1 Introduction

The world is demanding more clean energy across the electricity, industrial, and transportation sectors. This is evident in many regional, national, and organizational clean energy goals that have been established (Benahmed and Walter 2019). Meeting clean energy goals will require leveraging all of the clean energy sources available, including emissions-free dispatchable and variable sources, as well as large-scale energy storage and transmission upgrades.

The purpose of this report is to explore the potential roles of flexible nuclear energy generation in current and future clean energy systems. These systems will inherently require greater flexibility to accommodate the increasing contributions from variable renewable generation sources. This report brings together analysis from different parts of the globe to quantify the need and value of flexibility in diverse clean energy systems. This effort aims to provide a foundation for further research on groundbreaking capabilities in flexible nuclear systems to interested Clean Energy Ministerial (CEM) countries. For the purposes of this report, flexible nuclear energy is defined as:

"The ability of nuclear energy generation to economically provide energy services at the time and location they are needed by end-users. These energy services can include both electric and nonelectric applications utilizing both traditional and advanced nuclear power plants and integrated systems."

To realize a clean and resilient energy future, new patterns of energy generation, distribution, and use are emerging. Nuclear energy is the largest contributor to low-emissions electricity in advanced economies and totals 18% of total generation in 2018 in these countries as defined by the International Energy Agency (IEA) (IEA 2020a). The contribution from nuclear energy to clean electricity generation is even more significant in member countries of the CEM Nuclear Innovation: Clean Energy Future (NICE Future) initiative; however, the nuclear share of global electricity supply has been declining in recent years. The nuclear fleets are aging, many plants built in the 1970s and 1980s have been retired, and additions of new capacity have been limited.

Simultaneously, renewable energy technologies have been deployed in significant numbers around the world over the past decade. This includes growth in electricity generated by variable renewables such as wind and solar, and dispatchable renewables such as hydropower and geothermal resources. Despite expansion by all clean energy sources, including over 60 nuclear reactors currently under construction worldwide (IEA 2020a), global emissions only flattened in 2019, even as power sector emissions decreased (IEA 2020b). This suggests that additional work needs to be done to expand clean energy in the power sector and innovate technologies such as nuclear, wind, and solar, to provide energy services beyond electricity.

With the growing diversity of electricity sources, flexibility is a vital characteristic of reliable electricity systems, and may also provide value in serving nonelectric energy needs. Flexibility can be achieved in a number of ways on both the generation side and the use side. On the generation side, flexibility may entail ramping the power up or down to meet demand; energy may also be stored for later use, and used to produce alternative products such as thermal, electrical, or chemical energy, depending on the required time and power demand. On the use side, demand response approaches may be employed to shift demand when possible, thereby reducing peaks, slowing ramp rates, and limiting stress on the grid. The CEM NICE Future initiative's Flexible

Nuclear Campaign focuses on the potential roles of nuclear flexibility to supply both electric and nonelectric products for economy-wide flexibility needs.

In countries with substantial contribution from nuclear energy, nuclear power plants can be called on to reduce output at times to balance electricity supply and demand, following seasonal, weekly, and daily demand changes. Nuclear plants in France, for example, already have decades of experience in flexible operation due to the significant fraction of generation from nuclear energy (currently at approximately 70% but higher in previous years) (IEA 2019b). This high penetration of nuclear power requires plant output to be reduced at times in response to reduced demand.

Nuclear power plants operating in regions with significant hydropower generation, such as the Columbia Generating Station in the United States or the Bruce Nuclear Generating Station in Ontario, Canada, reduce power seasonally due to increased generation from hydroelectric sources in the spring. While this operating experience will be helpful to designers of next generation systems, it is important to note that the current driver for further increasing the flexibility of nuclear power systems—variable renewable generation—will require a very different dynamic response (e.g., response frequency and necessary magnitude of change may be significantly different).

2 Report Motivation and Structure

This report provides a broad overview of flexibility in energy systems and then focuses on a technology-specific context regarding how flexibility applies to nuclear energy. The report provides examples of experience in the flexible operation of nuclear plants. It also highlights important studies being conducted by participant countries and partners of the NICE Future initiative on modeling of the physical and economic value of flexible nuclear operation. Looking to the future, this report illustrates additional analytical work that, if conducted, could increase our understanding of the value of nuclear energy as a flexible energy resource. In particular, the report evaluates new revenue streams that could have a transformative impact for nuclear energy. This report features potential opportunities to expand international collaboration, showcased by our distinguished expert contributors. Our diverse contributors have shared specific ideas that can support the realization of a suite of flexible nuclear energy resources that can contribute to clean energy systems globally and can enhance the ability of nuclear energy and renewables to operate in greater harmony. As our contributors suggest, nuclear and renewables can be mutually enabling, and these two communities can learn from each other's technology approaches and experiences.

A purpose of the Flexible Nuclear Campaign is to explore opportunities to maximize nuclear innovations happening globally. This report begins by providing background information on flexibility in power systems generally, and in nuclear systems specifically. Subsequent chapters were provided external organizations to showcase perspectives, experiences, and analyses from partners of the NICE Future initiative.

3 Background of Power System Flexibility

Energy systems around the world are facing new operating constraints that did not exist a decade ago. As developing countries modernize, global energy demands are expected to nearly double while countries are simultaneously working to reduce emissions (UNDP 2018; IEA 2019a). The last decade has seen new generator technologies, such as wind and solar, emerge as cost competitive in the electricity sector. Sources like wind and solar energy have no fuel costs but are based on variable resources and require increased grid integration considerations to match their output to end-user loads. This chapter covers the changes in power systems resulting in greater flexibility in operations and then focuses on additional flexibility potential for nuclear power systems.

3.1 Trends in Flexibility in Power Systems

A major change occurring in the electric power sector is a shift away from a traditional base load model, where one generation source meets minimum system demand and is supplemented by fast-responding resources, toward a power system in which load is met by a diverse mixture of energy resources. Current trends suggest that the future grid is likely to include few base load operators that serve a minimum load all the time. Instead, trends suggest that a combination of “variable” and “dispatchable” resources will be used to reliably meet load (Chang et al. 2017). Such a combination is more complicated to operate but has the potential to be more reliable and affordable than current systems by optimally dispatching the least-cost generation technology when it is available. Figure 1 shows how grids have been operated historically using data from the Electric Reliability Council of Texas (ERCOT) and capacity expansion models. Historically, the grid has relied on base load operators that consume fuel to produce electricity (e.g., nuclear, fossil fuels), as roughly illustrated in Figure 1. When a large generation station fails in this configuration, the grid is subject to failure or to the requirement to bring on higher-cost generators. In modern grids, as demonstrated in Figure 2, Variable renewable energy (VRE) is being deployed rapidly, resulting in more variable production of electricity that is not synchronized to demand. Due to this mismatch, some generators can be curtailed. Depending on market structure, this can either be VRE, where energy is wasted, or more traditional generators such as nuclear reactors that are required to ramp down. (Dolley 2018). In either case, energy generation capacity is being wasted and overall system costs are increase. Figure 2 shows examples of these curtailments.

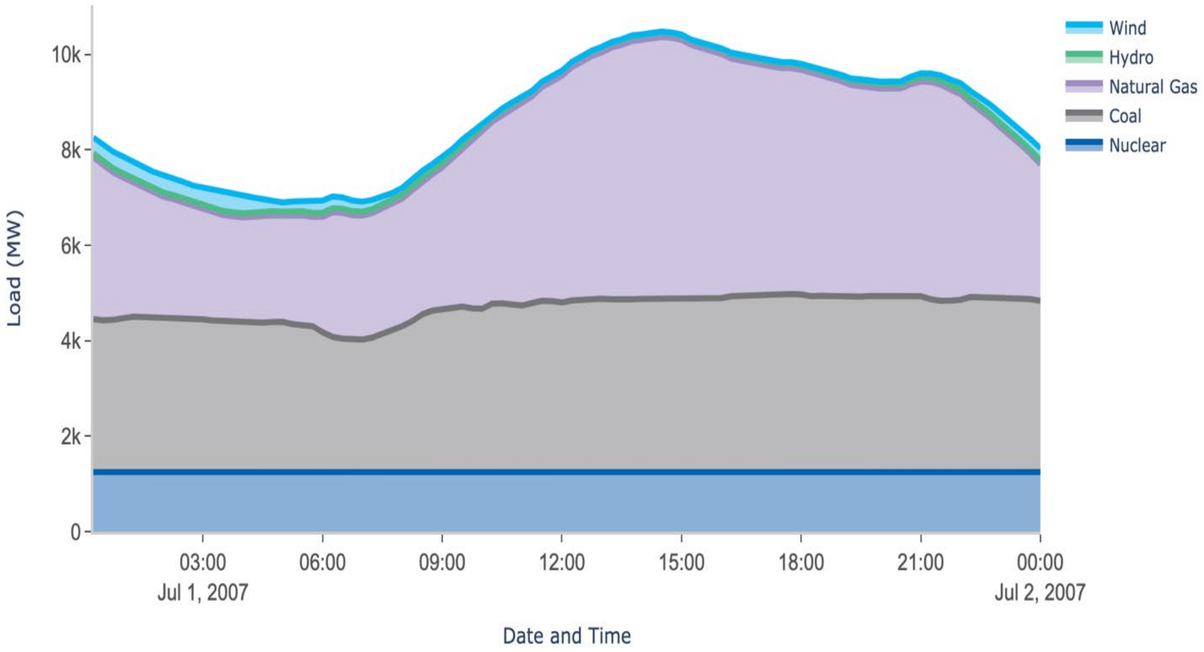

Figure 1. ERCOT generation by fuel source July 1, 2007

Source: (ERCOT 2020)

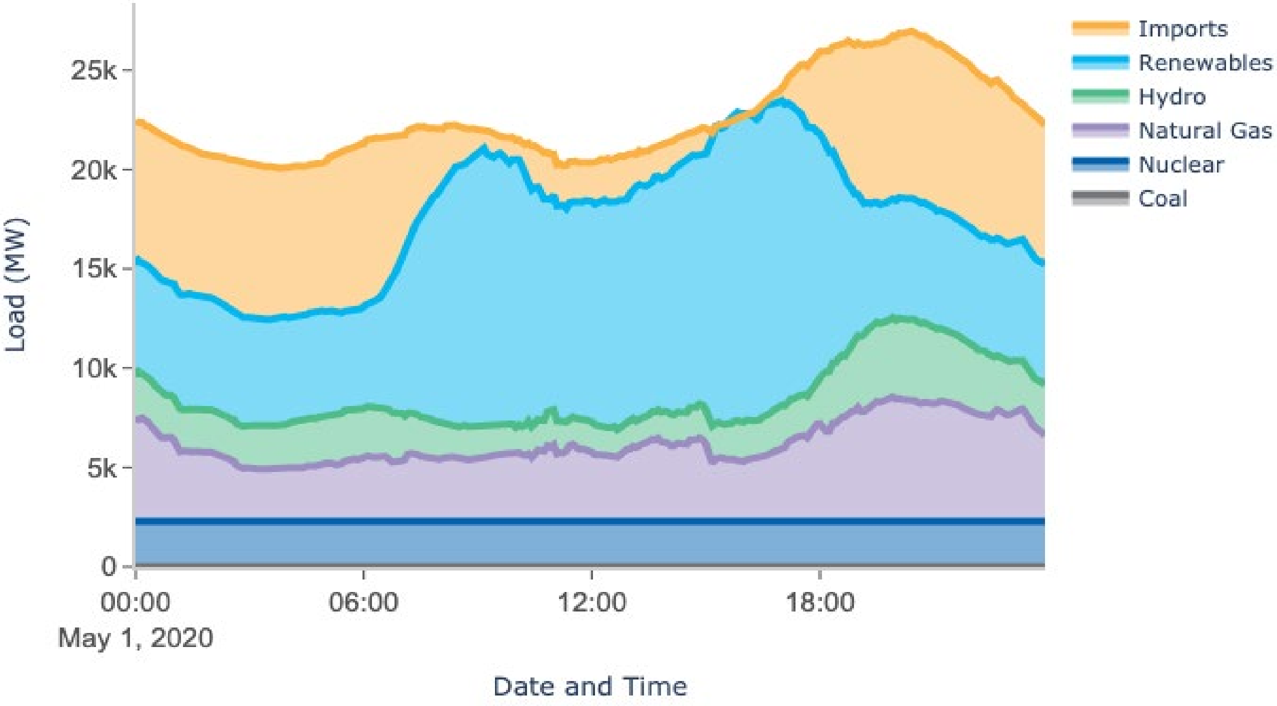

Figure 2. California Independent System Operator (CAISO) generation by fuel source May 1, 2020

Source: ("FERC: Documents & Filing - Forms - Form 714 - Annual Electric Balancing Authority Area and Planning Area Report - Data Downloads" n.d.)

3.1.1 Nonelectric Energy Services

The future grid is expected to incorporate flexible generators and loads while also providing economy-wide energy services to support high power system efficiency and reliability (Bragg-Sitton et al. 2016). This future scenario needs to move beyond the grid shown in Figure 2. It needs to incorporate nonelectric products to provide reliable electricity, high renewable energy penetrations, and economic compensation for dispatchable generators such as nuclear.

Today a majority of the energy generated by renewables (excluding technologies such as biomass, geothermal, and solar thermal) and nuclear generation technologies supports electricity demand. The transition to a more flexible energy system, for both electric and nonelectric applications, has the potential to create new value streams for all energy sources. While electricity is important, future nuclear energy systems could be designed to flexibly provide thermal and/or electrical energy to end uses when and where it is needed to realize the full potential of this low-emission, high energy-density resource. This creates a unique opportunity for the nuclear and renewable energy communities to build partnerships that expand energy services beyond the traditional electricity sector.

3.1.2 Sources of Power System Flexibility

Current electric power systems generally achieve flexibility via three mechanisms:

- Fast ramping energy generation sources (physical or virtual)
- Flexible energy loads (e.g., demand response or energy storage)
- Geographic market structures for energy imports and exports (Katz, Milligan, and Cochran 2015).

Fast ramping, flexible loads, and geographic imports apply to multiple energy systems (e.g., natural gas, water distribution, and telecommunications), but the electric power system is a useful example. Electric power systems have been procuring flexibility in order to provide instantaneous power for decades. Figure 3 shows electrical energy services mapped to their respective timescales. Besides energy and capacity there exist categories of operating reserves and ancillary services that have analogs in thermal and chemical power systems (Denholm, Sun, and Mai 2019).

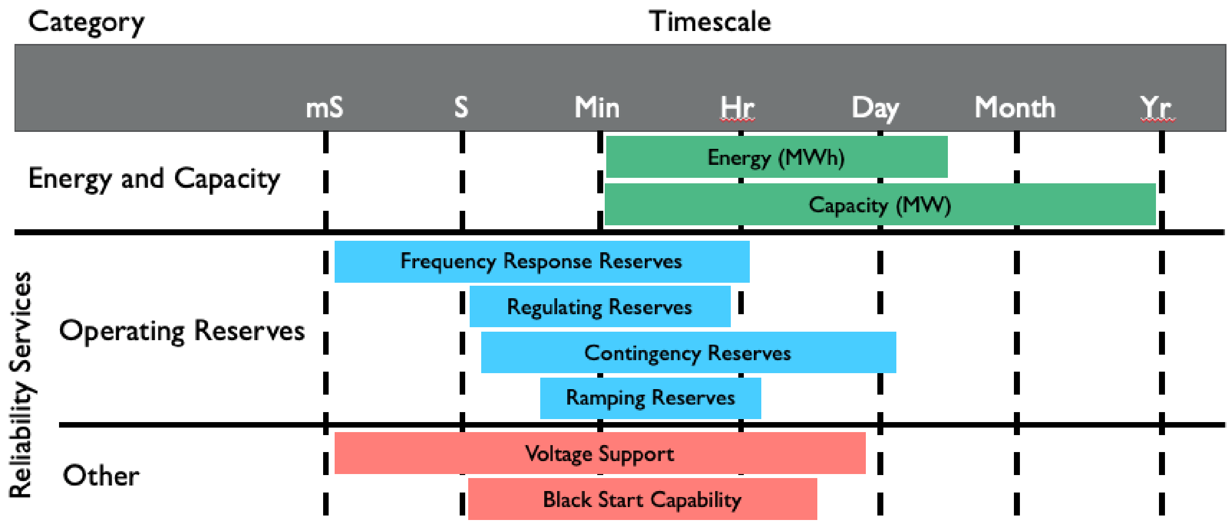

Figure 3. Electricity system generation sources and their respective operational timescales (all MW are in MWe)

Source: (Denholm, Sun, and Mai 2019)

Figure 4 provides an expansion on the information shown in Figure 3. In general, the electricity grid employs daily scheduling of slow ramping sources on the 12- to 24-hour timescale based on day-ahead weather and load forecasts. Load following occurs on the order of minutes to hours. Regulation occurs on the order of seconds to minutes (NREL 2011).

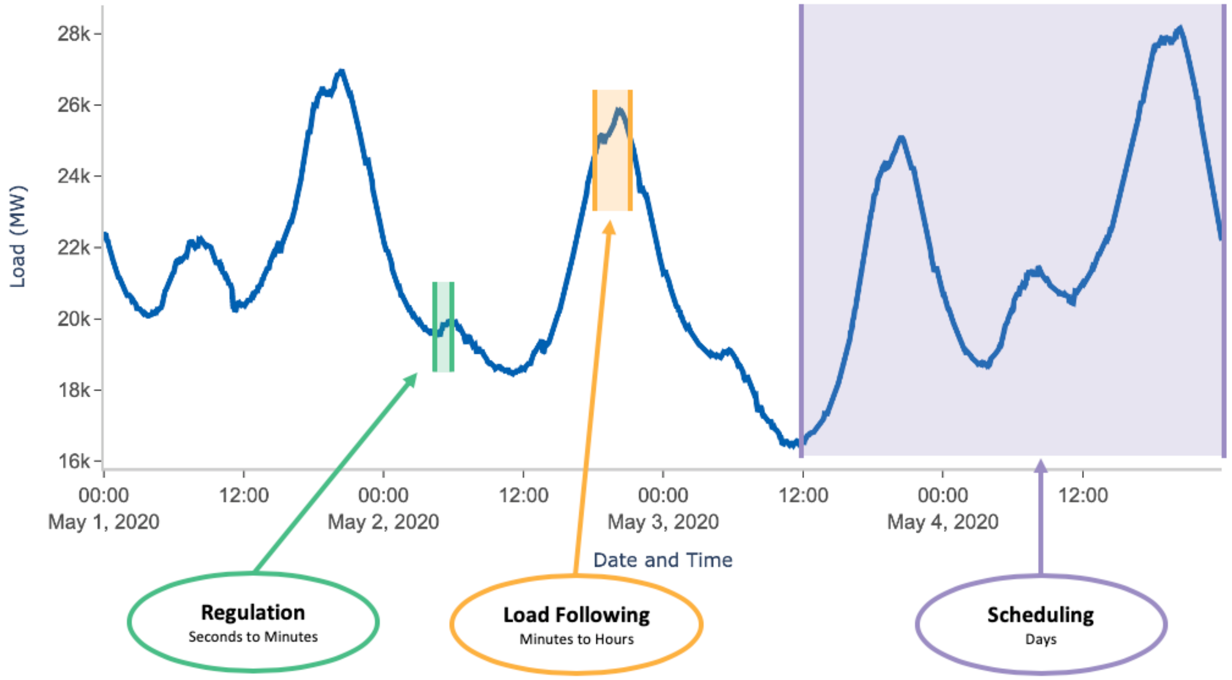

Figure 4. Energy services classified by timescales shown over load data from CAISO

Source: (CAISO 2020; NREL 2011)

3.1.3 Demand Response and Energy Storage

In electric systems, if peak load is unmet, significant measures such as load shedding or ramping reserves must be called upon. In order to prevent such effects, the available infrastructure capacity must exceed peak demand even if that demand occurs rarely. Electric utilities have been pioneers in the investigation of demand response and energy storage. These approaches essentially reduce and/or shift system demand to reduce infrastructure and generation capacity needs (O. Ma et al. 2016). Examples of demand response, such as precooling a space or regulating electric vehicle charging, can be employed to successfully reduce the overall system peak load to provide economic and operational value. Many large-scale load end-users could potentially participate in demand response. Energy storage, which can be employed in various forms (e.g., electrical, thermal, mechanical, chemical) plays a similar role in shifting supply to times of higher load.

3.1.4 Geographic Markets for Flexible Operation

A major benefit to flexible operation of electricity generators and grid asset utilization (especially in the case of large-scale plants) is to have large regional grids with inter-regional connections. Interconnections allow geographic diversity to minimize the impact of localized weather events that can affect all generation sources. Additionally, increasing electricity market granularity by moving from an hourly to a 15- or 5-minute electricity market can help to direct flexible resources where they provide the most value (Cui et al. 2017). Although flexibility derived from market structures is fundamentally tied to energy sources such as flexible generation and demand response, market structures and energy trading provide a value mechanism necessary for procuring flexible resources. For the United States, a study was conducted to estimate the value of increasing interconnections across the Western Electricity Coordinating Council. This study demonstrated that increased transmission capacity and cooperation among major balancing area authorities could increase the flexible operation of the electricity grid, particularly for enabling increased penetration of VRE and providing increased value for providers of flexible energy sources (GE Energy and NREL 2010).

3.2 Flexibility in Nuclear Systems

Nuclear power plants are fundamentally thermal energy (heat) generators that require power conversion systems to produce electricity, similar to fossil, solar thermal, and geothermal generators. Currently, the thermal energy that is released via fission reactions in the nuclear reactor core is captured by a working fluid and passed to a steam turbine to produce electricity. Advanced reactors will use many working fluids, including steam, as well as others, which is uncommon today. Therefore, future references in this report to steam turbines could also apply to other working fluids such as helium and molten salt, and other power conversion systems such as gas turbines. Hence, many of the back-end applications that create flexibility in other thermal systems are also applicable to nuclear energy. Key approaches to flexible operation of a nuclear plant include ramping core power via control maneuvers, reduced flow through the turbine (either via steam venting or redirection to alternate users in integrated systems), and energy storage providing options for demand response.

3.2.1 Core Ramping

Reducing the reactor thermal output by reducing fission is one approach to flexible nuclear operation. This can be accomplished by control rod movement or by modification of boron concentrations in the reactor core, which impact neutron absorption. Partial insertion of control rods that are specially designed to contain lower amounts of neutron absorbers than traditional control rods is one approach. While not always necessary, these “grey” control rods, if included in the design, are the standard approach to reducing the core thermal output; this is the typical approach used by plants in France (Jenkins et al. 2018; Ludwig et al. 2010; Morilhat et al. 2019). France has the most extensive operational experience in flexible nuclear plant operation using grey control rods (see Chapter **Error! Reference source not found.** for further details).

Traditionally, the French nuclear fleet has operated flexibly due to the large fraction of nuclear generation on the grid, requiring plants to be ramped up or down due to seasonal, weekly, and daily changes in load. Since 2010, France has added approximately 1.8 GW of variable renewable generation capacity annually and has been able to maintain grid reliability by matching the output of variable renewable and flexible nuclear generation (Morilhat et al. 2019). Multiple studies have demonstrated that flexible operation of the current nuclear fleet can complement variable renewable generation on certain timescales (Jenkins et al. 2018).

While very useful, core ramping has limitations. From a physics perspective, reducing core power results in the buildup of neutron absorbing isotopes that limit rapid cyclical ramping of core power. Additionally, reducing or increasing core power rapidly changes fuel temperatures, which can cause thermal and mechanical stresses that limit ramping rate and could potentially reduce fuel lifetime (Jenkins et al. 2018). From an economics perspective, core ramping is generally uncompensated, meaning that the reactor is generating less energy but incurring the same operating costs without receiving compensation. Nuclear operators are, therefore, not economically incentivized to participate in all energy markets. Although this is not true for all jurisdictions, such as France where the nuclear fleet is operated by a centralized authority, core ramping through grey control rods is often viewed as the first step, rather than the endgame, of flexible nuclear operation.

3.2.2 Integrated Energy Systems

Another mechanism for reducing electricity production from a nuclear plant is to vent steam before it reaches the generating turbine to rapidly ramp down power generation. While possible, and occasionally used in emergency scenarios, this ramping can be unprofitable and may result in decreased operational lifetime of the turbine assembly, so is not widely practiced (IAEA 2018).

Integrated energy systems seek to provide value in this approach to nuclear plant flexibility by redirecting this excess steam, thermal energy, and/or electricity to coupled, non-grid applications. When grid electricity demand is low, nuclear plants can divert energy from the turbine assembly to coupled processes (e.g., desalination, hydrogen production, district heating, industrial facilities). Some of these processes may also require electrical input, which could be provided directly by the nuclear plant behind the grid interconnect. Preliminary analyses indicate that this technology is economically viable in a range of scenarios and provides an alternative to wasting the heat merely to throttle electrical output (Alameri and King 2013; Garcia et al. 2013; Ruth et al. 2014). Similar to steam bypass operation, impact to the turbine assembly must be considered when defining maximum ramp rates and turndown that is possible without making additional modifications to the plant secondary. Significant research is currently being conducted to identify synergistic approaches to couple nuclear plant output with thermal loads (Boardman et al. 2019; Epiney et al. 2019; Frick et al. 2019).

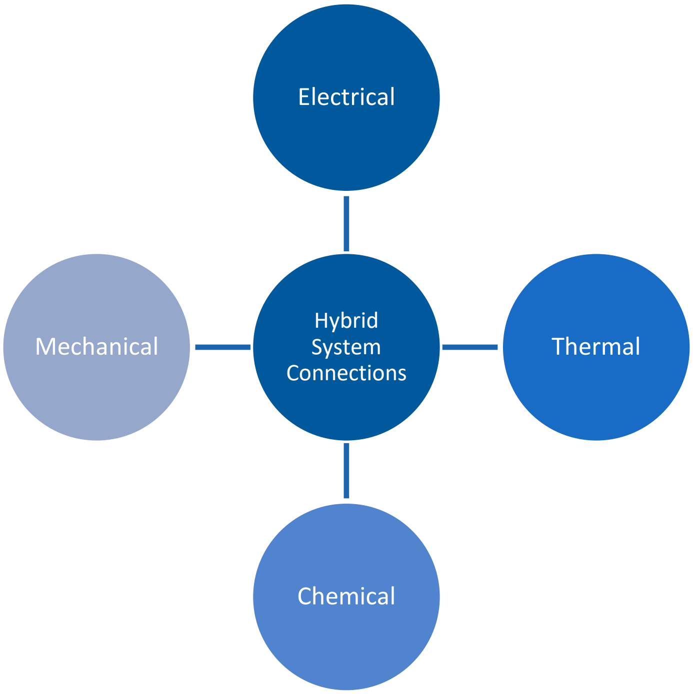

Figure 5. Interconnection mechanisms for nuclear flexibility

Source: (Suman 2018)

3.2.3 Demand Response and Energy Storage

Demand response and energy storage can shift energy production and demand across time. These approaches are being deployed rapidly at grid scale. For many large-scale operations, such as manufacturing and energy generation, a key is to move these processes "behind-the-meter,"[1] essentially making their operation appear flexible to the serving utility. This is particularly useful when a utility's tariff structure includes demand charges that increase cost based on the highest 15-minute average energy demand in a billing period or other similar tariffs. This is likewise the case for jurisdictions that have significant fluctuations in seasonal and diurnal electricity demand and pricing, which creates both challenges and opportunities (Bassett, Rupp, and Ting 2018). Since nuclear energy is both a large generator and has large "house loads," there exist many opportunities to locate behind-the-meter demand response or energy storage to shift electricity production and house loads for maximum economic benefit. This was shown to be economically valuable in the Finnish grid and for behind-the-meter lithium-ion battery storage, even though battery storage has not yet achieved economic competitiveness for pure energy arbitration (Forsberg, Brick, and Haratyk 2018; McLaren, Gagnon, and Mullendore 2017; Olkkonen et al. 2018). Although there have been economic cases for electrical energy storage, the fact that nuclear energy generation is a thermal generator means it would likely be more economical to pair it with thermal energy

---

[1] Behind the meter refers to assets, either generation or consumption, that exist behind a connection to the energy grid and often refers to assets that are "invisible" to a utility but provide local resilience or economic value. Since the metered electricity is often a customer's cost or generator's compensation, behind the meter assets are designed to align the generator's output or customer's demand with the most beneficial energy prices or provide resilience services.

storage, which is some of the most promising work in this space (Forsberg, Brick, and Haratyk 2018), as is further discussed in Chapter **Error! Reference source not found.**.

3.2.4 Modeling Techniques for Nuclear Flexibility

A necessary precursor to flexible nuclear energy use is accurate and detailed modeling that can demonstrate and quantify benefits to the grid. Disseminating these modeling results to key stakeholders can influence policy and inform investors and operators, paving the way for increased use. Later in this report, contributions from partner organizations showcase the cutting edge of modeling flexible nuclear operation. Different categories of modeling efforts are described in this section.

3.2.4.1 Physics-Based Modeling

Sometimes referred to as “balance of plant” models, the goal of physics-based modeling of the nuclear power plant is to demonstrate the behavior of the nuclear system as the power is ramped up and down. This is particularly important to ensure the safe operation of nuclear plants and to understand how a change in nuclear reactor thermal output propagates through the nuclear power plant. In modeling the physics of a nuclear power plant, both core reactor physics and thermal-fluid hydraulics must be considered. Multiple studies have been conducted to simulate the balance of plant for a variety of reactor systems, including both large-scale nuclear plants and small modular reactors (SMRs). Depending on their design and plant configuration, many studies show that SMRs can often be a valuable source of flexible output due to their smaller size and modular operation (Ingersoll et al. 2015; Q. Ma et al. 2019; Subki 2017).

3.2.4.2 Economic Dispatch Modeling

Although operational experience clearly demonstrates that it is physically possible for a nuclear reactor to safely ramp and provide power system flexibility, there may not be an economic incentive supporting flexible operation. Many electricity markets currently do not compensate flexible resources. These electricity markets could be restructured to incentivize such operation (Varro et al. 2019) as an initial step to creating a more flexible electricity grid. The purpose of economic modeling is to understand the economic competitiveness of energy system operation, potentially providing insight to the economic benefits of flexible nuclear operation and possible compensation mechanisms that could incentivize its development. There are multiple valuation mechanisms for a plant, some of which include net present value, overall profitability, and the effect of flexible nuclear operation on the locational marginal pricing of a power system. While today this is mostly focused on electricity markets, this effect is also applicable to thermal and chemical power systems. While analysis results can be varied as a function of the assumptions, deployment region, and technologies selected, among other variables, many studies have found that flexible nuclear energy can be economically competitive. This finding suggests that nuclear energy has a vital role to play in high-renewable energy future scenarios (Ingersoll et al. 2015; Jenkins et al. 2018; NEA 2019).

3.2.4.3 Large-Scale Studies of Flexibility in Nuclear Energy

Beyond evaluating individual unit behavior, there is a branch of modeling and simulation devoted to long-term energy planning. Because energy generation and transmission facilities are large capital investments with multiyear payback periods, this type of modeling attempts to provide scenario planning decades in the future. These studies utilize both physics and economics modeling. While not ideal for capturing the value of flexible unit operation, they do specify a certain necessary capacity of flexible grid resources for power system reliability (Brown et al. 2020; EPRI 2020) and play an important role in demonstrating to governments and grid operators the importance of flexible nuclear energy.

4 References

Alameri, Saeed A, and Jeffrey C King. 2013. “A Coupled Nuclear Reactor Thermal Energy Storage System for Enhanced Load Following Operation.” In *Proceedings of the International Nuclear Atlantic Conference - INAC 2013*, 12. Recife, Brazil. https://inis.iaea.org/collection/NCLCollectionStore/_Public/45/066/45066027.pdf.

Bassett, Kyle, Carriveau Rupp, and David Ting S.-K. 2018. “Energy Arbitrage and Market Opportunities for Energy Storage Facilities in Ontario.” *J Energy Storage* 20 (December): 478–84. https://doi.org/j.est.2018.10.015.

Benahmed, Farah, and Lindsey Walter. 2019. “Clean Energy Targets Are Trending.” *Third Way* (blog). December 11, 2019. https://www.thirdway.org/graphic/clean-energy-targets-are-trending.

Boardman, Richard D, Cristian Rabiti, Stephen G Hancock, Daniel S Wendt, Konor L Frick, Shannon M Bragg-Sitton, Hongqiang Hu, et al. 2019. “Evaluation of Non-Electric Market Options for a Light-Water Reactor in the Midwest.” INL/EXT-19-55090-Rev000, 1559965. Idaho Falls, ID: Idaho National Laboratory. https://doi.org/10.2172/1559965.

Bragg-Sitton, Shannon M., Richard Boardman, Cristian Rabiti, Jong Suk Kim, Michael McKellar, Piyush Sabharwall, Jun Chen, M. Sacit Cetiner, T. Jay Harrison, and A. Lou Qualls. 2016. “Nuclear-Renewable Hybrid Energy Systems: 2016 Technology Development Program Plan.” INL/EXT--16-38165, 1333006. https://doi.org/10.2172/1333006.

Brown, Maxwell, Wesley Cole, Kelly Eurek, Jon Becker, David Bielen, Ilya Chernyakhovskiy, Stuart Cohen, et al. 2020. “Regional Energy Deployment System (ReEDS) Model Documentation: Version 2019.” Technical Report NREL/TP-6A20-74111. Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy20osti/74111.pdf.

CAISO. 2020. “Supply and Renewables.” 2020. http://www.caiso.com/TodaysOutlook/Pages/supply.aspx.

Chang, Judy, Mariko Geronimo Aydin, Johannes Pfeifenberger, Kathleen Spees, and John Imon Pedtke. 2017. “Advancing Past ‘Baseload’ to a Flexible Grid.” The Brattle Group. http://files.brattle.com/files/7352_advancing_past_baseload_to_a_flexible_grid.pdf.

Cui, Mingjian, Jie Zhang, Hongyu Wu, and Bri-Mathias Hodge. 2017. “Wind-Friendly Flexible Ramping Product Design in Multi-Timescale Power System Operations.” *IEEE Trans Sustain Energy* 8 (3): 1064–75. https://doi.org/10.1109/TSTE.2017.2647781.

Denholm, Paul, Yinong Sun, and Trieu Mai. 2019. “An Introduction to Grid Services: Concepts, Technical Requirements, and Provision from Wind.” NREL/TP-6A20-72578. Golden, CO: National Renewable Energy Lab (NREL). https://www.osti.gov/biblio/1493402/.

Dolley, Steven. 2018. “Exelon Generation Cuts Output at Four Illinois Nuclear Units, Two Back at 100% Power.” *S&P Global Platts* (blog). May 11, 2018. https://www.spglobal.com/platts/en/market-insights/latest-news/electric-power/051118-exelon-generation-cuts-output-at-four-illinois-nuclear-units-two-back-at-100-power.

Epiney, Aaron S., James D. Richards, Jason K. Hansen, Paul W. Talbot, Pralhad Hanumant Burli, Cristian Rabiti, and Shannon M. Bragg-Sitton. 2019. “Case Study: Integrate

Nuclear Water Desalination—Regional Potable Water in Arizona." INL/EXT-20-55736-Rev001. Idaho Falls, ID: Idaho National Laboratory. https://doi.org/10.2172/1597896.

EPRI. 2020. "US-REGEN Model Documentation." Technical Update 3002016601. https://www.epri.com/research/products/000000003002016601.

ERCOT. 2020. "Generation." 2020. http://www.ercot.com/gridinfo/generation/.

"FERC: Documents & Filing - Forms - Form 714 - Annual Electric Balancing Authority Area and Planning Area Report - Data Downloads." n.d. Accessed April 30, 2020. https://www.ferc.gov/docs-filing/forms/form-714/data.asp.

Forsberg, Charles, Stephen Brick, and Geoffrey Haratyk. 2018. "Coupling Heat Storage to Nuclear Reactors for Variable Electricity Output with Baseload Reactor Operation." *Electr J* 31 (3): 23–31. https://doi.org/10.1016/j.tej.2018.03.008.

Frick, Konor, Paul Talbot, Daniel Wendt, Cristian Rabiti, Shannon Bragg-Sitton, Daniel Levie, Bethany Frew, Mark Ruth, Amgad Elgowainy, and Troy Hawkins. 2019. "Evaluation of Hydrogen Production Feasibility for a Light Water Reactor in the Midwest." Technical Report INL/EXT-19-55395. Idaho Falls, ID: Idaho National Laboratory. https://www.osti.gov/biblio/1569271/.

Garcia, Humberto E., Amit Mohanty, Wen-Chiao Lin, and Robert S. Cherry. 2013. "Dynamic Analysis of Hybrid Energy Systems under Flexible Operation and Variable Renewable Generation – Part I: Dynamic Performance Analysis." *Energy* 52 (April): 1–16. https://doi.org/10.1016/j.energy.2013.01.022.

GE Energy, and NREL. 2010. "Western Wind and Solar Integration Study." Technical Report NREL/SR-550-47434. Golden, CO: National Renewable Energy Laboratory. https://doi.org/10.2172/981991.

IAEA. 2018. "Non-Baseload Operation in Nuclear Power Plants: Load Following and Frequency Control Modes of Flexible Operation." NP-T-3.23. IAEA Nuclear Energy Series. Vienna, Austria: International Atomic Energy Agency. https://www.iaea.org/publications/11104/non-baseload-operation-in-nuclear-power-plants-load-following-and-frequency-control-modes-of-flexible-operation.

IEA. 2019a. "Status of Power System Transformation 2019: Power System Flexibility." Paris, France: International Energy Agency. https://www.iea.org/reports/status-of-power-system-transformation-2019.

———. 2019b. "World Energy Outlook 2019." Paris, France: International Energy Agency. https://www.iea.org/reports/world-energy-outlook-2019.

———. 2020a. "Data and Statistics." 2020. https://www.iea.org/data-and-statistics.

———. 2020b. "Global CO2 Emissions in 2019." Paris, France: IEA. https://www.iea.org/articles/global-co2-emissions-in-2019.

Ingersoll, D T, C Colbert, Z Houghton, R Snuggerud, J W Gaston, and M Empey. 2015. "Can Nuclear Power and Renewables Be Friends?" In *Proceedings of ICAPP 2015*, 9. Nice, France. https://ecee.colorado.edu/~ecen5009/Resources/Nuclear/Ingersoll2015.pdf.

Jenkins, J. D., Z. Zhou, R. Ponciroli, R. B. Vilim, F. Ganda, F. de Sisternes, and A. Botterud. 2018. "The Benefits of Nuclear Flexibility in Power System Operations with Renewable Energy." *Appl Energy* 222 (July): 872–84. https://doi.org/10.1016/j.apenergy.2018.03.002.

Katz, Jessica, Michael Milligan, and Jaquelin Cochran. 2015. "Sources of Operational Flexibility, Greening the Grid." NREL/FS-6A20-63039. Golden, CO: National Renewable Energy Laboratory. https://www.osti.gov/biblio/1252416.

Ludwig, Holger, Tatiana Salnikova, Andrew Stockman, and Ulrich Waas. 2010. “Load Cycling Capabilities of German Nuclear Power Plants (NPP).” *VGB PowerTech* 91 (5): 38–44.

Ma, Ookie, Kerry Cheung, Daniel J. Olsen, Nance Matson, Michael D. Sohn, Cody M. Rose, Junqiao Han Dudley, et al. 2016. “Demand Response and Energy Storage Integration Study.” Technical Report NREL/TP-6A20-61181; DOE/EE-1282. Golden, CO: National Renewable Energy Laboratory. https://doi.org/10.2172/1326329.

Ma, Quan, Xinyu Wei, Junyan Qing, Wen Jiao, and Risheng Xu. 2019. “Load Following of SMR Based on a Flexible Load.” *Energy* 183 (September): 733–46. https://doi.org/10.1016/j.energy.2019.06.172.

McLaren, Joyce A., Pieter J. Gagnon, and Seth Mullendore. 2017. “Identifying Potential Markets for Behind-the-Meter Battery Energy Storage: A Survey of U.S. Demand Charges.” Program Document NREL/BR-6A20-68963. Golden, CO: National Renewable Energy Laboratory. https://www.osti.gov/biblio/1374803.

Morilhat, Patrick, Stéphane Feutry, Christelle Le Maitre, and Jean Melaine Favennec. 2019. “Nuclear Power Plant Flexibility at EDF.” *Atw Internationale Zeitschrift Fuer Kernenergie* 64 (3): 131–40.

NEA. 2019. “The Costs of Decarbonisation: System Costs with High Shares of Nuclear and Renewables.” Paris, France: OECD Publishing. https://www.oecd-ilibrary.org/content/publication/9789264312180-en.

NREL. 2011. “The Importance of Flexible Electricity Supply.” Fact Sheet DOE/GO-102011-3201. Solar Integration Series. Golden, CO: Department of Energy Office of Energy Efficiency and Renewable Energy. https://www1.eere.energy.gov/solar/pdfs/50060.pdf.

Olkkonen, Ville, Jussi Ekström, Aira Hast, and Sanna Syri. 2018. “Utilising Demand Response in the Future Finnish Energy System with Increased Shares of Baseload Nuclear Power and Variable Renewable Energy.” *Energy* 164 (December): 204–17. https://doi.org/10.1016/j.energy.2018.08.210.

Ruth, Mark F., Owen R. Zinaman, Mark Antkowiak, Richard D. Boardman, Robert S. Cherry, and Morgan D. Bazilian. 2014. “Nuclear-Renewable Hybrid Energy Systems: Opportunities, Interconnections, and Needs.” *Energy Convers Manag* 78 (February): 684–94. https://doi.org/10.1016/j.enconman.2013.11.030.

Subki, M. Hadid. 2017. “Small Modular Reactors: Design Specificities of LWR- and HTGR-Type SMRs, Identification of Issues of Their Deployments.” Presented at the IAEA Technical Meeting on Challenges in the Application of the Design Safety Requirements for Nuclear Power Plants to Small and Medium Sized Reactors, Vienna, Austria, September 4. https://gnssn.iaea.org/NSNI/SMRP/Shared%20Documents/TM%204%20-%208%20September%202017/Light%20Water%20and%20High%20Temperature%20Gas%20Small%20Modular%20Reactor%20Status.pdf.

Suman, Siddharth. 2018. “Hybrid Nuclear-Renewable Energy Systems: A Review.” *J Clean Prod* 181 (April): 166–77. https://doi.org/10.1016/j.jclepro.2018.01.262.

UNDP. 2018. “Sustainable Development Goals.” April 20, 2018. https://www.undp.org/content/undp/en/home/sustainable-development-goals.html.

Varro, Laszlo, Brent Wanner, César Alejandro Hernández Alva, Antoine Herzog, and Peter Fraser. 2019. “Nuclear Power in a Clean Energy System.” International Energy Agency. https://webstore.iea.org/nuclear-power-in-a-clean-energy-system.