives in this scenario include:

- State/regional policies
  - Renewable portfolio standards and clean electricity standards
  - Energy storage mandates
  - ZEC policies
  - CO_2 caps/taxes both in the electric sector (Regional Greenhouse Gas Initiative, Colorado) and economy-wide (California) if models can represent these policies.
- Federal policies and incentives
  - Production/investment tax credits with phasedowns
  - 45Q tax credits

- Clean Air Act § 111(b) CO_2 performance standards (i.e., prohibiting investments in new coal plants without partial CO_2 capture).

Deep Decarbonization Scenarios

The goal of these scenarios, which reflect a policy push to lower CO_2 emissions, is to explore nuclear's competitiveness in relation to other low-/zero-/negative-CO_2 technologies. The national power sector cap would begin at current levels and linearly decrease to meet 80% and 100% CO_2 reductions by 2050 (relative to 2005 levels), as shown in Figure 1. These cap-and-trade policies would be implemented as a national cap with "where" flexibility (i.e., free national trade), no banking or borrowing, and no offsets or alternative compliance payments. The national CO_2 cap would be implemented alongside the federal/regional/state policies and incentives in the Reference ("Current Policies") scenario. Shadow prices on this constraint could illustrate when this cap becomes binding across models, in addition to the extent to which the policy drives changes in electric sector outcomes.

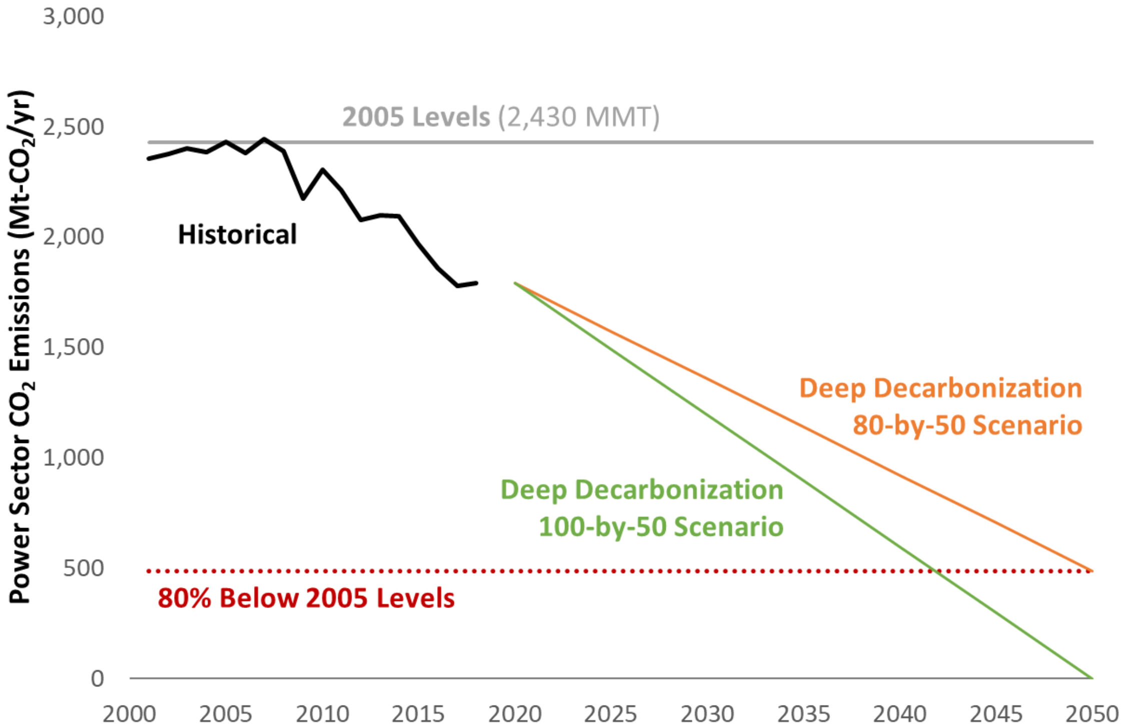

Figure *1*. Historical U.S. electric sector CO_2 emissions and proposed CO_2 cap trajectories for the Deep Decarbonization scenarios.

In addition to the electric sector caps, models should also incorporate a deep decarbonization trend for non-electric sectors where applicable. For models explicitly representing non-electric sectors, implement a carbon price of \$40/t-CO_2 starting in 2021 and escalating at 5% per year[a] (in real dollar terms). For models that do not explicitly represent non-electric sectors, include load growth assumptions and load shapes that reflect a deep decarbonization and higher electrification trend. Note that we are not harmonizing demand, which implies that load shapes and total load levels may differ across models.

[a] This carbon pricing trajectory aligns with the recommendations from the recent National Academies (2021) "Accelerating Decarbonization of the U.S. Energy System" report and Climate Leadership Council proposal.

Technology Scenario Specifics

Native Technology Assumptions

This scenario entails the adoption of all modeling teams' current assumptions for technology cost and performance. The goal of this scenario is to understand the competitiveness of existing/new nuclear technologies, using the models as they are currently parametrized.

Harmonized Technology Assumptions

In this scenario, all models use a common set of input assumptions for capital costs, fixed O&M costs, discounting, and financing. The goal is to evaluate the role of input assumptions versus model structure in projections of nuclear energy in the power sector. Specific assumptions include:

- **Cost and performance assumptions for new investments:** Use NREL's 2020 Annual Technology Baseline (https://atb.nrel.gov/electricity/2020/data.php), due to its public availability and transparency. All costs are exogenous over time (i.e., turn off endogenous technological learning if included in your model).
- **Fixed O&M costs for existing nuclear:** FERC Form 1 fixed O&M plus EUCG for maintenance capital costs.
- **Financing:** Discount rate (Weighted Average Cost of Capital, real dollar terms) of 3% and capital recovery period (economic lifetime) of 30 years for all investments (including all nuclear and non-nuclear generation options).
- **Construction time:** Construction time for SMRs is assumed to be five years, while other new nuclear capacity is assumed to be 10 years.

Partial Harmonization Scenarios

These scenarios align only costs in order to quantify the relative magnitudes of cost assumptions and discounting/financing in driving model outputs. Here, the cost and performance assumptions from the Harmonized Technology Assumptions section are used, but each model uses its native assumptions about financing and discounting.

Harmonized Technology Assumptions with Lower Nuclear Costs

Another scenario uses the same harmonized technology assumptions from before, but considers lower cost assumptions for new nuclear capital costs and existing nuclear fixed O&M costs. The goal in this scenario is to understand how nuclear's competitiveness changes with lower costs.

- New nuclear costs would be adjusted to $2,000/kW beginning in 2035. Figure 2 compares the NREL ATB 2020 cost used in the proposed reference case with the lower cost case. This stylized sensitivity examines how much lower costs for new nuclear impact deployment outcomes under different policy conditions.
- Fixed O&M costs for existing nuclear would be 25% lower than the reference values, assuming plant modernization can lower net costs (including modernization costs).[b]

[b] Information about nuclear plant modernization can be found in the EPRI Nuclear Plant Modernization Toolbox (https://www.epri.com/NuclearPlantMod) and guide to plant modernization research (https://www.epri.com/research/programs/111344). For an example of how modernization can impact existing nuclear plant operations, see the modernization white paper analysis in US-REGEN: EPRI (2019). "The Economics of Nuclear Plant Modernization in U.S. Markets," EPRI Product ID #3002014737 (https://www.epri.com/research/products/000000003002014737).

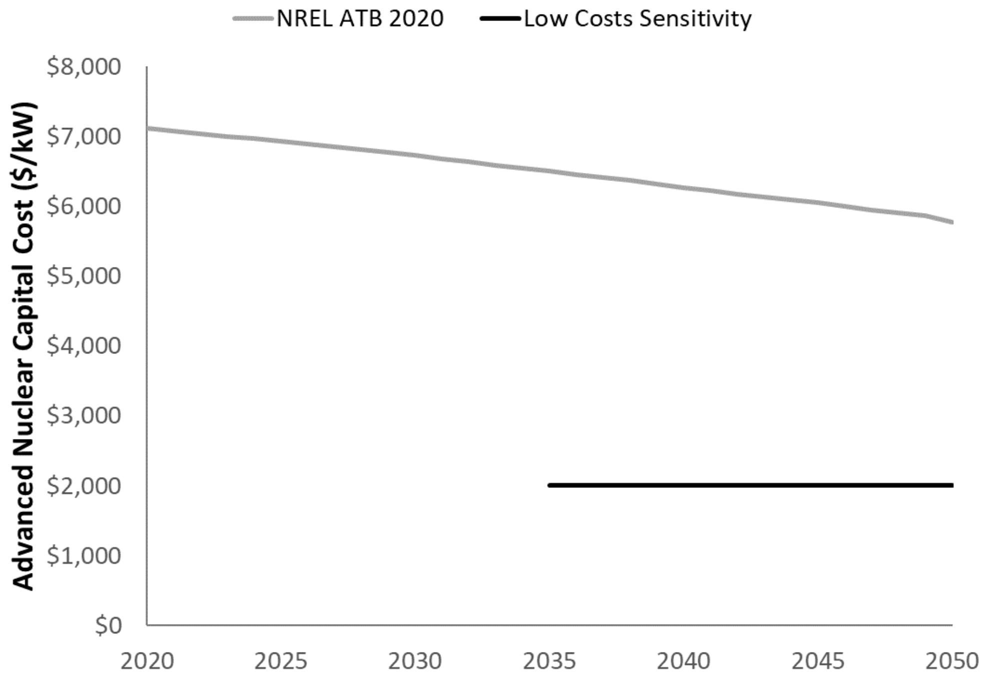

Figure *2*. New nuclear capital costs assumptions ($/kW) for the NREL ATB 2020 and EPRI (2021) SMR cost report.

Harmonized Technology Assumptions with Nuclear Carve-Out

In addition to harmonizing input assumptions, this scenario would harmonize model outputs for new nuclear additions over time, enabling us to understand how a nuclear capacity carve-out impacts outputs of interest across models. This scenario would enforce a national-level capacity constraint in which total installed new nuclear capacity meets the following stylized glidepath: 5 GW by 2035, 15 GW by 2040, 30 GW by 2045, and 50 GW by 2050. Models can compare the shadow prices on this constraint, realized capacity factors, and regional distribution of capacity.

<u>Input Harmonization</u>

The following areas would be harmonized across all scenarios:

- **Fuel prices:** Use EIA's Annual Energy Outlook 2021 "Reference" fuel prices for natural gas, coal, petroleum, and uranium. Fuel prices should be represented as inelastic.
- **Carbon removal ("negative emission") technologies:** Assume that bioenergy with carbon capture, direct air capture, and other negative-emission technologies are not included in these scenarios.
- **Retirements:** Incorporate a list of announced retirements for all capacity types (e.g., coal, nuclear, and gas), and assume that endogenous economic retirements can occur in any period. Use an exogenous assumption that all remaining nuclear plants can operate for 80 years if economic (upper bound constraint).

4. First Workshop Summary

The first workshop for the project took place in five sessions on April 5–7, 2021. An agenda and all slides from the workshop are provided in a dedicated folder on the project BOX site: https://epri.box.com/s/sc2vnt1s3m6lolpsz2vmffn6jhnsv4tk

The virtual workshop consisted of five two-hour sessions:

1. **Model overview and summary of nuclear-relevant studies:** Thirty minutes per modeling team, summarizing key model features for the benefit of new participants and highlighting recent model developments. This summary of nuclear-relevant studies transferred insights and provided a sense of the research conducted by individual model groups. This session began with a brief primer on capacity expansion modeling ("Uses and Limitations for National-Scale Capacity Expansion Models") to help structure the subsequent conversations.
2. **Panels on the representation of existing and new nuclear:** Each one-hour session involved model groups presenting for ~12 minutes each, followed by a 12-minute open discussion period. The existing nuclear session reviewed retirement dynamics/assumptions, license extension options, flexible operations, and other model features related to existing nuclear technologies. The new nuclear session discussed technology performance assumptions, cost projections, and financing.
3. **Review of day-one learnings, and panel on value streams and market participation:** After reflecting on the main takeaways from the first day, there was another panel session on how different value streams and market participation are treated for nuclear energy and other technologies (e.g., energy, capacity, ancillary services, and other attributes/products). In addition to each modeling group's 12-minute presentations and open discussion period, NREL presented research on nuclear eligibility of ZECs, including the impact on retirements and cost implications.
4. **Model intercomparison preliminary scenario results:** This session reviewed preliminary scenario outputs for the model intercomparison. Teams submitted their results via the data template in advance of the meeting, and these results were compiled into figures comparing metrics of interest (e.g., generation, capacity, cost) across models and scenarios.
5. **Brainstorm improvement possibilities, R&D gaps and needs, and intra-model comparisons:** The teams reflected on the takeaways from the workshop, and discussed next steps in the project, including plans for a second workshop.

The goal of the workshop was to conduct the research and make comparisons that would form the basis of reports and articles for this project.

The four modeling groups created tables to provide qualitative/quantitative comparisons across models. These were discussed at the workshop and will be published in the project report. Model comparison tables included:

- Model basics and computational details: Model, institution, objective function, computational requirements, planning horizon, foresight, sectoral coverage
- Power sector constraints and implementation: Temporal resolution, spatial resolution, plant retirement dynamics, deployment dynamics (e.g., least-cost linear program vs. logit choice), technological change, fuel prices, demand levels/shapes
- Existing nuclear technologies and assumptions: Source of fixed O&M costs and changes over time, ZEC policies, CES eligibility, uprates, license extensions, dispatchability and flexibility
- New nuclear technologies and assumptions
    - Set of new nuclear technologies

- Cost assumptions and source: Capital costs, fixed/variable O&M
- Dispatchability and flexibility assumptions
- Financing assumptions: Physical/economic lifetimes, discount rates, construction time and interest
- Cooling technologies
- Deployment constraints

- Market participation for nuclear: Resource adequacy requirements (and assumed contributions of different resources), ancillary services markets and eligibility, options for non-power value streams (e.g., hydrogen)
- Other low-/zero-/negative-emission technologies and their assumptions (e.g., costs over time, and capture rate for carbon-capture-equipped units)

There were several outcomes from the first workshop:

- The scenario definitions for the inter-model comparison were updated. Section 3 reflects these changes, which include adding a deeper decarbonization scenario that reaches zero emissions in the electric sector by 2050.
- The project team developed a list of intra-model comparisons that will be run before the second workshop. Section 5 provides a list of these comparisons.
- Monthly coordination calls with the project team will include presentations by modeling groups on select intra-model comparisons and by subject matter experts on topics to inform model development (e.g., flexibility-related parameters).
- The team will refine model comparison tables (e.g., adding a table on financing assumptions).
- The information generated during the workshop will be used for the final report. An outline for this report will be formally developed around the second workshop.

5. Next Steps

A few types of model-related activities will follow from the analysis and discussion at the first workshop:

1. **Sensitivity analysis:** Conduct model runs to understand the sensitivity of model outputs to variations in specific inputs (e.g., advanced nuclear costs) or to model features (e.g., temporal resolution), illuminating the relative significance of different model features and parameters.
2. **Model diagnostics:** Ensure that model outputs are behaving as expected (e.g., declining capacity value with higher penetration).
3. **Model intercomparison:** Refine the scenarios and reporting from Section 3.

Models also could undertake model upgrades, where a new feature is added or existing capabilities in the model are augmented. The degree of detail on each upgrade will depend on the outcomes of the first workshop.

A second workshop will be held by October 8, 2021, and the interim results made available to Idaho National Laboratory by October 22, 2021. Monthly webcasts or web-based virtual meetings among the team will be held between the first and second workshops.

Intra-model comparisons for the second workshop may include:

- Sensitivities on nuclear eligibility for ZECs, including the impact on retirements and cost implications (NREL) – Presented at Workshop #1
- Impacts of temporal resolution on nuclear deployment (EPRI)
- Financing and lifetime assumptions (EPRI)
- Flexibility of existing and advanced nuclear
- Sensitivity studies, where all nuclear costs are moved to capital/FOM so that short-run marginal costs are exactly $0/MWh in order to compare flexibility, etc.
- Treatment of endogenous retirements in sequential versus intertemporal optimization frameworks (NREL)
- Nuclear value stream analysis (NREL)
- Endogenous technical learning (EIA)
- Reserve margin formulation and ancillary services markets, especially for very deep decarbonization scenarios
- Treatment of end effects across models
- Hydrogen demand and hybrid systems
- Additional comparisons: Lumpy license extension costs (instead of amortized values), cooling water, existing endowment versus greenfield investments

Phase 2 is not currently funded. If approved, Phase 2 will run from October 30, 2021, to September 30, 2022, and involve the following deliverables and timelines:

- Free, publicly available EPRI Technical Report documenting the project approach, results, and key outcomes (published by April 30, 2022)
- Executive Summary published as a joint report, pending approval from each entity before using their names and logos (published by May 31, 2022)

- One or more publications derived from the EPRI report will be submitted for conference proceedings and/or to peer-review journals (submitted by September 30, 2022)
    - One report on model structure and assumptions, including model improvements undertaken as part of this project, potential areas for improving the representation of nuclear power in long-term planning models, and the ability to represent existing and potential policies focused on nuclear generation.
    - Another report focused on model results and how nuclear energy behaves under various economic, policy, or technical conditions.