Analyzing the Role of Advanced Nuclear Energy in Deep Decarbonization: A Review of Market Opportunities and Modeling Challenges

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OnLocation, Inc.

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OnLocation, Inc., was retained by the Nuclear Innovation Alliance for the purpose of conducting an independent assessment of the types of contributions nuclear energy, including advanced nuclear reactors, can provide in meeting climate mitigation goals and to highlight ways of improving the representation of advanced nuclear reactors in energy system models.

About OnLocation, Inc.

OnLocation, Inc., a KeyLogic Company, is recognized as a leading energy consultant providing objective quantitative analysis to a diverse set of energy policy stakeholders. Since 1984, OnLocation has served a broad range of government and industry clients with a common interest in energy and the environment. OnLocation's experienced professionals rely on thorough research and analysis to achieve practical and customized solutions for our clients. To help our clients understand the implications of the challenges facing our energy system, we develop, modify, and apply a variety of computer models to examine potential energy trends, impacts of proposed government policies and the associated financial and economic impacts of energy related investment decisions. Collectively, the staff of OnLocation has over 125 years of working experience with integrated energy models including the National Energy Modeling System (NEMS), EIA's widely recognized energy model. OnLocation's senior staff and associate consultants have provided insights and solutions to the business and policy challenges of the Department of Energy, Environmental Protection Agency, energy corporations and various non-governmental organizations that support policymakers in Congress and elsewhere.

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Executive Summary

Climate mitigation policies typically have focused on carbon-free renewable technologies such as wind and solar photovoltaics (PV), often coupled with battery storage. The costs of these technologies, especially solar PV and storage, have declined dramatically in recent years with the associated increased deployments. At the same time, there are many reasons why renewable technologies alone may not sufficiently decarbonize the power sector, including system reliability and resiliency, land requirements for large solar and wind farms, and associated transmission line expansion.

Even though it has been long recognized that effective climate mitigation requires a range of current and future technologies and practices, advanced nuclear technologies are often left out or not fully recognized as complementary options. **Advanced nuclear reactors can provide another carbon-free energy option to consider in multiple applications**. However, when policymakers and energy modelers think of nuclear technologies, they generally think of large expensive power plants that provide mostly baseload electric power. **New, smaller, and/or modular reactor designs**, either alone or paired with thermal energy storage, **promise to provide flexible operations crucial for electric grids with higher variable renewable generation**. In addition, **heat and steam produced by nuclear plants can be used to make clean hydrogen or other carbon-free fuels** that could be used as a substitute for fossil fuels in many applications. Nuclear power also could be used directly for **desalination** or **process heat for manufacturing** processes.

This paper examines the many ways that **nuclear energy, including advanced nuclear reactors, can play a significant role in meeting mitigation goals** and makes a **case for energy modelers to consider incorporating** characteristics and applications for **advanced reactors into their energy economic models**. Both the challenges and opportunities related to modeling new nuclear technologies and their potential applications are also discussed.

Advanced reactor technologies

There are several **new advanced nuclear reactor designs** at various stages of development that have **advantages over existing designs**, including a smaller footprint and use of different moderators, coolants, and types of fuel than traditional light water reactors. Currently, there are three main categories of advanced reactors: **Advanced Water-Cooled Reactors** offer many advantages over conventional light-water reactors, including inherent safety features, smaller size, and modularity; **Advanced Non-Water-Cooled Reactors** use alternative fuels and coolants such as gases, liquid metals, or molten salts instead of light water; and **Fusion Reactors** fuse atomic nuclei to produce energy vs. fission reactors that split atomic nuclei to produce energy (fission reactors make up all of the existing commercial reactors and a majority of new reactor designs). Furthermore, many advanced reactors are Small Modular Reactors (SMRs), which are defined by the U.S. Department of Energy (DOE) as reactors that are typically less than 300 MW and can be built using modular construction techniques.[1]

Recommendations

To account for the new design characteristics of advanced reactors, there are **relatively simple changes in assumptions that can be made in model structures**, especially in electric power generation. These include capital and operating costs, construction lead times, financial risk factors, and siting restrictions.

[1] Congressional Research Service, "Advanced Nuclear Reactors: Technology Overview and Current Issues," R45706, April 18, 2019.

In addition, parameters and model structures that determine the flexibility of nuclear operations also should be modified to reflect these capabilities in both advanced and current nuclear technologies. Representing **non-power applications of advanced nuclear reactors** is also important for **analyzing economy-wide deep decarbonization goals**, for example the production of hydrogen fuel and the use of SMRs to reduce emissions from the industrial sector by heat and power. To address the **full scope of advanced nuclear characteristics and benefits**, energy modelers will need to explore **new ways of modeling uncertainty, accounting for dynamics and feedback within markets, and interdependencies** with other infrastructures and risks. Overcoming these challenges will require systematic model advancement and careful calibration while balancing computational tractability and the number of independent variables.

Next Steps

Given the urgency and challenges decision makers face to implement effective climate mitigation policies, **now is the time for energy modelers to reassess how nuclear technologies are represented** in their models and how these technologies respond to policies, markets, and energy system interactions. Modelers can reach out to the Nuclear Innovation Alliance (NIA) to learn more about the characteristics of advanced nuclear technologies including downloading their Primer here [https://www.nuclearinnovationalliance.org/advanced-nuclear-reactor-technology-primer]. Participating in modeling workshops and comparison exercises (e.g., the Stanford University Energy Modeling Forum [EMF])[2] are an effective way to collaborate with other modelers to share best practices for representing new technologies such as advanced reactors. The Energy Information Administration (EIA) has sponsored information sessions for modelers as well, for example, representing variable renewable energy in energy models[3] and sessions with broader audiences on energy storage[4]. **We recommend that EIA, the DOE Office of Nuclear Energy, and other interested parties sponsor an advanced nuclear modeling workshop** that would benefit the energy modeling community through direct participation as well as dissemination of a paper summarizing the proceedings.

[2] Stanford University - Energy Modeling Forum, https://emf.stanford.edu

[3]Electric Capacity Expansion Modelling Workshop: Treatment of Variable Renewable Energy, July 11, 2016, https://www.eia.gov/renewable/workshop/)

[4] EIA Energy Storage Workshop, July 16, 2020 - https://www.eia.gov/electricity/workshop/batterystorage/

Introduction

There is a growing sense of urgency among policymakers that now is the time to enact wide-ranging climate policies to mitigate the effects of global warming, and energy modelers are taking notice. The debate about how we will reduce greenhouse gas (GHG) emissions, and specifically the types of technologies that will be most effective, typically focuses on carbon-free renewable technologies such as wind and solar photovoltaics (PV), often coupled with battery storage. The costs of these technologies, especially solar PV and storage, have declined dramatically in recent years, and deployments are increasing in many areas of the world.

There are many factors that suggest that renewable technologies alone may not be sufficient to completely decarbonize the power sector. These factors include land requirements for large solar and wind farms, the need for associated transmission lines, and the variable nature of the generation solar and wind produce. Combustion turbines and other natural gas technologies often fill the generation gap when these resources are not available, but they emit carbon dioxide (CO_2) and other pollutants. Battery storage can help smooth out and extend this variable generation on the grid for short-term operations; the most prevalent battery technology, lithium-ion batteries, has limited storage capacity of up to 4 to 8 hours of generation in a day. Longer duration storage options with capacity greater than 10 hours are needed for weekly, monthly, or seasonal variations but these technologies are currently either under development or cost prohibitive.[5] What is really needed in areas with high renewable penetration are non-emitting technologies with flexible operations. Carbon capture and storage from fossil fueled power plants provides one option, especially the Allam Cycle natural gas technology that has the potential for 100% CO_2 capture.[6] However, relatively high carbon capture costs and the development and permitting of a network of pipelines to transport captured CO_2 pose challenges.

Advanced nuclear technologies are often left out or not fully recognized as complementary options for renewable energy, yet advanced nuclear reactors provide another promising carbon-free energy option to consider in multiple applications. When policymakers and modelers think of nuclear technologies, they generally think of large expensive power plants that provide mostly baseload power. New, smaller, and/or modular reactor designs, either alone or paired with thermal energy storage, promise to provide flexible operations that will be crucial for electric grids with high variable renewable generation. In addition, heat and steam produced by nuclear plants can be used to make clean hydrogen or other carbon-free fuels that could be used as a substitute for fossil fuels in many applications. Nuclear power could also be used directly for desalination or process heat for manufacturing processes.

Policymakers have long used analyses based on computer simulation models to inform their deliberations of potential new policies and decisions about public investments including RD&D so it is critical that these tools and their characterization of technologies stay up-to-date and reflect each technology's diverse benefits. It is clear that meeting the challenge of climate change will require multiple technology options and all should be fully considered in these modeling tools. A recent NIA review of 15 high-profile deep decarbonization modeling studies published since 2016 concludes that

[5] For more information about long duration storage, visit https://news.energysage.com/long-duration-storage-what-you-need-to-know/.

[6] For more information about the Allam Cycle technology, visit https://netpower.com/.

those studies generally fall short of characterizing the full range of advanced nuclear capabilities.[7] Most of those studies model nuclear reactors that resemble traditional reactors, namely large, inflexible, non-modular, and single-use reactors with high capital costs.

This paper examines the many ways that nuclear energy, including advanced nuclear reactors, can play a significant role in meeting climate goals and will make a case for energy modelers to consider incorporating characteristics and applications for advanced reactors into their energy system models. Assumptions that modelers and decision-makers should re-examine in model structures will be described, as well as a discussion of the need for more comprehensive structural model changes to represent new ways of modeling uncertainty, accounting for dynamics and feedback within markets, and interdependencies with other infrastructures and risks. Both the challenges and opportunities related to modeling new nuclear technologies and their potential applications will also be discussed.

Advanced reactor technologies

A wide variety of new advanced nuclear reactor designs are at various stages of development, and all of them have advantages over existing designs. These new designs have a smaller footprint or land requirement than conventional nuclear plants, and many use different moderators, coolants, and types of fuel than traditional light water reactors.

There are three main categories of advanced reactors:

- Advanced Water-Cooled Reactors offer many advantages over conventional light-water reactors, including inherent safety features, smaller size, and modularity;
- Advanced Non-Water-Cooled Reactors use alternative fuels and coolants such as gases, liquid metals, or molten salts instead of light water;
- Fusion Reactors fuse atomic nuclei to produce energy vs. fission reactors that split atomic nuclei to produce energy. (Fission reactors make up all of the existing commercial reactors and a majority of new designs.)

Many advanced reactors are Small Modular Reactors (SMRs), which are defined by the U.S. Department of Energy (DOE) as reactors that are typically less than 300 MW and can be built using modular construction techniques. Additionally, there is another category of SMRs that are called Microreactors and these range from 1 – 20 MW in size.[8]

Different reactor designs are at different stages of maturity. For example, U.S. company NuScale Power has developed a 77 MWe reactor module using a light water SMR design that will be built at the Idaho National Laboratory. NuScale has cleared several hurdles in Nuclear Regulatory Commission (NRC) licensing processes and plans to begin operations in the late 2020s.[9] The U.S. DOE's Advanced Reactor Demonstration Program (ARDP) has awarded funding to several companies with reactor designs in various stages of development, with the goal of helping private industry demonstrate a variety of reactor concepts. Two of these companies, TerraPower and X-energy, were awarded funds to build

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[7] Luke, Max, "Deep Decarbonization Models Miss the Mark on Advanced Nuclear," forthcoming blog by Highland Energy Analytics, LLC written for the Nuclear Innovation Alliance, August 2021.

[8] Congressional Research Service, "Advanced Nuclear Reactors: Technology Overview and Current Issues," R45706, April 18, 2019.

[9] For more information about NuScale and its SMR technology, visit https://www.nuscalepower.com/.

demonstration projects that will commence operations in the next seven years. TerraPower's Natrium technology uses a sodium fast reactor combined with molten salt storage, and X-energy is developing a high temperature gas-cooled reactor.[10] More information about advanced reactor designs and their improved characteristics over conventional reactors can be found in the Nuclear Innovation Alliance (NIA) "The Case for Advanced Nuclear Energy" on the NIA website.[11]

Representing nuclear energy in climate and energy models

As abstractions of the real world, climate and energy-economic models provide analytical tools that can be used to explore potential outcomes of policies and investment decisions designed to achieve objectives such as reducing greenhouse gas (GHG) emissions from the energy sector. Models are used to assess the feasibility of technology pathways to decarbonize energy systems, the relative costs of different pathways and, in many cases, the various risks and uncertainties associated with different technology investments.

Energy models vary across a broad spectrum of geographic scope, economic sector coverage, and temporal resolution. In general, the wider the scope, the more aggregate the models must become. For example, integrated assessment models (IAMs) that generally project global emissions across all economic sectors for a century or more contain relatively aggregate representations of electricity generating technologies. On the other end of the spectrum, utility planning models focus on company assets and may contain hourly resolutions for a single year and focus on power plant operations, or may cover a 20- to 30-year planning horizon and include power plant capacity decisions as well as operations. The models of primary interest in this paper are those focused on the U.S. energy economy that are used to assess potential public policy, for example models like the U.S. Energy Information Administration's National Energy Modeling System (NEMS).[12] These models generally contain detailed representations of the electricity sector, along with other energy supply and demand sectors. As these models are applied to the tremendous challenge of exploring pathways to reduce GHG emissions, many of them are currently undergoing significant enhancements to incorporate new, emerging technologies that can be used to meet stringent policy goals, so this is a good time for modelers to consider the unique features of advanced nuclear reactors within their modeling tools.

A Nuclear Innovation Alliance review of 15 high-profile deep decarbonization modeling studies published in the past five years assesses the characterization of advanced reactor capabilities in each of those studies.[13] The review assesses whether the modeling parameters in each study are consistent with advanced reactor characteristics. Those technology characteristics and modeling parameters are summarized in Table 1. The review concludes that most models fall short of characterizing the full range

[10] U.S. Department of Energy news releases obtained from their website on May 10, 2021, https://www.energy.gov/ne/advanced-reactor-demonstration-program
[11] See https://www.nuclearinnovationalliance.org/
[12] NEMS is used by EIA to produce the Annual Energy Outlook that projects the evolution of the U.S. energy system over the next 20 to 30 years. EIA also uses NEMS for responding to Congressional requests concerning potential impacts of energy policies and technologies. For more information about NEMS, visit https://www.eia.gov/.
[13] Luke, Max, "Deep Decarbonization Models Miss the Mark on Advanced Nuclear," forthcoming blog by Highland Energy Analytics, LLC written for the Nuclear Innovation Alliance, May 2021.

of advanced nuclear capabilities. For example, just four studies model non-zero ramp rates[14] and the remainder either assume a fixed power production profile or do not indicate otherwise. Seven studies assume average new nuclear capital costs of more than $6,000/kW and only a single study assumes a capital cost lower than the average anticipated for commercial advanced nuclear designs. Only a single study models the use of nuclear energy in industrial heating and just two studies model the use of nuclear energy in hydrogen production.

Table 1: Summary of advanced nuclear characteristics and relevant modelling parameters

Category	Advanced nuclear characteristics	Relevant modelling parameters
Load following and flexibility	● Advanced nuclear designs include several characteristics that enable load following and flexibility: ○ Changes in reactor power output ○ Shutting off smaller reactors within larger facilities ○ Thermal heat storage with molten salts (e.g., Natrium) ○ On-site battery storage ○ Hydrogen or other co-product production	● Maximum ramping capability (% rated power/ hour) ● Minimum stable output (% rated power) ● Minimum up-time / down-time (hours) ● Start-up cost ($ / MW rated power)
O&M improvements	● With automation and improved materials, advanced reactor designs could have lower fixed and variable O&M costs compared to conventional reactors	● Fixed O&M ($/kW-year) ● Non-fuel variable O&M ($/kWh) ● Fuel cost ($/mmBtu)
Scaling and technological learning	● Advanced reactor power ratings vary greatly from 1.5 MWe to >1 GWe ● Construction times for advanced nuclear units are expected to be shorter than conventional units ● Advanced designs are likely to reach n^{th} of a kind (NOAK) more quickly than conventional designs ● Technological learning and capital cost reductions are likely to be faster than conventional designs	● Construction time (years) ● Capital cost ($/kW) ● Economic/useful life (years)
Refueling cycles	● Typical conventional reactors refuel every 18-24 months, with concurrent maintenance activities, contributing to capacity factors of 90-95 percent ● Many advanced reactor designs refuel less frequently if at all, contributing to potential capacity factors of 95-100 percent	● Scheduled outage rate (%) ● Capacity factor (%) ● Reactor core lifetime
Nuclear for diverse applications	● Advanced nuclear energy can be used for non-electric applications including district heating, cogeneration, industrial heating, hydrogen production, and desalination ● Coal facilities could be repowered with advanced reactors ● Microreactors can provide energy for microgrids and make nuclear power a distributed energy source for the first time	● Multiple nuclear technologies modeled ● Nuclear energy modeled as input to non-electric applications ● Repowering modeled

[14] The increase or reduction in output per minute

Modeling improvements in existing nuclear plants

In addition to modelers assessing their representations of advanced reactors, it is worth revisiting the characterization of existing nuclear plants. In particular, many models restrict how existing nuclear power plants are able to meet electricity load as it fluctuates by hour and by season.

Nuclear energy provides a much larger share of generation in many European countries than in the United States, which makes the need for nuclear facilities to provide load following (defined here as the ability to operate at different levels of output over the course of a day or a season) even more crucial to balancing the supply and demand of electricity. In France, for example, nuclear energy has provided flexible operations for more than 30 years, including load following and frequency control services required for grid stability, without any significant impact on reactor safety or maintenance costs. Electricité de France (EDF) uses a number of different techniques in its pressurized water reactors (PWRs) to provide flexible nuclear power, including using "grey" control rods and other materials specially designed to increase flexibility.[15] Germany also has built-in features in its plant designs, including PWRs and boiling water reactors (BWRs), to accommodate flexible operations, and Belgium facilities provide automatic primary frequency control services.[16]

In the United States, nuclear plants have been prevented from operating with automatic generation control (AGC) by U.S. Nuclear Regulatory Commission (NRC) policy but are allowed to load follow on a manual basis.[17] Many existing reactors are capable of load following; however, economic factors and the dynamics of regional energy markets limit the financial incentives to provide load following services. For instance, the original licensing basis of all Westinghouse PWRs includes and allows for load following; however, generally these plants operate most profitably when operating at full capacity in all hours of the day. It is also important to note that the operational flexibility that can be achieved with existing nuclear technologies, measured as the speed in which technologies can ramp power output up or down to match grid demand, is less than what natural gas technologies can provide, as shown in Table 2.[18]

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[15] Morilhat, Patrick, Stéphane Feutry, Christelle LeMaitre, Jean Melaine Favennec, "Nuclear Power Plant Flexibility at EDF," HAL Id: hal-01977209, preprint submitted on 23 Jan 2019.

[16] POWER, "Flexible Operation of Nuclear Power Plants Ramps Up," https://www.powermag.com, April 1, 2019.

[17] Jones, Donald," Can nuclear power plants deliver on all the attributes U.S. energy secretary Rick Perry claims" The Don Jones Articles, 10/11/2017.

[18] Clean Energy Ministerial, "Flexible Nuclear Energy for Clean Energy Systems," NREL/TP-6A50-77088, September 2020.

Table 2: Load Following Capabilities of Existing Nuclear Reactors Compared to Other Dispatchable Technologies

	Startup Time	Maximal Change in 30 sec	Maximum Ramp Rate (%/min)
Open cycle gas turbine	10-20 min	20%-30%	20%/min
Combined cycle gas turbine	30-60 min	10%-20%	5-10%/min
Coal power plant	1-10 hours	5%-10%	1-5%/min
Nuclear power plant (current technologies)	2 hours – 2 days	Up to 5%	1-5%/min

Source: Clean Energy Ministerial, "Flexible Nuclear Energy."

Modeling the attributes of advanced reactors

As discussed, advanced reactor designs incorporate many features and have unique properties that are improvements over traditional light water reactors. These features and improvements, however, can be challenging to represent in most energy-economic modeling used for climate change analyses. Several advanced nuclear characteristics can be incorporated through modifying model parameters while others may require more structural model modifications.

Following are a few key features and some ideas for incorporating them into these models:

Load following and flexibility

As discussed above, the ability to load-follow and provide flexible grid operations will be critical to the acceptance and value of advanced reactors. This key attribute of advanced nuclear reactors is becoming increasingly important in grid systems with high levels of variable renewable generation. Typically this is referred to as the ability to load follow, although generators increasingly need to follow net load (i.e., load net of renewable generation) rather than total load.

The Electric Power Research Institute (EPRI) developed a framework for evaluating the flexibility attributes of these advanced reactor designs; the framework is summarized in Table 3. The attributes are grouped into three categories: operational flexibility, deployment flexibility, and product flexibility. The EPRI analysis determined that advanced nuclear reactors could provide many of the benefits included in all three of these categories.[19]

Most models, NEMS included, assume that nuclear generators must run at close to full capacity and cannot be ramped up and down very quickly if at all. Depending on model structure, this can be remedied relatively simply by either increasing the ramp rates, decreasing the minimum load conditions

[19] Clean Energy Ministerial, "Flexible Nuclear Energy."

and/or changing the operating modes.[20] In the case of NEMS, the minimum load levels could be decreased and the operating modes for advanced reactors could be modified to be more like coal plants. With more flexibility, nuclear generators can not only provide power when renewable sources are not available, they can also provide operating reserves, such as spinning or non-spinning reserves,[21] that increase reliability in case of outages. This should be considered in models that explicitly represent these reserve requirements.

Table 3: Flexibility Attributes for Evaluating Advanced Reactor Designs

Main Attribute	Sub-Attribute	Benefits
Operational Flexibility	Maneuverability	Load following
	Compatibility with Hybrid Energy Systems	Economic operation with increasing penetration of variable generation, alternative missions
	Diversified Fuel Use	System resiliency, remote power, microgrid, emergency power applications
	Island Operation	Economics and security of fuel supply
Deployment Flexibility	Scalability	Ability to deploy at scale needed
	Siting	Ability to deploy where needed
	Constructability	Ability to deploy on schedule and on budget
Product Flexibility	Electricity	Reliable, dispatchable power supply
	Industrial Heat	Reliable, dispatchable process heat supply
	District Heating	Reliable, dispatchable district heating supply
	Desalination	Reliable, dispatchable fresh water supply
	Hydrogen	Reliable, dispatchable hydrogen supply
	Radioisotopes	Unique or high demand isotopes supply

Source: Clean Energy Ministerial, "Flexible Nuclear Energy."

[20] In NEMS the operating modes are defined for nuclear and fossil generators to represent their operational flexibility. For example, only combustion turbines are assumed to be able to operate exclusively in peak hours. Other generators must also operate at least at their minimum load conditions in other periods in order to be able to operate during peak hours. This reflects that steam generators require significant time to ramp up to full capacity. Nuclear plants currently are assumed to have the most restrictive operating modes.

[21] Spinning reserves are provided by power plants that are running at partial load and can ramp up quickly when needed, while non-spinning reserves include quick-start plants that can be started up rapidly. Both are needed by power systems to continuously meet varying loads. Many models explicitly represent these requirements.

Lower capital and operating costs

The most obvious and important technology attributes in most energy models of interest are capital and operating costs that are explicit inputs. Modelers and model users should examine the latest research to update their cost estimates as more information becomes available about new reactor designs rather than rely on data from recent projects using older designs. Advanced reactor capital costs are expected to decline over time due to government and private R&D efforts as well as through learning-by-doing in which industry experience in manufacturing and construction leads to cost reductions.[22] Models generally either assume a fixed path of cost reductions over time, regardless of deployment, or assume most or all cost reductions are driven by learning-by-doing. Ideally, both effects should be incorporated. Similarly, O&M costs are often assumed to have fixed values over time, but these too may decline over time as factors including automation and improved materials, reliability, logistics, and supply chain management are incorporated.[23]

Smaller size and modularity

Many advanced reactor designs focus on smaller sizes to reduce upfront investment costs and expand the number of locations where nuclear plants can be built. The smaller footprint allows these plants to be sited in areas never considered for large conventional plants, such as next to an industrial facility or as part of a microgrid. SMRs also have the advantage of using modular construction techniques, such as pre-fabrication of major components that can be shipped to the plant site, and standardized designs which can further reduce construction costs and lead times. The added benefit of standardized reactor designs is that they allow for NRC certification of a single design only once, and then the same certified design can be used at multiple sites. Site-specific reviews are still necessary for construction and operation, but a certified design can ease these reviews. While the smaller size of the SMRs may prevent some economies of scale for individual plants, the modularity of SMRs may enable economies of production for components.

Both the smaller sizes and the modular designs also allow for scaling of reactor sizes to meet customer power needs and site limitations, and they provide more flexibility in the face of uncertain load growth. Finally, by building plants one module at a time, it is possible to operate the first module and earn revenue while building the additional modules.[24]

The shorter construction time and modularity of SMRs and other advanced reactors should be adopted in models where construction times are explicitly represented. In models like NEMS, shorter construction times lead to lower total investment costs because interest during construction is reduced as financial returns are able to begin sooner than with the traditional longer construction times of conventional nuclear plants. Most models do not explicitly represent regulatory approval and site construction times, except perhaps through a parameter indicating the first online year feasible, but delays can have financial consequences for developers.

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[22] Nuclear Energy Agency, Organisation For Economic Co-Operation And Development, "Unlocking Reductions in the Construction Costs of Nuclear: A Practical Guide for Stakeholders," 2020.

[23] Nuclear Energy Agency, 2020.

[24] Congressional Research Service, "Advanced Nuclear Reactors: Technology Overview and Current Issues," R45706, April 18, 2019.

Because many models, including the electricity module of NEMS, assume perfect or near-perfect foresight about electricity demand growth, the value of shorter licensing and construction times (along with smaller size units) that lower the risk associated with uncertain demand is not represented. Representing the advantages of this smaller size and modularity of advanced reactors may require more fundamental model modifications to reflect uncertainty and market reactions to capacity investment. These more structural issues are discussed below.

Less frequent refueling

Many advanced reactors are designed to use fuel more efficiently or can recycle used nuclear fuel that has been reprocessed.[25] Either approach can reduce the volume of nuclear waste produced. Efficient fuel use will also reduce the frequency of refueling, which often requires lengthy scheduled outages. Some reactors will be able to perform "online" refueling, meaning that the reactor can be refueled without needing to shut down, and other reactors may not need to refuel at all during their lifetime. Shorter or fewer scheduled outages lead to lower maintenance costs and higher availability for these facilities.

While finding an appropriate long-term solution for used nuclear fuel is still a challenge, Finland has begun construction of a long-term geological repository for used nuclear fuel. The project is expected to be completed by 2023 and could be a model for other nations that use nuclear energy.[26]

The longer refueling cycles of advanced reactors compared to traditional reactors translate into shorter planned maintenance periods and higher availability in climate solution models. As a result, there are more opportunities for selling power or supplying operating reserves that will make these technologies more cost-effective. Outage assumptions are usually user-specified technology parameters in models that should be re-examined for advanced nuclear representation.

Inherent safety features

Reactor safety issues, both perceived and real, of nuclear energy play a role in the investment and operation decisions of the plant.[27] Many advanced reactor designs have inherent or passive design features to ensure safety. For example, some advanced reactors may locate key reactor components in a pool of water or may incorporate other methods to dissipate heat that do not rely on pumps or other active systems.[28] In addition, the chemical properties of some of the coolants used in other advanced designs are inherently safer than light water. One example is molten lead used in lead-cooled reactors. Molten lead is relatively inert and has a high rate of retention of radioactive fission products that may prevent them from being released into the atmosphere in case of an accident. However, these safety features will need to be demonstrated on a commercial scale.[29]

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[25] Nuclear Innovation Alliance (NIA), "The Case for Advanced Nuclear Energy," March 2021.
[26] Forbes, "Finland Breaks Ground On World's First Deep Geologic Nuclear Waste Repository," May 31, 2021.
[27] Deutch, J., Kanter, A., Moniz, E., & Poneman, D. (2004). Making the world safe for nuclear energy. Survival, 46(4), 65-79.
[28] Congressional Research Service, "Advanced Nuclear Reactors."
[29] Ibid

Most economic energy system models do not expressly address safety risk of technologies. To the extent that modelers have introduced proxies to represent the safety risks of nuclear technologies, these proxies should be updated to reflect the inherent safety characteristics of advanced reactors. Probabilistic or robust optimization models can endogenously account for risk factors within optimization problems,[1] but these models are computationally expensive. Given the application of energy system models for broad policy analysis, rather than specific site planning, and the inherent safety features of advanced reactors, it does not seem necessary to use these more sophisticated modeling techniques to account for energy technology safety considerations. There may, however, be merit to the application of these modeling techniques for other financial and performance risks unrelated specifically to nuclear power.

Regional Applicability

Some states have enacted policies that restrict the construction of new nuclear capacity.[30] The rationale is often based on concerns about the lack of a permanent nuclear waste disposal site and/or perceived financial and environmental risks of nuclear energy. The advantages of advanced nuclear reactors including smaller capacity size, improved fuel efficiency, and expected greater financial attractiveness along with the pressing concerns of climate change may lead states to reconsider these policies. A few have already done so.[31]

To reflect these existing state policies, many models incorporate state or regional restrictions on siting nuclear plants. These should be reconsidered for advanced reactors, especially for SMRs, in anticipation of potential changes in policy as these reactors enter the market especially when models are used for climate mitigation scenarios. Critically, it is important to recognize that many state restrictions are not outright prohibitions (e.g., they may just require state legislature approval); modelers should recognize this nuance. In addition, modelers should annually review these state policies, just as many do regarding state Renewable Portfolio or Clean Energy Standards.

Diverse applications for advanced reactors

Future nuclear facilities will have many of the attributes described above that will make them suitable for use in many different applications, not only for electricity production but also for hydrogen production, industrial processes, district heating, energy storage, desalination, and many other applications.

Hydrogen Production

Hydrogen itself is a carbon-free energy-dense fuel and, depending how it is produced, can be carbon-free on a lifecycle basis. Hydrogen can replace fossil fuels in the power sector but also in industrial processes that require heat and steam and in transportation-related industries such as aviation fuel and heavy shipping. One of the drawbacks of hydrogen fuels is the large amount of energy required to produce them. Although many people have discussed using renewable energy to produce hydrogen, wind and solar power's low capacity factors and large land requirements increase costs and limit the

[30] National Conference of State Legislatures, "States Restrictions on New Nuclear Power Facility Construction," 5/19/2017.
[31] National Conference of State Legislatures, 2017.

amount of hydrogen that can be produced, especially if renewables are also needed for grid electricity in order to decarbonize the power sector.[32] Using a high capacity factor energy source, like nuclear power, to produce carbon-free hydrogen can result in lower production costs and greater volumes of hydrogen without the drawbacks of using renewable energy for this process. For example, Arizona Public Service Co. is working with the U.S. Department of Energy to produce hydrogen at its Palo Verde nuclear plant for use as a carbon-free alternative fuel in its natural gas plants.[33]

Most advanced reactor designs employ higher operating temperatures than existing light water reactors. Higher temperatures improve thermal efficiencies, making these reactors well suited for providing heat for industrial processes and hydrogen production. Advanced reactors can also be built as SMR's to match the thermal needs of potential industrial customers.[34]

Many energy models are being enhanced to incorporate various hydrogen pathways and should include advanced nuclear technologies among the technology options. Depending on the model, hydrogen production may be represented by low temperature electrolysis using electricity from the grid (solar/wind/nuclear) or pairing electricity with a dedicated heat source, such as nuclear energy, to produce hydrogen through high temperature electrolysis. In addition, the economies of joint production of electricity for consumer demands and for hydrogen production should be considered. The technology suite should also be expanded beyond electrolysis and steam-methane reforming options to include long-term technology pathways like thermo-chemical water splitting using heat from high-temperature nuclear reactors.

Other Complementary Applications

Employing both the power and heat produced by a nuclear plant in complementary applications can improve its efficiency and operating performance by allowing the plant to operate at full capacity and avoid the need for flexible operations during periods of high renewable generation as well as providing an additional revenue stream. In addition to hydrogen production, excess power and heat can be used for industrial processes, district heating, or desalination.[35] Another method of providing flexible operations is to pair nuclear with electricity storage. A recent DOE report highlights several different storage options that may pair well with nuclear energy including battery storage, compressed air energy storage (CAES), and thermal storage options such as molten salt or hot- and cold-water storage tanks.[36]

Electricity models often restrict themselves to supply and demand for electricity and do not incorporate non-electric energy benefits of power generation technologies such as resilience, blackstart capabilities, and local economic benefits. Incorporating these benefits either requires quantifying them exogenously (i.e., developing parameters outside the model), or endogenously accounting for their placement close

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[32] Ingersoll, Eric and Kirsty Gogan, "Missing Link to a Livable Climate: How Hydrogen-Enabled Synthetic Fuels Can Help Deliver the Paris Goals," LucidCatalyst, September 2020.

[33] Potter, Ellie for S&P Global Market Intelligence, "'Not bonkers': Hydrogen could give US nuclear plants new lease on life," April 05, 2021.

[34] Ibid

[35] International Atomic Energy Agency (IAEA), "Non-Baseload Operation in Nuclear Power Plants: Load Following and Frequency Control Modes of Flexible Operation," IAEA Nuclear Energy Series No. NP-T-3.23, 2018.

[36] Coleman, Justin, Shannon Bragg-Sitton, Ph.D., and Eric Dufek, Ph.D., "An Evaluation of Energy Storage Options for Nuclear Power," Idaho National Laboratory, INL/EXT-17-42420, June 2017.

to industrial locations. Such benefits can also be applied to district heating and cogeneration. Better modeling of interdependent infrastructures can help quantify the benefits of advanced reactors as well.

A fundamental approach would be to build the co-benefits and spatially distributed energy supply sources within the modeling frameworks during the initial model design, rather than attaching these considerations to already existing power models in an adjunct manner. In existing integrated energy models, such as NEMS, an incremental approach would be to include microreactors in the industrial sector in a similar manner as natural gas cogeneration is represented currently. Heat is used to meet steam demands, and electricity can be either used within industry or sold to the grid depending on the amount produced relative to demand. Given the high temperatures associated with some advanced reactor designs, it is likely that they could provide carbon-free heat for various industrial processes as well, especially in industries where electrification is not applicable. This may require more detail in the representation of industrial processes in models in order to properly account for the variety of heating sources and applications.

Potential Model Modifications and Challenges

Modeling future energy scenarios that transition to a low-carbon economy requires advances that complement but also go beyond the challenges in modeling advanced reactor characteristics using parameter changes alone. For example, representing uncertainty, reliability, risk, externalities, and variability are challenges associated with many future energy modeling scenarios.[37] These challenges are discussed below along with some recommendations on how modelers might overcome them when modeling advanced reactors.

A key characteristic that is often overlooked in modeling advanced nuclear reactors is the smaller size and modularity of these reactors.[38] The smaller modular size when evaluated from a traditional energy lens tends to be a disadvantage with regard to capacity when compared to larger reactors due to diseconomies of scale.[39] However, the smaller modular size has advantages as outlined in the earlier section of this paper such as reduced financial risk, greater facility in matching load growth, increased efficiency of co-location with industrial heat demands, and economies of manufacturing of modular components. To account for these and other attributes of advanced reactors, energy models must overcome two fundamental challenges: how they represent uncertainty and how they represent market reactions to capacity investment.[40] This latter issue of market risk applies especially to new technologies including advanced reactor technologies because of their lack of market experience.

First, given the future uncertainty of our energy mix and the policies and energy markets that will influence it, large investments in any energy generation technology, especially newly emerging technologies, pose greater risks than smaller investments. Most current energy models do not model this uncertainty and are thus unable to quantify the benefits of smaller capital costs on risk

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[37] Pfenninger, S., Hawkes, A., & Keirstead, J. (2014). Energy systems modeling for twenty-first century energy challenges. Renewable and Sustainable Energy Reviews, 33, 74-86.

[38] Mignacca, B., & Locatelli, G. (2020). Economics and finance of Small Modular Reactors: A systematic review and research agenda. Renewable and Sustainable Energy Reviews, 118, 109519.

[39] Locatelli, G., Bingham, C., & Mancini, M. (2014). Small modular reactors: A comprehensive overview of their economics and strategic aspects. Progress in Nuclear Energy, 73, 75-85.

[40] Gollier, C., Proult, D., Thais, F., & Walgenwitz, G. (2005). Choice of nuclear power investments under price uncertainty: valuing modularity. Energy Economics, 27(4), 667-685.

minimization. Incorporating this uncertainty is not easy, as it requires both computational effort and assumptions about the type of uncertainty. One solution to overcome this challenge is to use a stochastic optimization model to value the advanced reactor under uncertainty.[41] However, this method is often computationally expensive and requires formulating an uncertainty distribution, which introduces further assumptions into the modeling as well as increasing the degrees of freedom. Another workaround could be to use a measure such as conditional value at risk (cVAR) within deterministic models to quantify the value of the risk associated with investment.[42] However, this often simplifies future scenarios, and does not endogenize the uncertainty within the modeling framework. There are other ways of valuing the investment in advanced reactors given future uncertainty, and it might be that different scenarios require different methodologies.

The second modeling challenge pertains to anticipating the market reaction to the entrance of advanced reactors. Often, new technologies with characteristics that are desirable but different from what is already in the market can find a particular niche that disrupts traditional market dynamics. This type of effect was seen during the shale gas boom and was expected of cellulosic biofuels. However, the investment decisions for these new technologies are not just constrained by their own physical characteristics, but also constrained by how the market will react to them. Smaller, modular reactors, along with other smaller-scale generation technologies, could catalyze a significant shift to decentralized power production. Most energy models are based on a central power paradigm that represents distributed generation as limited niche markets. Representing structural market changes endogenously within models is extremely challenging. One possibility is to construct the capability for a distributed system and explore the implications through alternative scenarios.

Summary of recommendations for future modeling

In summary, to account for the characteristics of advanced reactors, there are some relatively simple changes in assumptions that can be made in current model structures, especially those focused on the role of nuclear energy in power generation. Key assumptions to re-examine include capital and operating costs, construction lead times, financial risk factors, and siting restrictions. Parameters and model structures that determine the flexibility of nuclear operations should also be modified to reflect these capabilities in advanced nuclear technologies, as well as existing reactors, although these modifications will vary by model type.

To address the full scope of advanced nuclear characteristics and benefits, energy modelers will need to explore new ways of modeling uncertainty, accounting for dynamics and feedback within markets, and interdependencies with other infrastructures and risks. While individual tools exist in the modeling toolbox to account for these issues, applying them to advanced reactors can be difficult because of computational burden and additional assumptions. Further, incorporating all these individual modeling advances collectively is a much larger challenge. Overcoming these challenges will require systematic model advancement and careful calibration while balancing computational tractability and the number of independent variables.

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[41] Kuhn, D., Parpas, P., & Rustem, B. (2008). Stochastic optimization of investment planning problems in the electric power industry. Process systems engineering, 5.

[42] Fortin, I., Fuss, S., Hlouskova, J., Khabarov, N., Obersteiner, M., & Szolgayova, J. (2008). An integrated CVaR and real options approach to investments in the energy sector. The Journal of Energy Markets, 1(2), 61-86.

Representing non-power applications of advanced nuclear reactors is also important for analyzing economy-wide deep decarbonization goals. Hydrogen production options should include electricity from nuclear power and ideally take into consideration the use of heat as well as production by high temperature electrolysis. SMRs have the potential to reduce emissions from the industrial sector by providing distributed generation as well as heat and should be included in future mitigation scenarios.

Next Steps

Policy makers are making important choices that will influence the transition to a climate-friendly energy system. Improving energy models to represent a broader range of potential carbon-free technologies, including advanced nuclear reactors, in a realistic manner with a more complete representation of their key characteristics is essential for providing sound analysis to these decision makers. Now is the time for modelers to reassess how nuclear technologies are represented in their models, especially given recent advances in these technologies, in both the power sector as well as other potential applications.

Modelers can reach out to NIA to learn more about the characteristics of advanced nuclear technologies including downloading their Primer here [https://www.nuclearinnovationalliance.org/advanced-nuclear-reactor-technology-primer]. Participating in modeling workshops and comparison exercises such as those conducted by the Stanford Energy Modeling Forum (EMF) are an effective way to collaborate with other modelers to share best practices for representing new technologies such as advanced reactors. The Energy Information Administration (EIA) has sponsored information sessions for modelers as well, such as a recent one on representations of variable renewable energy in capacity expansion models,[43] as well as sessions with broader audiences such as a workshop on electricity storage[44] These workshops and information exchanges work best when they bring together market participants, subject matter experts, and policy analysts in addition to modelers. We recommend that EIA, the DOE Office of Nuclear Energy, and other interested parties consider sponsoring advanced nuclear modeling workshops that would benefit the energy modeling community through direct participation as well as dissemination of a paper summarizing the proceedings.

All of these options are important methods for sharing ideas and techniques for improving the representation of advanced reactors in energy system models so that these technologies are fully represented in analyses that inform the climate change policy debate.

[43]Electric Capacity Expansion Modelling Workshop: Treatment of Variable Renewable Energy, July 11, 2016, https://www.eia.gov/renewable/workshop/)

[44] EIA Energy Storage Workshop, July 16, 2020 https://www.eia.gov/electricity/workshop/batterystorage/