Modeling Advanced Nuclear Energy Technologies

Gaps and Opportunities

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Acknowledgements:

This report is the product of the participation of more than 100 individuals affiliated with twelve advanced nuclear reactor technology companies, three utilities that own and operate commercial nuclear energy facilities, eleven energy system modeling and research groups, twelve government bodies or national laboratories, and eight nonprofit policy organizations listed in the Appendix. NIA thanks each one of those individuals and the organizations they represent for their contributions to this report. NIA is grateful to Andrew Sowder and the EPRI team who made our in-person workshop possible.

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1. Introduction

In the past four years, 12 U.S. states passed legislation to fully decarbonize the electricity sector by 2050. Three of those state laws require 85-100 percent reductions in economy-wide greenhouse gas (GHG) emissions. More than 30 U.S. electric and gas utilities have pledged to reduce CO_2 or GHG emissions by similar amounts. In 2021, President Biden set a target to achieve net zero economy wide GHG emissions by 2050. In August 2022, the United States enacted the Inflation Reduction Act, which includes clean energy funding and tax credits for clean electricity and clean hydrogen that are expected to substantially reduce GHG emissions.

Policy makers rely on a large and expanding collection of techno-economic modeling tools to help them consider the potential benefits, costs, and risks associated with a multitude of technological options and pathways. It is essential that those tools fairly characterize the technical and economic capabilities of all types of technologies likely to contribute to deep reductions in GHG emissions, including advanced nuclear energy technologies.

Most modeling tools fall short of characterizing the full range of advanced nuclear energy capabilities, especially those associated with operational flexibility that will become more valuable in evolving electricity systems. Many advanced nuclear reactor designs are capable of operational flexibility including ramping, load-following, co-production of multiple forms of energy, and linkage with energy storage. Certain designs include shut-off of smaller reactors within larger plants, thermal heat storage with molten salt, on-site battery storage, or hydrogen or other co-product production. Some advanced nuclear reactor designs refuel less frequently than conventional designs. There are numerous advanced nuclear reactor designs, with power output ranging from 1.5 MWe to more than 1 GWe, that can be used in a variety of applications including electricity generation, district heating, co-generation, industrial heating, hydrogen production, water desalination, and repowering idled plants.

Most models assume flat, fixed hourly nuclear power production levels or only modest nuclear ramping capabilities. Very few models allow assessments of the use of nuclear energy in association with thermal storage, or in district heating, co-generation, industrial heating, hydrogen production, water desalination, repowering, or other non-electric load end uses. Most models do not characterize the costs of innovative advanced nuclear energy technologies or the changes in capital costs over time that are expected due to cumulative construction experience. Very few models assume significant advanced nuclear energy capital and O&M cost reductions.

The imperative to expand supplies of dispatchable zero-carbon emission electricity has spawned a substantial policy and commercial interest in pursuing advanced nuclear technology using innovative management, manufacturing, and construction approaches. Such interest has been supported by major analyses of underlying nuclear cost drivers that have recommended changes that can reduce the cost of building new nuclear capacity.[1] However, the cost information and implications of those studies have not yet been widely evaluated or adopted by the energy system modeling community.

[1] See, for example, "The Future of Nuclear Energy in a Carbon-Constrained World," MIT Energy Initiative, 2018; "Advanced Nuclear Technology: Economic-Based Research and Development Roadmap for Nuclear Power Plant Construction," EPRI, 2019; "Unlocking Reductions in the Construction Costs of Nuclear: A Practical Guide for Stakeholders," NEA, 2020.

In the summer of 2022, the Nuclear Innovation Alliance (NIA) launched an effort: (1) to establish a collective understanding of the gaps that exist between the real and anticipated costs and capabilities of advanced nuclear energy technologies, on the one hand, and the characterization of those costs and capabilities in prominent energy system modeling efforts, on the other hand; and (2) to outline collectively a set of actions that could be taken by the energy modeling community and the federal government to help close those gaps.

The effort proceeded as follows:

(1) During a virtual session on July 7, 2022, members of the modeling community presented summaries of how their models characterize advanced nuclear energy technologies. Members of the advanced nuclear energy engineering and design community listened to modelers' presentations, asked clarification questions, and provided initial feedback on modelers' presentations.

(2) During the month of July 2022, each member of the modeling community who participated in the effort was asked to respond to a limited set of concise questions related to the default characterization of advanced nuclear energy technologies in a specific model. Likewise, each member of the advanced nuclear energy engineering and design community who participated in the effort was asked to respond to a limited set of concise questions related to the anticipated capabilities of a specific advanced nuclear reactor design.

(3) During the month of August 2022, the organizers of this effort summarized the gaps between the anticipated capabilities of advanced nuclear energy technologies and the characterization of those capabilities in modeling tools. The organizers also developed a set of straw recommendations that would help "close the gap" between the capabilities of advanced nuclear energy technologies and the characterization of those capabilities in prominent modeling efforts.

(4) During an in-person working session on September 19, 2022, in Washington, D.C., participants were asked to discuss and provide feedback on the straw recommendations referred to in (3). The organizers of this effort used what they heard and learned from participants on September 19 to generate the final recommendations in **Section 3** of this report.

In this report, the word "we" refers to the NIA team who organized this effort: Judi Greenwald, (Executive Director, NIA), Chumani Mokoena (Intern, NIA), and Max Luke (Consultant, Highland Energy Analytics). The word "participants" refers to the much larger group of advanced nuclear energy technology developers, energy system modelers, policy makers, and other experts, organizers and supporters that participated in either or both the July 7 and September 19 sessions. Please refer to the **Appendix** for a list of the names and affiliations of those individuals.

2. Summary of Findings that Inform Recommendations

During the virtual session on July 7, 2022, we learned about the characterization of advanced nuclear energy technologies in ten widely used energy system models.[2] We highlight three important takeaways from that session:

- First, we confirmed that capital cost is a very important—perhaps *the* most important modeling parameter. Several modeler participants indicated that capital cost has a larger impact on advanced nuclear energy deployment than any other input parameter, in part because of the limited operational capabilities assumed in current models.

- Second, we learned that increasing the number and types of (1) advanced nuclear energy technologies/reactor designs, and/or (2) energy services and flexibilities that advanced nuclear energy technologies provide, can improve the projected economics of advanced nuclear energy technologies in energy system models.

- Finally, several of the modeler participants indicated they would readily update their default cost and performance assumptions if better cost and performance data were available.

We also sent questionnaires to modelers and advanced nuclear reactor developers. We received ten completed questionnaires from modelers and ten completed questionnaires from advanced nuclear reactor developers. An analysis of the completed questionnaires confirms that there are significant gaps between the capabilities of advanced nuclear energy technologies according to advanced reactor developers, and the representation of those capabilities in energy system models. In particular:

- Eight of ten of the energy system models simulate just two nuclear energy technology types, with limited or no operational flexibility: (1) an AP1000 and (2) a generic small modular reactor (SMR). Just two of the models explicitly simulate a molten salt reactor (MSR) and/or a high-temperature gas-cooled reactor (HTGR) with thermal storage.

    - In contrast, variants of almost all advanced nuclear technology categories—including SMR, MSR, HTGR, sodium fast reactor (SFR), lead fast reactor (LFR), fluoride salt-cooled high-temperature reactor (FHR), and other advanced nuclear energy technology categories—feature high degrees of operational flexibility. The companies that responded to questionnaires are developing five of these advanced nuclear energy technology categories.

- The average of the estimated "Initial Year" capital costs of new nuclear facilities used in the ten energy system models, as reported by the energy system modelers we surveyed,

[2] US-REGEN (EPRI), NEMS (EIA), ReEDS (NREL), IPM (EPA), PATHWAYS & RESOLVE (E3), EnergyPATHWAYS and RIO (EER), EPPA (MIT), GenX (Princeton University & MIT), EnCompass (Anchor Power Solutions), WIS:dom (VCE).

is $7,100/kWe ($4,800-9,100/kWe) (2020 dollars).[3] Considering the eight energy system models that assume the highest initial capital costs, the average is $7,600/kWe ($6,300-9,100/kWe). Still considering those eight models, the average default initial capital cost of an AP1000 is $7,200/kWe ($6,300-8,300/kWe). That of an SMR is $8,100/kWe ($7,400-9,100/kWe).

  - In comparison, the average of the first-of-a-kind (FOAK) capital cost estimates for reactors with rated capacities larger than 20 MWe, reported by advanced nuclear developers, is $4,800/kWe ($3,600-6,500/kWe).[4]

- The average of the estimated "End Year" (comparable to nth-of-a-kind [NOAK]) capital costs of new nuclear facilities used in the energy system models, is $6,000/kWe ($4,400-6,600/kWe).[5] The average "End Year" capital cost of an AP1000 is $5,900/kWe ($4,400-6,700/kWe). That of an SMR is $6,200/kWe ($5,600-6,700/kWe).

  - In comparison, the average of the NOAK capital cost estimates for reactors with rated capacities larger than 20 MWe, reported by advanced nuclear reactor developers, is $3,300/kWe ($2,200-5,000/kWe).

- Five of ten energy system modelers assume that advanced nuclear energy technologies can provide one or more of the following energy services: industrial processes and heat, combined heat and power, hydrogen production, water desalination, synthetic fuels production, marine propulsion, and the replacement of coal-fired boilers with advanced nuclear reactors ("coal repowering").

  - In contrast, all ten advanced nuclear reactor developers are designing for the supply of one or more of those energy services:

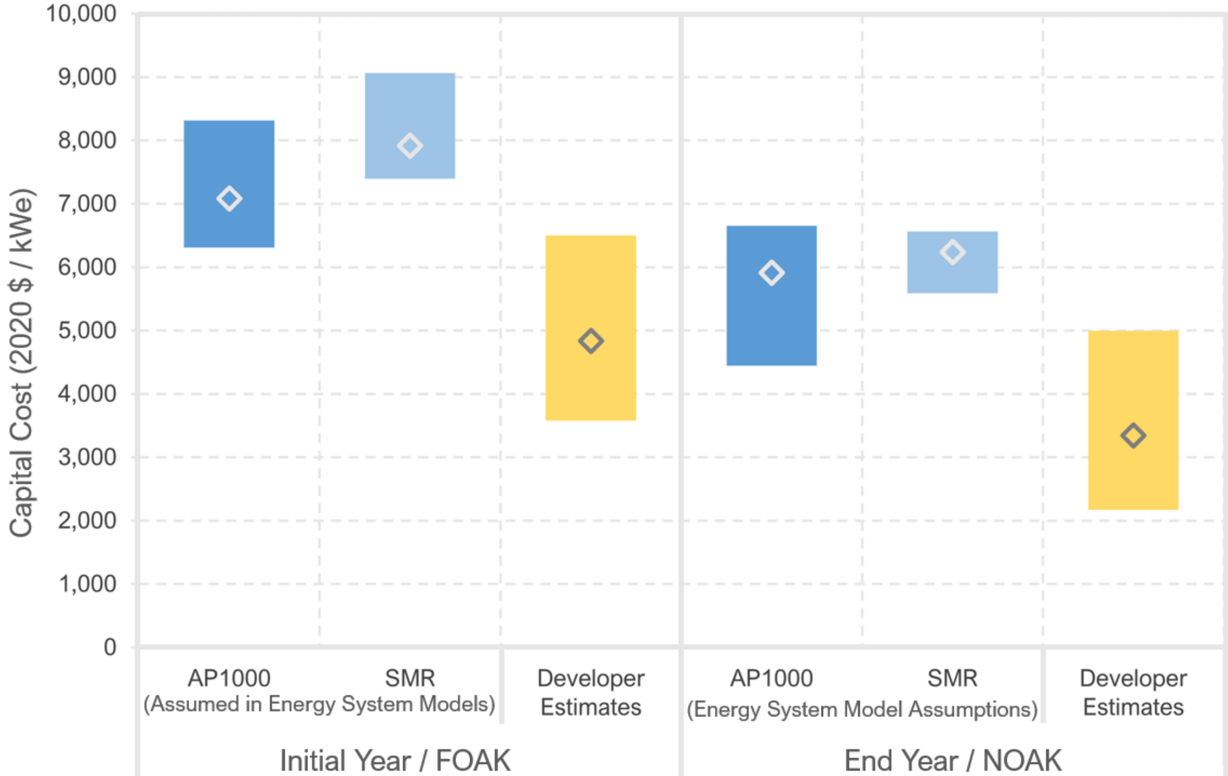
Energy Service	Number of Companies
Industrial processes and heat	10
Combined heat and power	8
Hydrogen production	8
Water desalination	7
Synthetic fuels production	1
Marine propulsion	1
Coal repowering	1

[3] The "Initial Year" capital cost of a new nuclear facility is the capital cost of that type of reactor in the first (initial) year that the reactor technology is deployed in the model. We deliberately use the word "initial," rather than the phrase "first-of-a-kind," because many of the models simulate AP1000 reactors, several of which currently operate globally. However, we consider the "Initial Year" capital costs used in energy system models comparable to the FOAK capital costs reported by advanced nuclear energy developers.

[4] Seven of ten developers surveyed are designing reactors with rated capacities larger than 20 MWe.

[5] The "End Year" capital cost of a new nuclear facility is the capital cost of that type of reactor in the 30th year after the first (initial) year that the reactor technology is deployed in the model. We consider "End Year" costs a reasonable proxy for NOAK costs. The reported average ($6,000/kWe) and range ($4,400-6,600/kWe) correspond to the seven (of ten) energy system models in which the rate of reduction of capital costs is a function of time and *not* a function of deployment (*i.e.*, capacity or number of units deployed). Of the three energy system models that simulate reductions of capital costs as a function of deployment, we cannot determine "End Year" capital costs *a priori*, *i.e.*, without running those models.

***Figure 1**. Default Capital Costs Used in Energy System Models and Capital Costs Reported by Advanced Nuclear Reactor Developers*



***Note 1**: The blue areas reflect the ranges of default capital costs used in energy system models, as reported by energy system modelers, associated with an AP1000 and an SMR. "Initial Year" capital costs are shown in the left panel of Figure 1 and "End Year" capital costs are shown in the right panel of Figure 1. "Initial Year" and "End Year" are defined in footnotes 3 and 5, respectively. The blue areas do not include data related to the three energy system models that simulate reductions of capital costs as a function of deployment, for the same reason as described in footnote 5.*

***Note 2**: The yellow areas reflect the ranges of capital costs reported by advanced nuclear reactor developers, associated with reactors with rated capacities larger than 20 MWe. FOAK capital costs are shown in the left panel of Figure 1 and NOAK capital costs are shown in the right panel of Figure 1.*

***Note 3**: Diamonds denote the average of each capital cost range.*

Two recently published studies conducted independently of the present effort provide further evidence of the significant differences between the capabilities of advanced nuclear energy technologies and the characterization of those capabilities in energy system models. In the first study, published by SMR Start and titled "The Economics of Small Modular Reactors," the authors report the following cost and performance characteristics for SMRs (2020 dollars):[6]

- FOAK capital cost of $3,800 and NOAK capital cost of $2,000/kWe;
- Combined fixed and variable O&M costs of $15-22/MWh;
- Fuel costs of $8/MWh, inclusive of the cost of fuel management;
- Capacity factors of up to 95%; and
- Construction times of 30-36 months.

In the second study, published by the Breakthrough Institute and titled "Advancing Nuclear Energy: Evaluating Deployment, Investment, and Impact in America's Clean Energy Future," the authors report the following cost and performance parameters for SMRs and HGTRs (2020 dollars):[7]

Parameter	Unit	SMR	HTGR
Learning rate	%	5-12	5-12
Capital cost (FOAK)	$/kWe	5,100-7,000	5,518-7,500
Fixed cost	$/kWe-year	98	39-189
Variable O&M cost	$/MWh	3.08	0.00-0.35
Ramping cost	$/MW/h	2.75	2.75
Start-up cost	$/MW	119	119
Heat rate	MMBtu/MWh	10.23	8.53
Reactor capacity	MWe	150	80
Maximum power	MWe	150	80
Minimum power	MWe	30	32
Max. down ramp	MWe	15	4
Max. up ramp	MWe	15	4
Outage rate	%	10	5
Water consumption	Liters/kWh	1.51	0.91

In addition to the findings presented above, which pertain to "non-micro-reactors" with rated capacities greater than 20 MWe, we also collected data related to micro-reactors with rated capacities less than or equal to 20 MWe. Of the ten completed questionnaires we received from advanced nuclear energy developers, four contain information related to micro-reactors, but only two of those contain FOAK and NOAK capital cost estimates in units of $/kWe. Those two sets of estimates yield the following capital cost ranges:

- NOAK costs of $2,600/kWe to $16,000/kWe, and

[6] "The Economics of Small Modular Reactors," SMR Start, March 2021.
[7] A. Stein, *et al.*, "Advancing Nuclear Energy: Evaluating Deployment, Investment, and Impact in America's Clean Energy Future," The Breakthrough Institute, July 2022.

- FOAK costs of $5,400/kWe to $20,000/kWe.

We also reviewed a study published by the Nuclear Energy Institute (NEI) titled "Cost Competitiveness of Micro-Reactors for Remote Markets."[8] The authors of the NEI study estimate capital costs of FOAK micro-reactors of $10,000-20,000/kWe, and of NOAK micro-reactors of $4,000-15,000/kWe. The authors of the NEI study also estimate the following additional micro-reactor cost and performance parameters:

- Fixed O&M costs of $250/kWe to $450/kWe;
- Fuel costs of $6/MWh to $14/MWh, inclusive of the cost of fuel management;
- Decommissioning costs of $3/MWh to $7/MWh;
- Refueling costs of $13 million to $27 million per refuel;
- Capacity factors of up to 95%;
- Construction times of 6 months to 2 years;
- Plant lives of 10 years to 60 years; and
- Fuel lives of 5 years to 20 years.

We initially developed straw recommendations based on the results of the modeler and developer questionnaires and the SMR Start and NEI studies referred to above. Our central straw recommendation was the establishment of an advanced nuclear energy cost and performance database that improves upon existing advanced nuclear energy cost and performance databases. We also proposed a straw recommendation related to more near-term updates to cost and performance model input assumptions. Participants' reactions to those straw recommendations during the workshop in Washington, D.C., on September 19, 2022, informed the final recommendations that we present below in **Section 3**.

[8] M. Nichol and H. Desai, "Cost Competitiveness of Micro-Reactors for Remote Markets," Nuclear Energy Institute, April 2019.

3. Final Recommendations and Next Steps

3.1. Advanced Nuclear Energy Cost and Performance Database

On September 19, 2022, we asked participants to respond to a straw recommendation to establish an advanced nuclear energy cost and performance database that improves upon existing available data related to advanced nuclear energy costs and performance. Participants agree that the institutionalization of an advanced nuclear energy cost and performance database will help close the gaps between the real and anticipated capabilities of advanced nuclear energy technologies and the characterization of those capabilities in prominent modeling efforts. Our first final recommendation is as follows:

> Recommendation 1: **Establish an advanced nuclear energy cost and performance database that improves upon existing data related to nuclear energy costs and performance; that relies on the latest information related to advanced nuclear reactor technologies; that considers the full range of advanced nuclear reactor designs; and that conforms to a "robust" database development process** (see Recommendation 4)

On September 19, we recommended that the development of the new database be overseen by a DOE office or national lab with expertise in advanced nuclear energy technologies. We discussed several options for potential hosts, including the DOE's Office of Nuclear Energy (NE), the Idaho National Laboratory (INL), an NE or INL initiative or program, or another national lab with the required expertise in advanced nuclear energy technologies. All participants support such an idea. Our second final recommendation is as follows:

> Recommendation 2: **The development of the database should be overseen by a DOE office or national lab with expertise in advanced nuclear energy technologies; and a national lab or academic institution should host the database.**

In the event a DOE office or national lab with expertise in advanced nuclear energy technologies does not agree to oversee the development of, and host, the database, we recommend that either another national lab or an academic institution perform those functions instead. We learned from one of our participants that the Zero-carbon Energy Systems Research and Optimization (ZERO) Lab at Princeton University could perform such functions.

We understand that the organization that oversees the development of the database—whether that organization is a DOE office, national lab, or academic institution—might not have prior experience developing such a database. Therefore, we spent most of the morning of September 19 discussing with participants the possibility of leveraging an existing database that many energy system modelers use: the National Renewable Energy Laboratory (NREL) Annual Technology Baseline (ATB) database.

A September 19 participant affiliated with NREL, and other participants familiar with ATB database, provided useful summaries of the types of data in NREL ATB. All participants agree that some of those same data inputs should be used in the advanced nuclear energy database. Moreover, a September 19 participant affiliated with the Energy Information Administration (EIA) provided a useful summary of the process by which the EIA generates energy technology cost and performance data for use in the National Energy Modeling System (NEMS).

Due to limited time at the September 19 workshop, it was not possible to develop a comprehensive list of all the data inputs that will be entered into the advanced nuclear energy database. Moreover, the discussion on September 19 did not yield a comprehensive description of the processes by which NREL ATB data or EIA NEMS data currently are generated. Fortunately, after the September 19 workshop, NREL staff members involved with ATB offered to provide support with the development of the advanced nuclear energy database. The September 19 participant affiliated with EIA also offered to lend support to the effort. Our third final recommendation is as follows:

Recommendation 3: After the organization in Recommendation 2 is identified, representatives from that organization should meet with the appropriate representatives from NREL to initiate a two-month collaboration in which NREL supports the organization with developing (a) lists of all data inputs that will be collected and/or generated and entered into the database, and (b) the processes by which those data inputs will be collected/generated initially and periodically.

We suggest that NIA help to facilitate the collaboration described in Recommendation 3. Moreover, we suggest that the collaboration in Recommendation 3 include the September 19 participant affiliated with EIA; and also any participants in the **Appendix** who are not affiliated with either NREL or the organization identified in Recommendation 2, but who express an interest in contributing to Recommendation 3 and who would provide expertise that would benefit the collaboration described in Recommendation 3.

Also, since the September 19 workshop, the Gateway for Innovation in Nuclear (GAIN) program has begun to define the practical steps of gathering data, maintaining data confidentiality, making some portions of the database public, and getting the database up and running.

After (a) and (b) in Recommendation 3 have been resolved, or sooner if the GAIN effort so allows, the organization identified in Recommendation 2 should be able to estimate with reasonable accuracy the upfront and ongoing budget associated with the advanced nuclear energy cost and performance database; and therefore, should be able to make an informed decision about whether that organization can support the effort. If it can support the effort, we recommend that the organization establish a "robust" database development process, defined in Recommendation 4:

Recommendation 4: **Establish a "robust" database development process**

a. The database should be developed collaboratively by a group of advanced nuclear energy technology developers, energy system modelers, and NGO experts, drawing upon the participants assembled as part of this effort.
b. The database development should be informed by GAIN's current scoping effort.
c. The data generation process should be informed by the latest available studies, reports, and information related to advanced nuclear costs, cost drivers, and learning rates.
d. The new database should be developed over a pre-defined period or no more than six months, via a pre-defined number of in-person, virtual, and/or hybrid workshop sessions.
e. The scheduling, agenda-setting, and facilitation of that development process should be overseen by the organization identified in Recommendation 2, with assistance from NIA or another independent organization.
f. Data furnished by nuclear energy companies should be confidential and subject to NDAs.
g. There should be a public-facing version of the database, and it must protect the confidentiality of any proprietary data furnished by nuclear energy companies.
h. A process should be established for the independent review of all data inputs and of the processes used to collect and/or generate those data inputs.
i. Published data should be presented in normalized/standardized units to the extent possible, to facilitate its appropriate usage and enable valid comparisons.
j. The new database should be housed on the website of the organization identified in Recommendation 2 and updated at least once per year.
k. Updates to the database should follow a clearly defined and repeatable process to ensure the stability of values reported in the database.

Recommendations 1-4 reflect our deliberate attempt to keep the database development process open-ended and flexible in order to produce the most useful data inputs. We believe the best process, and ultimately the best database, will be one that the organizations and stakeholders identified in Recommendations 1-4 are empowered to own and lead. Nonetheless, we think that some specificity is warranted related to two classes of advanced nuclear energy technologies that risk being overlooked if we do not explicitly include them in the recommendations: advanced reactors with thermal energy storage (ARTES) and micro-reactors.

Both ARTES and micro-reactors are generally under-represented in optimization-based energy system planning models. Adequately characterizing ARTES requires optimization techniques and behavioral and market assumptions that exceed the capabilities and resolution of most models. Micro-reactors cost more than non-micro-reactors on a per-MW basis and therefore don't get built in linear optimization-based models.

Nonetheless, both such technologies add value to energy systems. Results from the few models that *do* adequately characterize ARTES suggest that ARTES adds considerable value and reduces the overall costs of the energy systems in which it is deployed. Likewise, micro-reactors are likely to serve remote and/or off-grid markets that are separate from (or that only partially overlap with) the bulk energy markets that non-micro-reactors serve. Although those markets are relatively small, they may be reflected in next generations of energy system planning models and/or in bottom-up energy system planning exercises such as in integrated resources plans (IRPs). Our fifth final recommendation is as follows:

Recommendation 5: Ensure that the database development process, and the database itself, considers the potential system benefits and markets served by two classes of advanced nuclear energy technologies that are under-represented in optimization-based energy system planning models: advanced reactors with thermal energy storage (ARTES) and micro-reactors. Consider including both ARTES and micro-reactors as distinct technology types within the database.

3.2. Near-Term Updates to Default Model Assumptions

The purpose of the advanced nuclear energy cost and performance database, described above in **Subsection 3.1**, is to offer to energy system modelers a set of accurate and reliable advanced nuclear reactor cost and performance data inputs that will inform and improve the results of energy system models. The credibility of the advanced nuclear energy database will depend on the organizations involved in the development of the database and the processes by which data are collected and/or generated and entered into the database.

Getting those elements right will take time. In **Subsection 3.1**, we recommend that the database be developed and launched to the public in a period of no more than six months. During that time, as the advanced nuclear energy database is being developed, we urge energy system modelers to make any updates that they can to their default energy system model inputs, that would help close the gaps between the anticipated capabilities of advanced nuclear reactor technologies and the characterization of those capabilities in prominent modeling efforts. Our sixth final recommendation is as follows:

Recommendation 6: **In the more immediate term, while the advanced nuclear energy database is being developed, update default system model assumptions to reflect ranges based on advanced nuclear reactor developer survey results from this effort, and the cost and performance parameters published in recent studies, including the SMR Start and Breakthrough Institute studies discussed in Section 2.**

a. Update models to expand advanced reactor technology types represented in default model runs; at a minimum, include two representative advanced reactors (e.g., a representative SMR and a representative HTGR), and characterize those two representative advanced reactors using the following cost and input performance parameters.

b. For each of the representative advanced reactors, assume an initial capital cost of new nuclear energy facilities of $5,550/kWe, 2020 dollars, the mid-point of the full range of estimates reported in (a) the advanced nuclear energy developer surveys; (b) the SMR Start study, and (c) the Breakthrough Institute study; otherwise assume an initial capital cost of some value within that range $3,600-7,500/kWe.

c. If the model treats the rate of reduction of capital costs as an exogenous, user-defined function of time, update year-2050 (or model end-year) capital cost default assumptions as follows:

    i. For each of the representative advanced reactors, assume a year-2050 (or model end-year) capital cost of new nuclear energy facilities of $3,500/kWe, 2020 dollars, the mid-point of the full range of estimates reported in (a) and (b); otherwise assume an initial capital cost of some value within that range $2,000-5,000/kWe.

d. If the model simulates reductions of capital costs as a function of capacity deployed, assume a learning rate of 5-12% for each doubling of advanced nuclear capacity (MWe), consistent with the Breakthrough Institute report.

e. Regardless of whether the model treats the rate of reduction of capital costs as a function of time, or as a function of deployment, update other (non-capital cost-related) cost and performance assumptions, consistent with the Breakthrough Institute report, Tables 1-2 and 1-3.

Recommendation 6 does not include any suggestions related to ARTES or to micro-reactors. Although we collected cost and performance information related to ARTES and to micro-reactors, and although we reviewed and considered the Breakthrough Institute report (which reports ranges of cost and performance parameters for ARTES) and the NEI report titled "Cost Competitiveness of Micro-Reactors for Remote Markets," we concluded that the data we reviewed requires additional evaluation before recommending any near-term updates to energy system models related to ARTES or to micro-reactors.

Nonetheless, we anticipate and recommend (in Recommendation 5) that the advanced nuclear energy cost and performance database, described in **Subsection 3.1**, includes distinct sets of cost and performance parameters for each of ARTES and micro-reactors. Moreover, we urge energy system modelers to think through how to appropriately represent ARTES and micro-reactors in all models, including linear optimization-based models, given that ARTES and micro-reactors will play important roles in bulk/wholesale and remote/off-grid energy markets.

Appendix: Participants

Name	Organization	Category
Irfan Ali	ARC Clean Technology	Adv. Nuclear Developer
James Wolf	ARC Clean Technology	Adv. Nuclear Developer
Abbey Donahue	BWX Technologies, Inc. (BWXT)	Adv. Nuclear Developer
Elisa Calvo Tone	Framatome	Adv. Nuclear Developer
Jeff Fleck	Framatome	Adv. Nuclear Developer
Joel Drennan	Framatome	Adv. Nuclear Developer
Hangbok Choi	General Atomics	Adv. Nuclear Developer
John Bolin	General Atomics	Adv. Nuclear Developer
Mohammad Alavi	General Atomics	Adv. Nuclear Developer
Dinara Ermakova	Kairos Power	Adv. Nuclear Developer
Lou Martinez Sancho	Kairos Power	Adv. Nuclear Developer
Phil Frost	NuScale Power	Adv. Nuclear Developer
Ross Snuggerud	NuScale Power	Adv. Nuclear Developer
Jackie Siebens	Oklo Inc	Adv. Nuclear Developer
Christopher Fendley	TerraPower	Adv. Nuclear Developer
Frank Akstulewicz	Terrestrial Energy	Adv. Nuclear Developer
Robin Rickman	Terrestrial Energy	Adv. Nuclear Developer
Cristian Rabiti	Ultra Safe Nuclear Corporation (USNC)	Adv. Nuclear Developer
James Richards	Ultra Safe Nuclear Corporation (USNC)	Adv. Nuclear Developer
David Hawkins	Westinghouse Electric Corporation	Adv. Nuclear Developer
Michael Valore	Westinghouse Electric Corporation	Adv. Nuclear Developer
Guy Packard	X-energy	Adv. Nuclear Developer
Thomas Braudt	X-energy	Adv. Nuclear Developer
Adam Reichenbach	Duke Energy	Utility Nuclear Developer
Jared Knode	Energy Northwest	Utility Nuclear Developer
Ugi Otgonbaatar	Exelon Corporation	Utility Nuclear Developer
John Bistline	Electric Power Research Institute (EPRI)	Energy System Modeler
John Taber	Electric Power Research Institute (EPRI)	Energy System Modeler
Arne Olson	Energy and Environmental Economics, Inc. (E3)	Energy System Modeler
Augustine Kwon	Energy Information Administration (EIA)	Energy System Modeler
Chris Namovicz	Energy Information Administration (EIA)	Energy System Modeler
Laura Martin	Energy Information Administration (EIA)	Energy System Modeler
Slade Johnson	Energy Information Administration (EIA)	Energy System Modeler
Erich Eschmann	Environmental Protection Agency (EPA)	Energy System Modeler
Andrew Waddell	Evolved Energy Research (EER)	Energy System Modeler
Ben Haley	Evolved Energy Research (EER)	Energy System Modeler
Jeremy Hargreaves	Evolved Energy Research (EER)	Energy System Modeler
Jim Williams	Evolved Energy Research (EER)	Energy System Modeler
Ryan Jones	Evolved Energy Research (EER)	Energy System Modeler
Ric O'Connell	GridLab	Energy System Modeler
Sergey Paltsev	Massachusetts Institute of Technology (MIT)	Energy System Modeler
Caitlin Murphy	National Renewable Energy Laboratory (NREL)	Energy System Modeler
Jonathan Ho	National Renewable Energy Laboratory (NREL)	Energy System Modeler
Sonny Kim	Pacific Northwest National Laboratory (PNNL)	Energy System Modeler
Fangwei Cheng	Princeton University	Energy System Modeler
Jesse Jenkins	Princeton University	Energy System Modeler
Wilson Ricks	Princeton University	Energy System Modeler
Chris Clack	Vibrabt Clean Energy (VCE)	Energy System Modeler
Bob Ledoux	Advanced Research Projects Agency-Energy (ARPA-E)	Government / Policy
Harry Andreades	Advanced Research Projects Agency-Energy (ARPA-E)	Government / Policy

Jen Shafer	Advanced Research Projects Agency-Energy (ARPA-E)	Government / Policy
Alyse Huffman	House Committee on Science, Space and Technology (SST)	Government / Policy
Brent Dixon	Idaho National Laboratory (INL)	Government / Policy
Chris Lohse	Idaho National Laboratory (INL)	Government / Policy
Christine King	Idaho National Laboratory (INL)	Government / Policy
Sanjay Mukhi	Idaho National Laboratory (INL)	Government / Policy
Shannon Bragg-Sitton	Idaho National Laboratory (INL)	Government / Policy
Chin Cheung	Loan Programs Office (LPO)	Government / Policy
Markus Popa	Loan Programs Office (LPO)	Government / Policy
Kiera Zitelman	National Assoc. of Reg. Utility Commissioners (NARUC)	Government / Policy
Gian Porro	National Renewable Energy Laboratory (NREL)	Government / Policy
Laura Vimmerstedt	National Renewable Energy Laboratory (NREL)	Government / Policy
Mark Ruth	National Renewable Energy Laboratory (NREL)	Government / Policy
Andy Worrall	Oak Ridge National Laboratory (ORNL)	Government / Policy
Alice Caponiti	Office of Nuclear Energy (NE)	Government / Policy
Alison Hahn	Office of Nuclear Energy (NE)	Government / Policy
Janelle Eddins	Office of Nuclear Energy (NE)	Government / Policy
Jason Marcinkoski	Office of Nuclear Energy (NE)	Government / Policy
Jason Tokey	Office of Nuclear Energy (NE)	Government / Policy
Aaron Goldner	Senate Committee on Appropriations	Government / Policy
Bradley Williams	Senate Committee on Energy and Natural Resources (ENR)	Government / Policy
David Rosner	Senate Committee on Energy and Natural Resources (ENR)	Government / Policy
Andy Zach	Senate Committee on Environment and Public Works (EPW)	Government / Policy
Will Dixon	Senate Committee on Environment and Public Works (EPW)	Government / Policy
Stephanie Mack	Senator Sheldon Whitehouse	Government / Policy
Stephen Greene	Atlantic Council	Nonprofit / Policy
Adam Stein	Breakthrough Institute (BTI)	Nonprofit / Policy
Armond Cohen	Clean Air Task Force (CATF)	Nonprofit / Policy
Jon-Michael Murray	Clean Air Task Force (CATF)	Nonprofit / Policy
Leslie Abrahams	Clean Air Task Force (CATF)	Nonprofit / Policy
Spencer Nelson	ClearPath	Nonprofit / Policy
Colter Schroer	Good Energy Collective (GEC)	Nonprofit / Policy
Jessica Lovering	Good Energy Collective (GEC)	Nonprofit / Policy
Chirayu Batra	LucidCatalyst	Nonprofit / Policy
Eric Ingersoll	LucidCatalyst	Nonprofit / Policy
Justin Aborn	LucidCatalyst	Nonprofit / Policy
Marcus Nichol	Nuclear Energy Institute (NEI)	Nonprofit / Policy
Matt Crozat	Nuclear Energy Institute (NEI)	Nonprofit / Policy
Lindsey Walter	Third Way	Nonprofit / Policy
Andrew Sowder	Electric Power Research Institute (EPRI)	Organizer / Support Team
Craig Stover	Electric Power Research Institute (EPRI)	Organizer / Support Team
Daniel Moneghan	Electric Power Research Institute (EPRI)	Organizer / Support Team
Emma Wong	Electric Power Research Institute (EPRI)	Organizer / Support Team
Francisco Ralston Fonseca	Electric Power Research Institute (EPRI)	Organizer / Support Team
Mary Davidson	Electric Power Research Institute (EPRI)	Organizer / Support Team
Max Luke	Highland Energy Analytics	Organizer / Support Team
Chumani Mokoena	Nuclear Innovation Alliance (NIA)	Organizer / Support Team
Devin Watts	Nuclear Innovation Alliance (NIA)	Organizer / Support Team
Judi Greenwald	Nuclear Innovation Alliance (NIA)	Organizer / Support Team
Frances Wood	OnLocation	Organizer / Support Team
Francisco De La Chesnaye	OnLocation	Organizer / Support Team
Sharon Showalter	OnLocation	Organizer / Support Team