NICE Future

Nuclear Innovation: Clean Energy Future

Flexible Nuclear Energy for Clean Energy Systems

A product of the Flexible Nuclear Campaign for Nuclear-Renewables Integration (FNC), a campaign of the Nuclear Innovation: Clean Energy Future (NICE Future) initiative under the Clean Energy Ministerial (CEM), coordinated by the National Renewable Energy Laboratory (NREL) in its capacity as the NICE Future operating agent.

CLEAN ENERGY MINISTERIAL

Advancing Clean Energy Together

Technical Report
NREL/TP-6A50-77088
September 2020

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The Joint Institute for Strategic Energy Analysis (JISEA) and its institutional affiliate, the National Renewable Energy Laboratory (NREL), coordinate and provide technical expertise for the NICE Future initiative and serve as a liaison to the Clean Energy Ministerial (CEM) Secretariat. NREL implements NICE Future initiative activities based on guidance from CEM, and initiative participants, partners and stakeholders. NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

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Perspectives by Co-Lead Countries

Under the Clean Energy Ministerial (CEM), the U.S. Department of Energy (DOE), Natural Resources Canada (NRCan), Ministry of Economy, Trade, and Industry (METI) of Japan, and the Department of Business, Energy, and Industrial Strategy (BEIS) of the United Kingdom, seek to accelerate global clean energy transitions.

This commitment is reflected in our continued support of technology development and innovation in our current and future energy systems. Our organizations have each supported a variety of research and development activities and initiatives in collaboration with national laboratories, academia, and industry partners that explore and utilize different technologies to meet a variety of energy demands.

Nuclear energy is an important part of the global clean energy supply, providing nearly one-third of the world's non-emitting electricity and complementing and enabling other clean energy sources, including renewables. Recognizing this current and future potential for nuclear energy, the Nuclear Innovation: Clean Energy Future (NICE Future) initiative was launched in 2018 at the Ninth CEM in Copenhagen, Denmark.

Since its launch, the NICE Future initiative has succeeded in initiating broad, cross-sectoral dialogue among CEM member countries to highlight the roles that nuclear energy can play in bolstering economic growth, energy security, and access, and environmental stewardship. This includes exploring and building awareness about how innovative nuclear energy technologies across both large and small-scale applications, such as small modular reactors (SMRs) and other advanced reactors, can drive clean growth.

To explore and communicate the increasingly flexible roles that nuclear energy technologies can play in integrated clean energy systems of the future, the NICE Future initiative proudly launched the Flexible Nuclear Campaign for Nuclear-Renewables Integration (Flexible Nuclear Campaign) at the 10th CEM in Vancouver, Canada in 2019.

The International Energy Agency's (IEA's) *2019 World Energy Outlook* forecasts that electricity generation from variable renewables could range from 36% to 67% by 2040. As more renewables connect to the grid, many countries are developing innovative options to employ more flexible operation of traditional and base load energy sources, like nuclear, to produce electricity and heat to meet demand.

This report brought together experts from around the globe to share expertise and study opportunities for innovative and advanced nuclear systems to operate flexibly and work in tandem with renewables, contributing to clean energy systems of the future.

As demonstrated in technical analyses summarized in this report, nuclear energy offers flexibility in certain electricity markets around the world, and new nuclear technologies could extend the versatility of nuclear energy systems further.

At its most basic, nuclear energy can operate flexibly by ramping power output up or down to match grid demand; however, nuclear energy's services extend beyond just electricity generation. Around the world, research is underway to explore how nuclear systems can use generated thermal

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energy directly to heat households, drive industrial processes, or produce nonelectric commodities such as purified water. In some instances, hydrogen produced by nuclear systems can be used to store energy for later electricity production or used as a feedstock to produce a variety of products, from fertilizers and steel to new synthetic fuels. Additionally, by operating alongside chemical plants and renewables, current and future nuclear energy systems can be used to generate a host of alternative revenue streams and help lower emissions of carbon dioxide, sulfur dioxide, nitrogen oxide, mercury, and particulates that cause smog across the energy, transportation, and industrial sectors. With new smaller reactors currently under development and anticipated for near-term deployment, nuclear can bring this versatility virtually anywhere at almost any scale by matching a community's energy needs with a specific reactor technology.

We are excited about the innovative systems that are being explored to power our future. By harnessing nuclear energy innovation through closer global cooperation, the world will be cleaner, healthier, and more prosperous.

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Foreword From Lead Nongovernmental Organizations (NGOs): ClearPath and Energy for Humanity

We applaud the commitment and vision shown by governments in the creation of the Clean Energy Ministerial's (CEM) Nuclear Innovation: Clean Energy Future (NICE Future) initiative and the Flexible Nuclear Campaign for Nuclear-Renewables Integration (Flexible Nuclear Campaign) launched under the initiative, which seeks to provide evidence of the combined multiple roles that nuclear and renewables together can play in delivering affordable, reliable, and clean energy systems.

What is the NICE Future initiative?

- Launched at the 9th Clean Energy Ministerial (May 2018, Copenhagen), the Nuclear Innovation: Clean Energy Future (NICE Future) initiative is an international collaboration that envisions a world in which nuclear energy innovation and applications advance clean energy goals.
- Initiative participants are exploring innovative technologies and diverse uses of nuclear energy, including nuclear-renewables integration, flexible electricity grids, rural electrification, industrial processes, water purification, clean transportation fuels, and alternative energy carriers such as hydrogen.
- At the 10th Clean Energy Ministerial (May 2019, Vancouver), several participants in the initiative launched the Flexible Nuclear Campaign for Nuclear-Renewables Integration, a joint effort between civil society and governments to enlist global experts in the valuation of flexible nuclear systems working in concert with renewables. This report is part of that work stream.

Based on the evidence provided in this report, our organizations urge all members of the CEM to continue to lead the reinvention of global energy supply, especially in the wake of the COVID-19 pandemic, as protecting human health through cleaner air and economic recovery come into view as leading challenges.

The scale of our ambition must be commensurate with the scale and urgency required by our combined economic, environmental, and energy challenges.

The last decade has seen the development of wind and solar generation into affordable technologies that can help significantly reduce emissions from the electricity sector. Flexible advanced nuclear reactors can complement and enable higher penetrations of variable renewables in future energy systems. However, the combined commitment, creativity, and technical and business innovations that have helped to commercialize renewables affordably and at scale have not been applied extensively to other technologies.

The time has come to realize the expanded role that a wider range of technologies will need to play in de-risking pathways to significantly lower emissions. Specifically, this means applying lessons learned from renewables' successes as templates for broader and deeper emissions reductions. This also means looking to other large-scale, high-productivity industries, such as shipping and aviation. Innovative delivery and deployment models in "designed-for-purpose" facilities can quickly achieve very low costs and large-scale deployment of a range of clean technologies for rapid, near-term emissions reductions.

In this critical decade, we aim to expand the suite of clean energy options to include flexible nuclear technologies and products that are cost competitive, present lower risk to investors, and can meet a broad range of market applications.

These advanced nuclear products must be designed to address the clean energy transitions being pursued by countries and to meet market requirements for flexibility, affordability, security, and availability in future energy systems with high penetrations of renewables. Rapid commercialization of these valuable technologies is needed to transform a significant percentage of the world's total energy consumption over the coming decades.

In addition to nuclear energy's traditional supply of electricity, the existing fleet and advanced nuclear reactors have the potential to supply heat to homes, businesses and industrial processes; produce hydrogen and synthetic fuels to support cleaner transport, including the hard-to-abate sectors of aviation and shipping; desalinate and purify seawater in regions suffering water scarcity; support access to modern energy services in remote and developing communities; and offer industry an emissions-free source of high-temperature heat, all as part of energy transitions that can benefit society and lift up living standards around the world.

Forthcoming advanced nuclear and other small modular reactor (SMR) technologies could enable sustainable development and cleaner energy transitions simultaneously. We applaud the efforts of the CEM to realize the potential of these technologies and call on all capable and desiring countries to collaborate to accelerate their development and commercialization over the next decade for rapid global deployment.

As NGOs focused on increasing the range of clean energy options, there are several immediate actions we recommend for consideration by countries and stakeholders:

- **Governments:** Promote clean energy and encourage more collaboration between nuclear energy and renewable energy experts and stakeholders that go beyond energy ministries to reach across all relevant agencies that address clean energy technologies and opportunities, with the assignment to work together to create clean energy systems.

- **Policymakers**: Develop ambitious and achievable strategies for energy transitions and innovation, climate change, power, heat, industry, and transport. Invest effort and resources, including in improved market designs and incentives that can foster healthy competition, encourage efficiencies, and better realize the untapped potential of the full range of options available.

  As countries look to design economic recovery measures that can reduce emissions while creating jobs and bolstering our economies, they should seek to recognize and evaluate the various opportunities of flexible nuclear technologies to form part of the solution.

- **Climate and energy modelers**: Broaden the range of emissions reduction pathways through the inclusion of a broader set of technology options. Having more options both alleviates

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pressure elsewhere in the system and creates new opportunities. Mapping realistic, achievable pathways to significantly reduce emissions while ensuring economic growth is a crucial part of mobilizing investors, supply chains, policymakers, and the public for success.

- **Analysts and technologists**: Focus on emissions reductions to address and act upon the gaps in the literature, where alternative pathways are either drastically under-represented or entirely omitted from the range of clean energy options, including the roles flexible nuclear energy can play alongside renewables to drive down costs and emissions across the whole energy system.

- **Investors:** Consider a portfolio approach to clean energy investments spread across a range of technology options in order to reduce exposure to risk. Consistent, technology-inclusive access to finance is vital to realizing this objective.

- **Business leaders**: Help create markets for the cleaner energy technologies currently under development and invest in demonstrating these technologies so that those markets might be fully realized, resulting in economies of scale and market-driven emissions reductions.

Our view is that to achieve these clean energy transitions, within meaningful timescales, a new form of dialogue is needed. Accordingly, we welcome the CEM's efforts to frame the discussion in terms of whole systems thinking—across power, heat, industry, and transport.

How can we design the highest possible performance system (flexible, clean, reliable, affordable, resilient) with a diverse portfolio of technologies?

We need a discussion that enables evidence-based decision-making focused on shared goals and outcomes. Our future energy systems will need to be low-emissions, reliable, affordable, and flexible. They should provide social, economic, and environmental benefits, including reducing air pollution, protecting habitats and biodiversity on land and in the oceans, driving jobs and general economic prosperity, and improving quality of life and access to opportunities, including for women and children throughout the world—all while providing increased energy supply, both electricity and fuels, without emissions and radically reducing the impact on the environment.

We believe that a determined focus on evidence-based, outcomes-focused, decision-making will deliver the progress that we need at the speed and scale of action needed to address our shared global challenges.

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Executive Summary

The *Flexible Nuclear Energy for Clean Energy Systems* report provides a collection of technical analyses that, in the aggregate, demonstrate the current and potential future roles for nuclear energy in providing flexibility in meeting energy demands. For the purposes of this report, flexibility 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.

Power systems around the world are undergoing rapid and significant transformations. Driven by new cost-effective, low-emissions technologies and growing consensus on the need for economy-wide clean energy, the past decade has seen accelerated change and innovation in the ways that humans produce, transmit, and consume energy. These changes are only the beginning. The next decade will almost assuredly bring more innovation and change to advance the use of clean energy across all sectors in order to address multiple global challenges (e.g., universal energy access, energy security, economic recovery, environmental stewardship, climate resilience, and global health). As part of their individual energy transitions, countries are increasingly seeking ways to procure the flexibility needed to ensure reliable, affordable, and clean energy for their economies. Leveraging flexibility and diversity in energy system location, types of energy generation used, timing and scale of production, diverse energy applications, and multiple energy carriers and storage will be essential to achieving economy-wide clean energy transitions.

All energy assets can provide flexibility in some way. For example, aggregating and automating the operation of distributed resources, such as distributed solar photovoltaics (PV) or household appliances, using technology that did not exist a decade ago, is leading to entirely new business models and greater energy system flexibility. Nuclear energy is no different. Nuclear energy is experiencing rapid innovation, especially within the last decade. Nuclear energy is quickly increasing visibility for its existing and potential flexible properties alongside its traditional base load roles. While nuclear energy has constraints regarding how rapidly power can be maneuvered up or down, or how low of a power it can be operated at for an extended period of time, nuclear systems offer unique value to key types of system flexibility.

Today, nuclear energy already provides certain types of electric system flexibility on the megawatt (MW) to gigawatt (GW) scale in some countries. This flexibility is a valuable resource of clean energy but, to this point, nuclear energy has mostly been used for electricity production. Looking to the future, new innovations will provide ever-increasing types of flexibility from nuclear energy. Both existing and future nuclear plants are being re-imagined as novel sources of not only dispatchable electricity, but also thermal energy and chemical production, through novel integration with energy storage, conversion technologies, and hydrogen production. Several pilot projects are underway around the globe that will revolutionize and diversify the output of currently operating GW-scale systems.

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Advanced Generation IV nuclear reactors[1] can be smaller, more distributed, and faster in changing their energy outputs. As a result, advanced reactors may have the opportunity to be designed to provide a host of novel electric and nonelectric energy services. In short, nuclear innovation has the potential to revolutionize clean energy systems.

This report reflects a collection of international experience and novel research from partner organizations of the Nuclear Innovation: Clean Energy Future (NICE Future) initiative. While the data and analysis presented may reveal differences among chapters due to individual authors' particular perspectives or focus, collectively they seek to explore the value of flexible nuclear energy. Looking across the chapters, several key points emerge that are summarized here at a high level.

There is already an established body of knowledge surrounding flexible operation of existing nuclear plants. Work in reactor physics, thermal hydraulics, and material science has demonstrated that nuclear reactors can safely provide flexible power output. Both research and operational data have contributed to a global body of knowledge on the subject. Several countries, including some featured in this report, have decades of experience in flexible operation of existing nuclear reactors. Additionally, multiple organizations have researched potential safety-related impacts of flexible nuclear operation. Their research has shown that flexible operation poses no known threats to nuclear safety. While some countries have significant experience in operating existing nuclear power plants flexibly, for other countries it may be difficult to adopt flexible operation that may require dedicated equipment and additional regulatory review and compliance. Existing reactors have the ability to provide flexible electricity output within established constraints that are a function of the reactor design. Additionally, flexibility has different implications for each country's power systems.

Innovation can increase the flexibility of existing nuclear reactors to produce both clean electricity and beneficial nonelectric products. Many organizations are researching how nuclear reactors can increase the speed with which they change their electrical output and diversify their energy products. Due to their large capacity and thermal output, operating nuclear reactors can support "bolt-on" enhancements or operational alterations to store energy for later use. Reactors can also provide thermal energy in addition to electricity to support production of diverse products such as hydrogen and chemicals. These enhancements could allow plants to operate continuously at their full rated power levels while flexibly supporting grid operations.

Advanced reactors will present even more opportunities for flexibility in nuclear systems. Despite the significant and valuable innovation occurring around existing GW-scale reactor systems, there are some energy services that only advanced reactors will be able to support. While some advanced reactors will be on the GW scale, many advanced reactor concepts could be built on the scale of 1–100 MW. These new reactor designs can be distributed to areas with smaller energy demand that cannot support traditional GW-scale plants, and some are being designed specifically to support these regions. Off-grid applications, such as providing heat and power to remote communities and industries (e.g., mining), are key examples of the types of uses that advanced reactors can flexibly support. Additionally, these designs can be coupled to novel energy

[1] For more information on Generation IV reactors, see Chapter 13.

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storage systems, such as thermal energy storage or hydrogen production, to further increase flexibility.

Nuclear flexibility can be key in enabling other clean energy generators. Clean energy sources have seen rapid innovation and cost reduction in the last decades. While solar PV and wind power are two of the most commonly cited, other energy sources such as distributed run-of-the-river hydropower, dispatchable geothermal (both deep and shallow), biomass, concentrating solar power, and fossil energy with carbon capture have also experienced rapid technological and economic advances in the last decade. Each advancement in energy generation technology requires engineers and policymakers to re-imagine and broaden their views on possible energy interconnections. Nuclear energy has the potential to couple with many other energy sources in a synergistic fashion that results in integrated systems that are more than the sum of their parts.

The clean energy systems deployed by each country will depend on local natural resources, geography, topology, infrastructure, and societal values. The Clean Energy Ministerial's (CEM's) mission is to facilitate clean energy transitions by sharing diverse international experiences. Accordingly, the NICE Future initiative invites energy ministers to re-examine the opportunities and potential benefits offered by nuclear energy, whether or not nuclear energy is currently part of their energy systems. This report provides information on flexible nuclear energy operation and innovations that will be valuable for economy-wide clean energy transitions in those countries that choose to realize them.

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List of Acronyms

ANRE	Agency for Natural Resources and Energy
APS	Arizona Public Service
BEIS	Business, Energy, and Industrial Strategy
CAISO	California Independent System Operator
CapEx	Capital Expenditure
CCC	U.K. Committee on Climate Change
CEM	Clean Energy Ministerial
CNL	Canadian Nuclear Laboratories
CSP	concentrated solar power
DOE	U.S. Department of Energy
DOE-NE	DOE Office of Nuclear Energy
EDF	Électricité de France
EPRI	Electric Power Research Institute
ERCOT	Electric Reliability Council of Texas
GHG	greenhouse gas
GIF	Generation IV International Forum
HERON	Heuristic Energy Resource Optimization Network
HTGR	high-temperature gas-cooled reactor
HTSE	high-temperature steam electrolysis
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
INL	Idaho National Laboratory
JAEA	Japan Atomic Energy Agency
LWR	light-water reactor
MIT	Massachusetts Institute of Technology
METI	Ministry of Economy, Trade, and Industry
MSR	molten salt reactor
NGO	nongovernmental organization
NICE Future	Nuclear Innovation: Clean Energy Future
NRCan	Natural Resources Canada
NREL	National Renewable Energy Laboratory
PV	photovoltaic
PWR	pressurized water reactor
RAVEN	Reactor Analysis and Virtual Control Environment
ReEDS	Regional Energy Deployment System
SFR	sodium-cooled fast reactor
SMR	small modular reactor
TEAL	Tool for Economic Analysis
TEDS	Thermal Energy Distribution System
VRE	variable renewable energy

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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

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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 2019c). 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).

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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.

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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.

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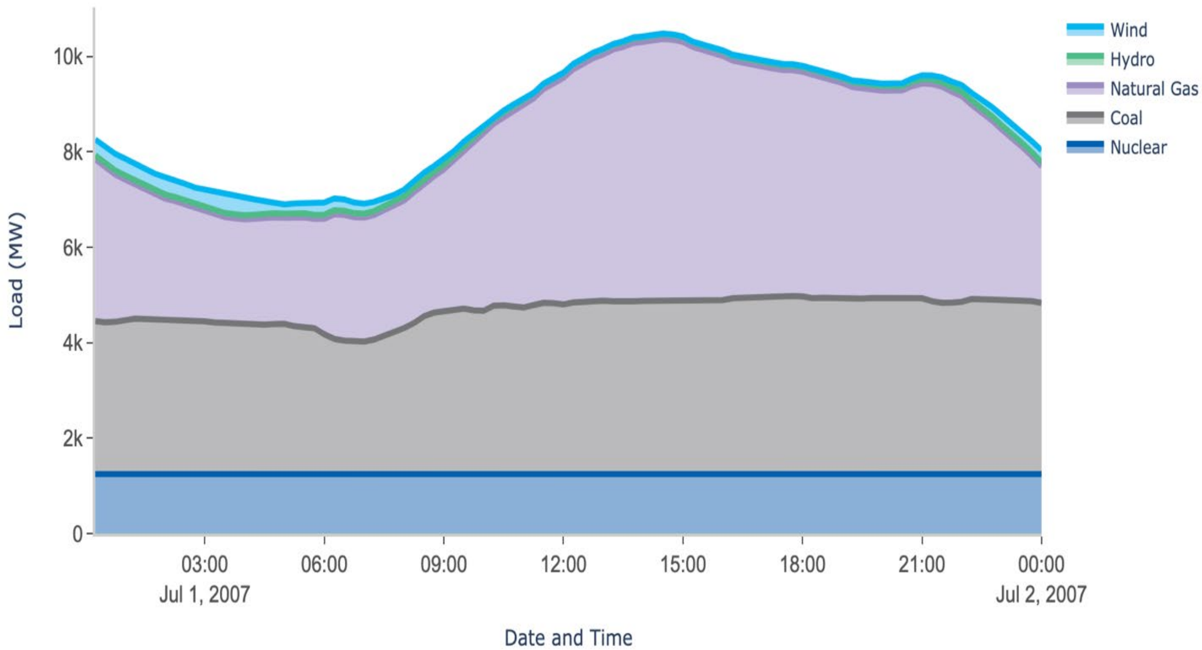

Figure 1. ERCOT generation by fuel source July 1, 2007

Source: (ERCOT 2020)

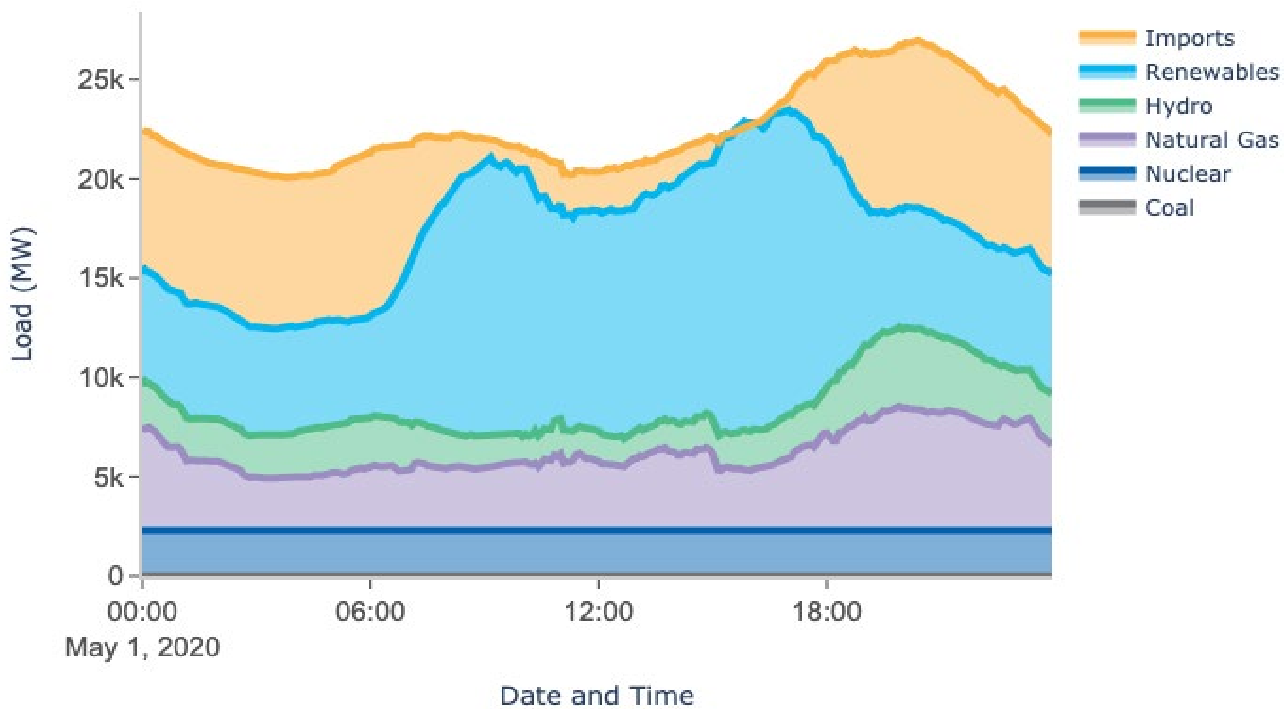

Figure 2. California Independent System Operator (CAISO) generation by fuel source May 1, 2020

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

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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).

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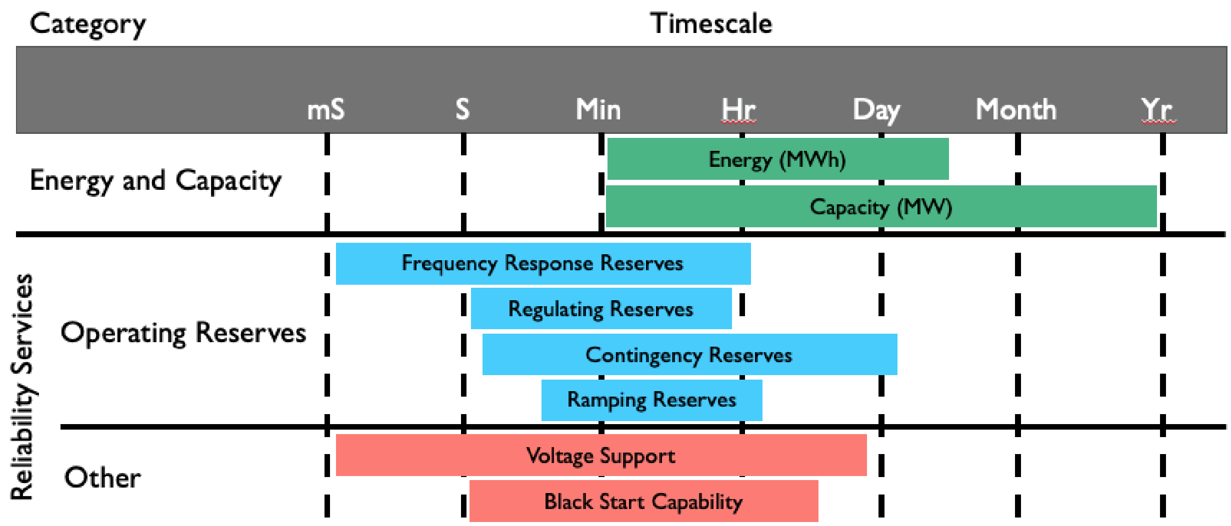

Figure 3. Electricity system generation sources and their respective operational timescales (all MW are in MWe)

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).

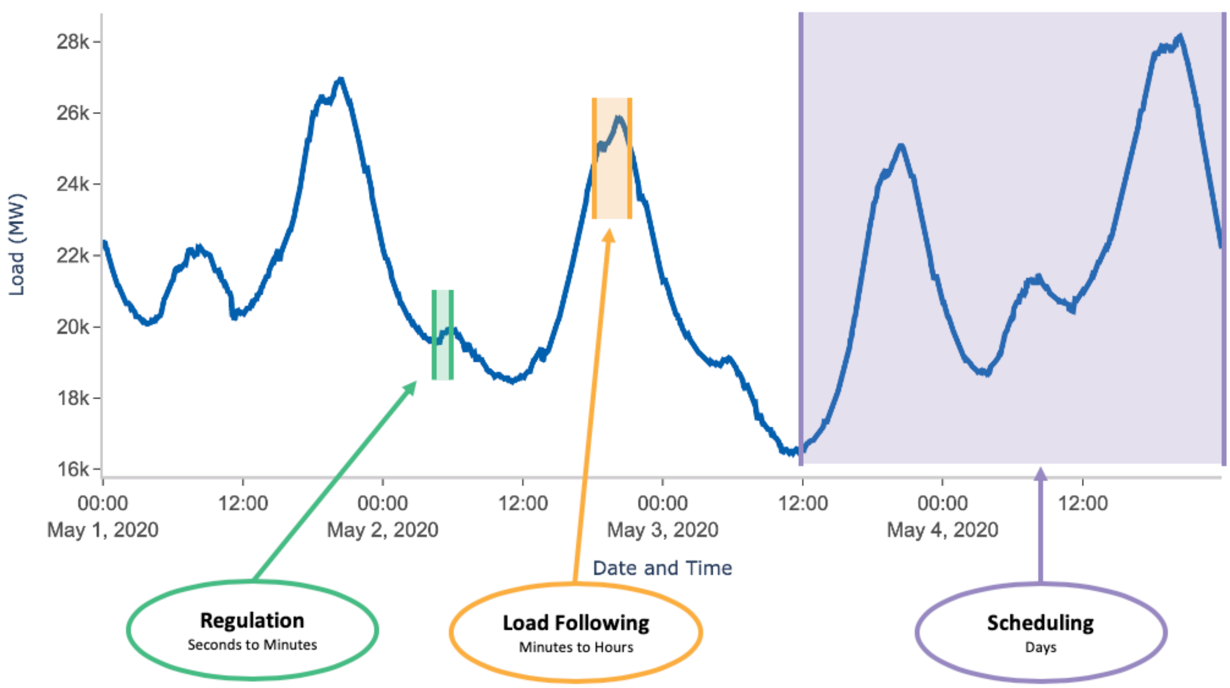

Figure 4. Energy services classified by timescales shown over load data from CAISO

Source: (CAISO 2020; NREL 2011)

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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

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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 5 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 2018a).

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; M. F. 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, Talbot, et al. 2019).

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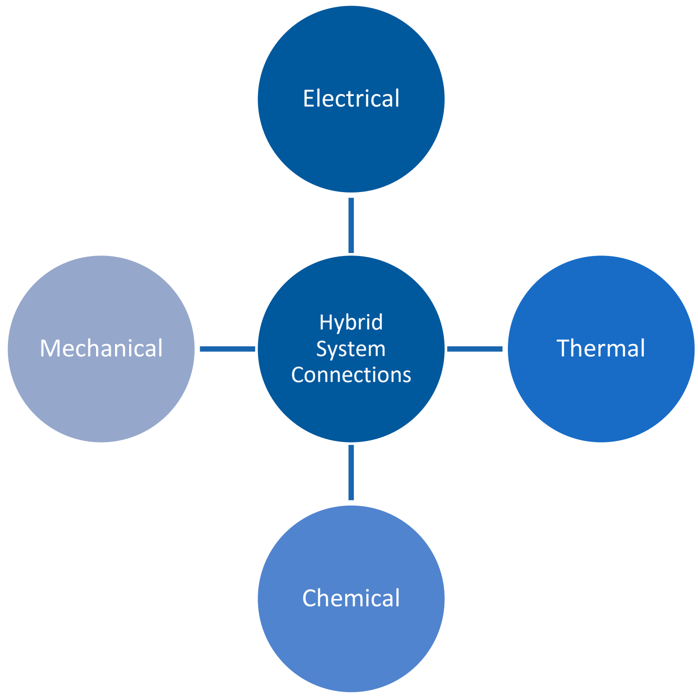

Figure 5. Interconnection mechanisms for nuclear flexibility

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,"[2] 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

[2] 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 7.

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

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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. 2020b; EPRI 2020a) and play an important role in demonstrating to governments and grid operators the importance of flexible nuclear energy.

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4 Canadian Nuclear Laboratories: Canada's Past Experience and Future Goals for Nuclear Flexibility

Prepared by Gordon Burton, Megan Moore, and Ali Siddiqui of Canadian Nuclear Laboratories, Canada's premier nuclear science and technology organization.

Canadian Nuclear Laboratories (CNL) is Canada's premier nuclear science and technology organization. CNL has a dual mission to support the needs of the federal government through the Federal Nuclear Science and Technology Work Plan, which is managed by Atomic Energy Canada Limited, while also competing to provide commercial services both nationally and globally. CNL develops peaceful and innovative applications of nuclear technology for the existing nuclear fleet (CANDU® and light water reactors, LWRs) and for future advanced reactors, including SMR technologies.

CNL's long-term plans and mission include demonstrating the commercial viability of advanced reactor designs/SMRs and providing the world with sustainable energy solutions. For example, the extension of reactor operating lifetimes (e.g., refurbishment), hydrogen energy technologies, and advanced fuel development for the reactor designs of tomorrow. The following research areas will be discussed in this chapter.

- Hybrid energy system models to couple various clean technologies and to assess the associated economic benefits of those systems
- Clean hydrogen technologies (i.e., production, storage, safety) to provide clean energy alternatives to support a national hydrogen economy
- A Clean Energy Demonstration Innovation and Research park to demonstrate the integration of renewable energy and other clean technologies with the flexible operation of an SMR at the Chalk River site.

These research areas led by CNL support the Flexible Nuclear Campaign for the CEM NICE Future initiative. Natural Resources Canada is the federal department in Canada responsible for nuclear energy policy and leads Canada's engagement at the CEM. Natural Resources Canada (NRCan) draws upon scientific expertise at CNL to support Canada's participation.

4.1 Hybrid Energy System Background

In Canada, the energy landscape is changing, creating opportunities for many provinces to transition to low-carbon energy sources. The changes include:

- Target reduction of greenhouse gas (GHG) emissions related to energy production toward net-zero emissions by 2050 (Wilkinson 2019);
- Transition of Indigenous communities from reliance on diesel-fueled power to clean, renewable, and reliable energy by 2030 (Trudeau 2019);
- Increased focus on maintaining grid reliability and minimizing system costs while increasing the penetration of VRE sources

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- Increasing energy demands expected from disruptive changes in other areas, such as transportation and manufacturing (e.g., vehicle electrification) ("Pan-Canadian Framework on Clean Growth and Climate Change" 2016).

Clean energy systems of the future will need to include all sources of clean energy to be viable and sustainable. The traditional base load electricity production from nuclear reactors is necessarily affected with increased penetration of variable renewable technologies (such as wind and solar). This results in de-rating of reactors in order to give preference to the production from variable renewable technologies. However, nuclear and renewable technologies are preferred over GHG-emitting technologies. For this reason, nuclear reactors and variable renewable technologies are no longer perceived to be at odds with each other. Instead, an energy system is required that leverages the unique capabilities of each technology to create an "all of the above" clean solution that is reliable and cost-effective.

In 2018, CNL initiated a research project under Atomic Energy of Canada Limited's Federal Nuclear Science and Technology Work Plan to develop a hybrid energy system optimization model. This model was developed to study the interactions between different supply and demand sources in hourly, seasonal, and annual timeframes, to better understand the trade-offs of different energy systems and what is required to transition to a cost-effective low-carbon energy system in different regions across Canada. With an objective to identify the lowest-cost energy system that meets GHG target emissions, the hybrid energy system optimization model highlights how different technologies can be combined to complement each other, as shown in Figure 6.

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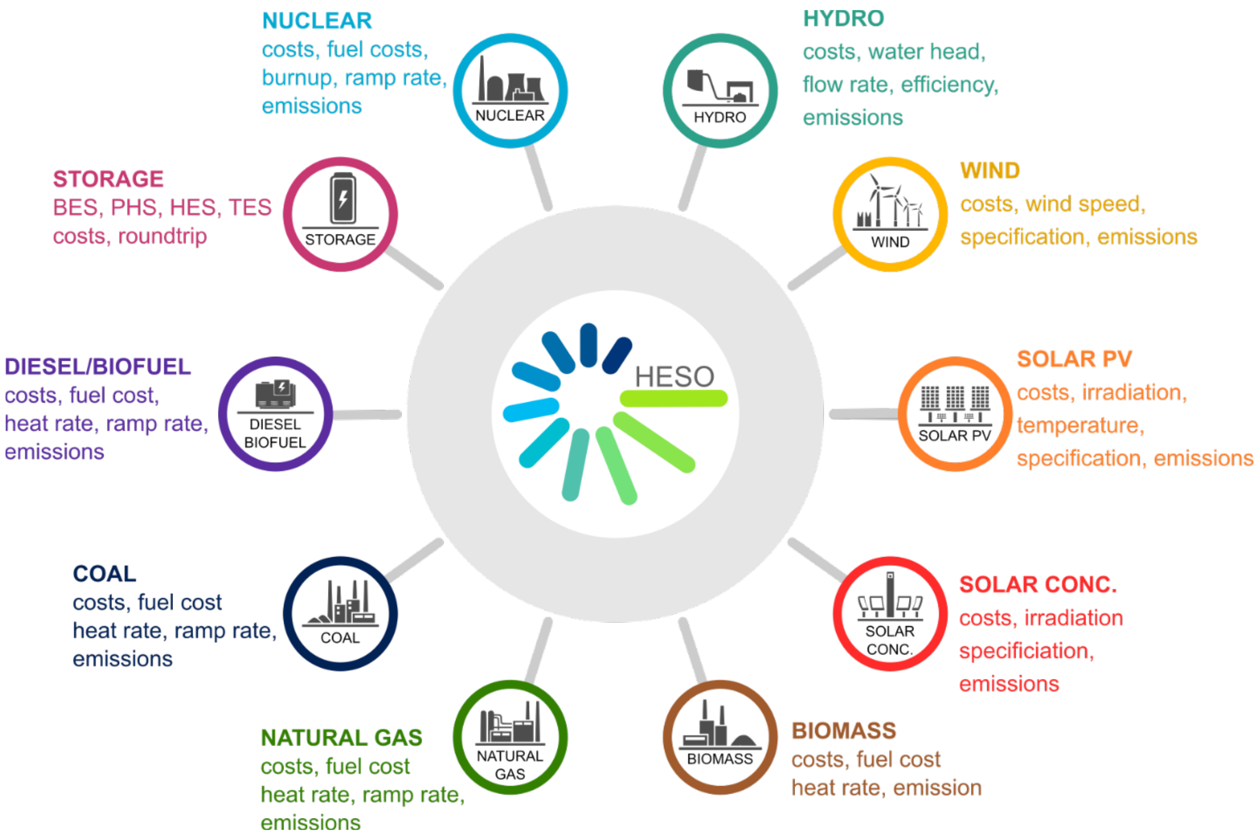

Figure 6. Hybrid energy system optimization model inputs

Source: CNL. Used with permissions.

In 2020, a number of cases were evaluated using this model, including one that studied the impact of electrifying residential water heating.

4.2 Residential Water Heating Electrification Case Study

The two main methods for heating water in Canada are electric or fossil-fueled (most commonly natural gas). A case study was performed to understand the impact of converting fossil-fueled water heaters to electric water heaters in a given region. It is expected that low-carbon electricity sources, such as nuclear, could displace the natural gas through electrification and reduce overall emissions.

The scenario assumed just over 42 TWh of thermal energy is currently supplied by natural gas to heat water, emitting just under 21 megatonnes (MT) of GHG annually. The electricity grid currently produces 135 TWh of electricity, emitting only 2.65 MT of GHG. Several alternate scenarios were studied where a portion of the fossil-fuel water heaters were to converted electric water heaters, ranging from 25% penetration to 100% penetration.

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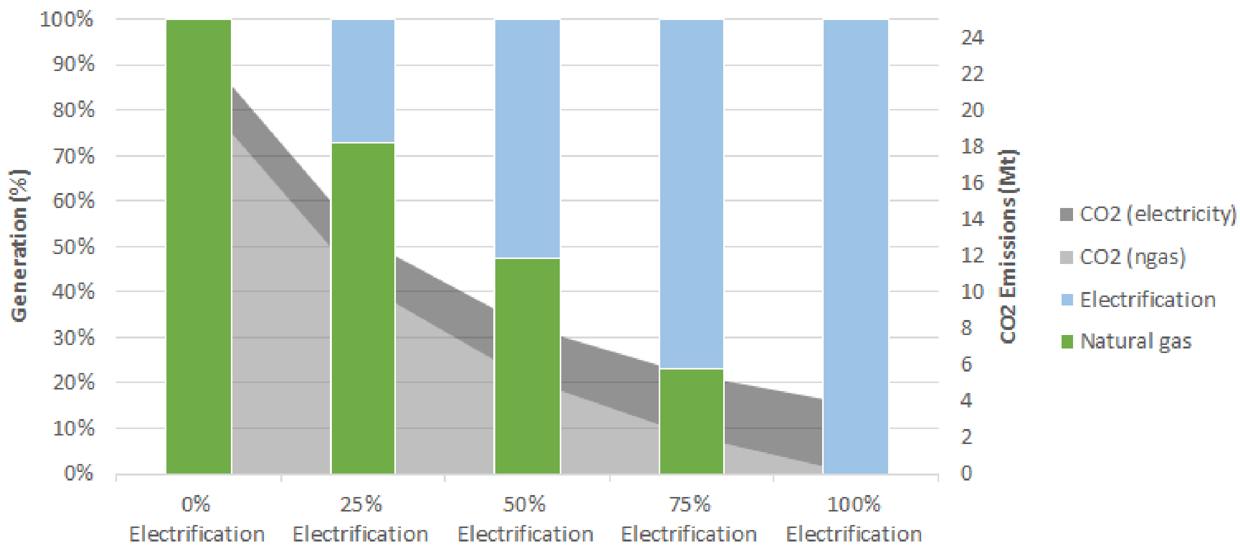

Figure 7. Reduction of GHG emissions by electrification of water heating

Source: CNL. Used with permissions.

Figure 7 shows that electrification will result in a significant decrease in GHG emissions from water heaters, with only a slight increase in GHG emissions from electricity production. This was achieved, while keeping the cost of electricity constant, by increasing generation from wind, solar and conventional nuclear power plants to maintain the same total percentage of generation, while also increasing electricity generation from natural gas to address the increased variability in the system as shown in Figure 8. It is expected that advanced nuclear reactors will have improved load following capabilities that could further reduce GHG emissions by displacing natural gas electricity generation and allow for a higher penetration of wind and solar.

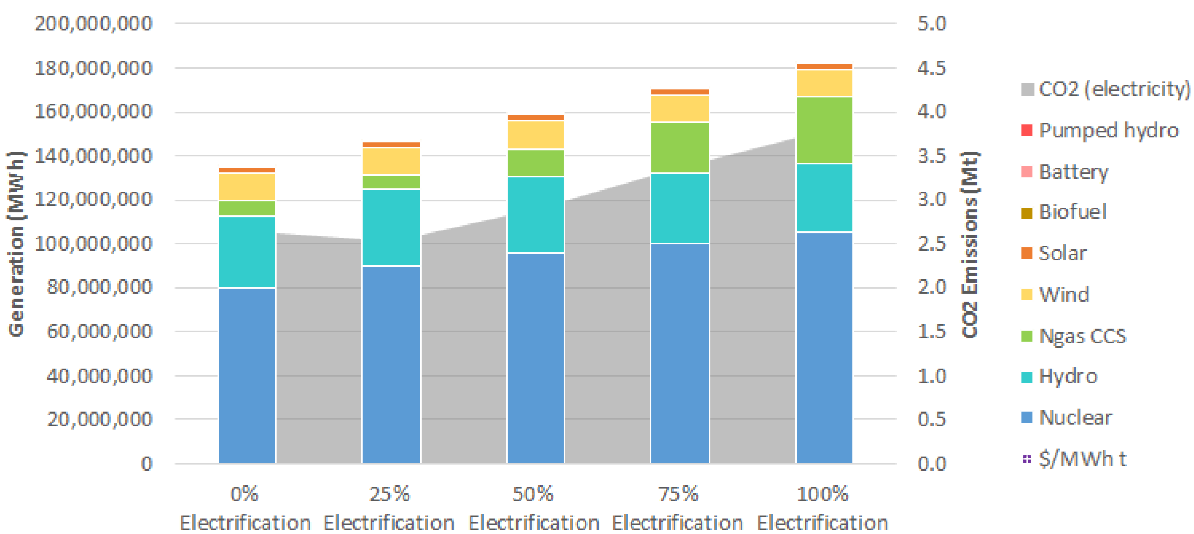

Figure 8. Ontario electricity generation by source based on electrification level (energy generation)

Source: CNL. Used with permissions.

Although promising, additional work is required to improve the cost-competitiveness of electric heat. The poor roundtrip efficiency compared to direct heat with fossil fuels and North America's

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abundance of low-priced natural gas makes electric heat prohibitively expensive in many parts of Canada. While natural gas prices remain low, alternative products, such as clean hydrogen, may be better for this application.

4.3 Coupling of Nuclear to Industrial Processes for Greater Flexibility

One of a nuclear reactors greatest strength in a flexible energy system is its ability to provide both heat and electricity. Historically, most nuclear reactors have focused on electricity production to meet base load demand. When electricity demand dropped below base load levels, generation is reduced, which also reduced the revenues earned during that period. However, by leveraging the heat produced by a nuclear reactor, nuclear energy can enable several opportunities to improve flexible operations as part of a clean energy system, while also increasing revenues.

One approach to flexible operations requires coupling the nuclear reactor to an industrial process that can utilize the high temperature heat from a reactor (e.g., hydrogen production). Operation can be shifted between products in response to variability in electricity demand by changing the pathway of the steam. When electricity demand is high, all steam is sent through the turbine set to generate electricity. During periods of low demand, some (or all) of the steam is diverted to the industrial process.

To support product flexibility, CNL is advancing research into aspects of the hydrogen economy to ensure hydrogen production and storage can be used safely as part of the flexible energy solutions of tomorrow.

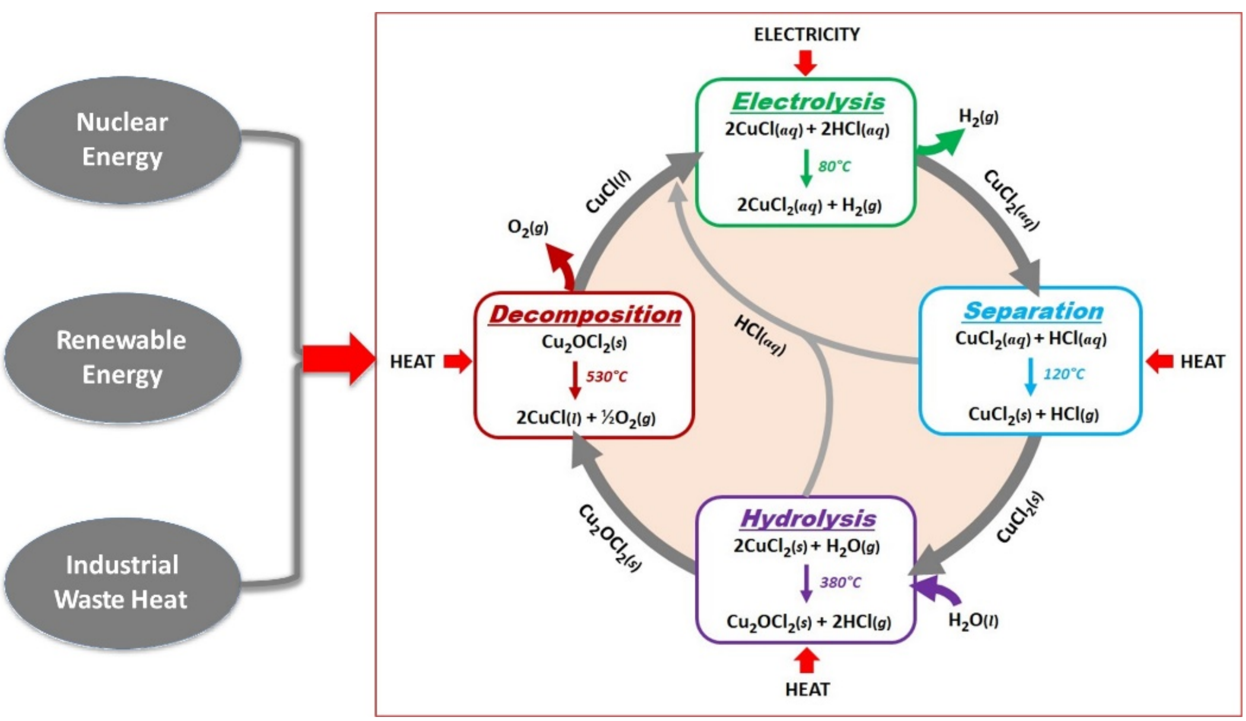

Figure 9. Hybrid Cu-Cl thermochemical hydrogen production

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CNL is leveraging a long history of hydrogen research as applied to the CANDU industry in heavy water production, hydrogen safety and tritium management, and, most recently, hydrogen

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production and fuel cell research. CNL is presently demonstrating the full copper-chlorine (Cu-Cl) process, a hybrid thermochemical cycle using heat and electricity to produce hydrogen at the lab scale (shown in Figure 9), progressing toward large-scale hydrogen production without GHG emissions. Thermochemical cycles have an advantage for large scales, and potentially higher efficiency, than electrolysis, owing to direct use of thermal energy. The Cu-Cl cycle consists of three chemical reaction steps (electrolysis, hydrolysis, and decomposition) and auxiliary physical processes (water removal by drying/crystallization, species separation, and heat recovery). The overall reaction of the cycle is the splitting of water into hydrogen and oxygen:

$$H_2O \rightarrow H_2 + \frac{1}{2} O_2$$

In simplest terms, the CuCl thermochemical cycle uses water, heat, and electricity as inputs to produce hydrogen and oxygen. The copper containing compounds are circulated throughout the process and are not consumed. The attractive features of the Cu-Cl process, compared to other thermochemical cycles, are the lower operating temperatures (highest temperature for the cycle is 530 C, well-suited for coupling to many Gen IV technologies. Therefore, corrosion issues are more tractable than for other higher-temperature cycles. The main technical challenges of the Cu-Cl process are related to the complex reactions associated with some steps and the difficulty with solid material transfer (particularly at elevated temperatures). CNL is working to address these challenges and to generate data for scaling up the process from laboratory scale, to pilot scale, and ultimately to industrial production scale.

CNL is also developing technologies to store hydrogen in metal alloys, liquid organics, and underground hydrogen locations. CNL has contributed to the development of conventional hydrogen safety applications to advance the safe use of hydrogen as an energy storage medium and as a fuel in the broader economy leveraging hydrogen safety expertise derived from nuclear sector applications. Recently, CNL expanded its capability to model the entire hydrogen system network required for fuel cell powered passenger trains (e.g., rail (CH2M, EY, and CNL 2018)). The modeling capability can also be applied to demonstrate the viability of coupling nuclear reactors to other industrial processes for greater system-wide flexibility.

4.4 Other Initiatives

The Government of Canada provided an investment of $1.2 billion over 10 years, beginning in 2016, to revitalize the Chalk River Laboratories. This investment on new and renewed science infrastructure will support the nuclear research needs of the Canadian Government and the evolving science and technology needs of the Canadian and global nuclear industry. It will build a world-class nuclear science and technology campus and position the organization as a global leader in nuclear science and technology, growing its commercial business and building a modern, efficient and collaborative campus environment at the Chalk River Laboratories.

This investment will support CNL's long-term goals in to demonstrate the commercial viability of advanced reactors, including the small and very small modular designs. The ability to demonstrate the flexibility of nuclear power using SMRs coupled with other technologies and energy sources requires an operating demonstration unit. Accordingly, CNL is pursuing initiatives, in addition to those identified above, to advance the deployment of SMRs in Canada. CNL has a strategic goal to deploy a SMR at one of our managed sites by 2026. To date, several SMR vendors have expressed an interest in siting a demonstration reactor project through CNL's SMR Siting

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Invitation Process while, in parallel, working on aspects of licensing with the Canadian Nuclear Safety Commission, the national regulator. In 2019, CNL launched the Canadian Nuclear Research Initiative to help advance research and development needs of SMR technologies. In the Canadian Nuclear Research Initiative program, CNL and SMR vendors pursue joint research projects, to be executed at CNL, focused on accelerating the deployment of SMRs in Canada and developing innovative solutions for the SMR industry.

The deployment of SMRs is a major milestone toward flexible nuclear operation in Canada, as their smaller size and advanced reactor technology will enable clean nuclear to be leveraged in some of the harder to decarbonize areas such as remote communities or industrial sites. In conjunction with siting an SMR at CNL, the Clean Energy Demonstration Innovation and Research park concept is being developed. The intent of this Clean Energy Demonstration Innovation and Research Park is to bring industrial partners and technology developers together with SMR vendors to demonstrate the ability to couple SMRs with other technologies, thereby increasing the flexibility of the system. The park will be a venue to showcase the technologies for interested stakeholders, resolve technical issues (e.g., licensing) and demonstrate integration of technologies (e.g., hydrogen production, district heating, desalination) to inform optimal energy usage during all times of the day and periods of the year.

Today, CNL continues its commitment to ensure Canadians and the world receive clean energy, health, and environmental benefits from nuclear science and technology with confidence that nuclear safety and security are assured.

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5 Idaho National Laboratory: Nuclear Flexibility via Multiple Products in Integrated Energy Systems

Prepared by Shannon Bragg-Sitton and Konor Frick of the Idaho National Laboratory (INL), a laboratory operated under DOE's laboratory complex.

INL is 1 of 17 DOE National Laboratories in the United States. INL, managed by Battelle Energy Alliance for the DOE Office of Nuclear Energy (DOE-NE), is the leading center for nuclear energy research and development. It is INL's vision to change the world's energy future and secure our nation's critical infrastructure. As such, the INL mission is to discover, demonstrate, and secure innovative nuclear energy solutions, other clean energy options, and critical infrastructure. INL's Integrated Energy Systems initiative, highlighted in the work presented here, is central to achieving a future in which energy demands across multiple use sectors are met by a combination of non-emitting energy sources to provide an optimized energy future. This chapter highlights work led by INL, in collaboration with other national laboratories, including Argonne National Laboratory, Oak Ridge National Laboratory, and NREL, to evaluate integrated energy system options that utilize nuclear energy in new ways. By working with key collaborators in the nuclear industry, these analytical studies are now becoming a reality in demonstration projects.

As established in the introduction to this report, nuclear energy systems can be flexible via many pathways, including operational flexibility (varying core power through various approaches) or product flexibility. This section focuses on nuclear flexibility via the production of alternative products in response to varying net demand for electricity. Recognizing that nuclear reactors have a demonstrated record of flexible power output, as described in the chapters provided by EDF and Exelon, this operational mode may not be economically desirable under all scenarios or within all electricity markets, nor does it efficiently use the capital that has been invested in these thermal generation systems.

The primary focus of the DOE-NE Program on Integrated Energy Systems, led by researchers at INL, has been to assess the potential for integrated energy systems to enhance the flexibility of the energy supplied by nuclear plants and to thereby maximize the use of the clean energy provided by these systems (Bragg-Sitton et al. 2020). This work begins with the question: "What additional product streams can be made using excess energy?" This question must be addressed within the context of a specific deployment location, which has implications relative to the electricity market structure, supply, and demand; available feedstock for industrial processes; and available product markets. Product streams, ranging from potable water to hydrogen, synthetic fuels, ammonia-based fertilizers, and various chemicals, have been considered. Each product stream has its own market and market drivers and its own geographic location that would maximize profitability. Some of these products would only require electricity to support production, while others require both thermal and electrical energy.

5.1 Modeling and Simulation Toolset

The DOE-NE Integrated Energy Systems program has developed a computational framework that leverages various modeling and simulation tools to specifically support the specialized requirements for designing, evaluating, and optimizing integrated energy systems configurations within the context of various market structures. This specialized framework is applied to assess

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the technical and economic viability of potential system constructs for both loosely coupled (electricity-only integration) and tightly coupled system designs. These systems require the dynamic exchange of large amounts of data, process conditions, energy streams, and control commands to operate efficiently. The integrated energy system simulation framework is designed to support both steady state and dynamic system operation, ensuring that energy balances are maintained under all conditions. Subsystems are defined with sufficient fidelity to assess technical performance; once a feasible technical solution is defined, economic performance optimization can be applied within defined operational and technical performance constraints. Five key components make up the simulation ecosystem, which is continuously being enhanced to ensure that it can support an evaluation of system options (e.g., multiple reactor concepts, process options, energy markets):

1. Renewable energy profiles and energy demand, represented by stochastic time series
2. Probabilistic analysis and optimization algorithms, implemented in the INL-developed Reactor Analysis and Virtual Control Environment (RAVEN) (Cristian Rabiti et al. 2017)
3. Detailed process models for plant design and systems integration at the level of process unit operations (e.g., heat exchangers, pumps, compressors, chemical reactors)
4. Reduced order models representing dynamic physical behavior of subsystems developed from plant design models (e.g., generation technologies, power conversion, energy users), developed in the Modelica language (Modelica Association 2018)
5. Integrated energy system-specific RAVEN plugins for economic performance analysis, Tool for Economic AnaLysis (TEAL, formerly called CashFlow) (C Rabiti et al. 2017), and Heuristic Energy Resource Optimization Network (HERON) (Talbot, Gairola, et al. 2020).

This simulation approach is applied to illuminate the economic potential of using nuclear energy to support various process applications. The framework applies a probabilistic approach in conducting these analyses to allow the model to capture the inherent uncertainties in projecting project costs and revenues. The integrated energy system simulation framework supports simultaneous stochastic modeling of several markets and units, as shown in Figure 10.

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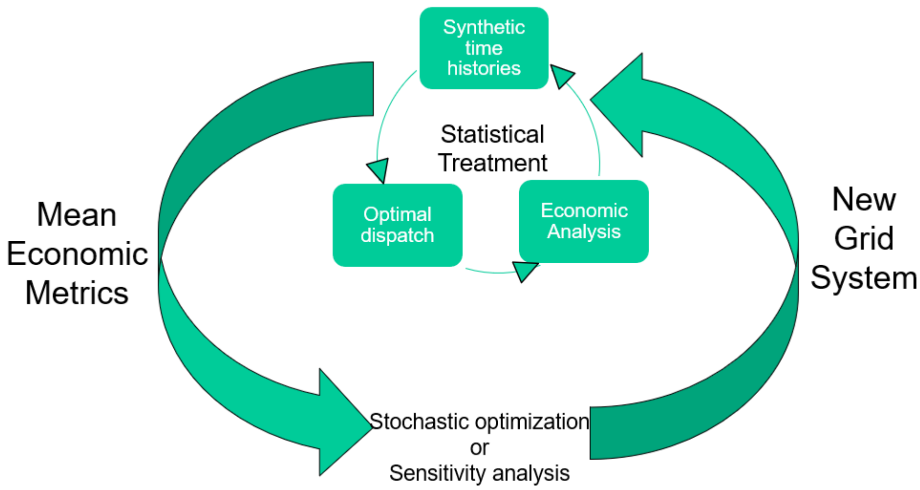

Figure 10. Stochastic technoeconomic analysis workflow

Source: INL. Used with permissions.

RAVEN acts as the workhorse of the integrated energy system framework. Its tasks include:

- Creation of exogenous market conditions (i.e., electricity demand, Variable Renewable Electricity generation) via reconstruction of trends, using:
    - Fourier decomposition
    - Stochastic behavior, using auto regressive moving averages (Talbot, Rabiti, et al. 2020).
- Parallel dispatching of the software representing the physical model on both desktop and high-performance computing machines
- Optimization of the system design and operation
- Uncertainty quantification.

To accomplish this, RAVEN relies heavily on artificial intelligence algorithms to reduce computational cost of performing uncertainty quantification, reliability analysis, and parametric studies. This is achieved by training machine learning algorithms to surrogate models of complex physical systems.

TEAL is a plugin that enables RAVEN to compute several financial indices, including net present value, internal rate of return, and profitability index. TEAL monitors the simulation, performed by RAVEN, and extracts the values of a set of prescribed cost drivers to build the financial indices. Those indices can be used as a goal function for the optimization search. TEAL also includes flexible options to deal with taxes, inflation, and discounting and offers capabilities to compute a combined cash flow for components or subsystems that have different lifetimes.

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HERON is a plugin that enables RAVEN to perform stochastic technoeconomic analyses of grid-energy systems in a generic approach. The primary functions of HERON are to generate the complex RAVEN workflows necessary to optimize component capacities under stochastic systems and to perform optimal dispatch of the system resources. HERON can analyze systems with complex components transferring a variety of commodities, including production components and varied markets.

High-fidelity dynamic process models are created in the Modelica language. The Modelica language is a nonproprietary, object-oriented, equation-based language that supports the modeling of complex, physical systems; thus, it has been widely adopted across industry for commercial application. Modelica is an inherently time-dependent modeling language that allows for the rapid interconnection of independently developed models, thus supporting system interconnectivity and the development of novel control strategies, while still encompassing overall system physics. Models are used to evaluate system design options, characterize system inertia, calculate thermal losses, and determine efficiency of integrated systems. Current models in the INL library include thermal energy storage, electrical energy storage, reverse osmosis, four-loop nuclear power plants, integral pressurized water reactors (PWR) (based on the IRIS reactor), natural gas turbines, high-temperature steam electrolysis (HTSE), and switchyards. Additional dynamic models are developed as needed to support the growing suite of case studies.

Analysis of a proposed integrated energy system configuration is initiated by selecting a deployment location and technologies to be included in the study. An analysis might consider the use of existing plants (e.g., a current fleet nuclear plant with an established capacity) or may consider a greenfield build of all subsystems. The intended deployment location establishes the electricity and product markets, demand structures, and so on. RAVEN then takes the regional market data, creates an Auto Regressive Moving Averages and Fourier representation of the data, and then samples it to create synthetic time histories of the original data that preserves the underlying trend; it is statistically identical but represents different potential transient scenarios. Time-dependent electricity demand and/or prices, solar and/or wind generation data, market requirements, and other input data necessary to drive the optimization is fed into the dispatch plugin HERON. HERON uses this information to create a dispatch schedule for all the plants based upon a user defined goal function (e.g., marginal cost, maximum net present value, reliability in covering total demand). These dispatch scenarios are then used as input to the physical Modelica models to drive the simulation. Any missed demand that results from technical constraints, such as ramp rates and physical limitations for the various subsystems, is reported, leading to a change in the dispatch strategy or application of a penalty function in the analysis. The net present value is then computed using the CashFlow plugin based on demand that is met, missed demand, and ancillary product sales. This process is repeated until an optimal solution is found.

This framework has been a key tool in successfully simulating regional energy networks to provide economically optimized solutions for nuclear utilities. Results of specific case studies have led to utility plans to demonstrate integrated energy systems at existing nuclear plants in the United States, specifically hydrogen production, as reported later in this chapter.

5.2 Experimental Toolset

The laboratory research team is developing experimental systems for concept demonstrations to support the validation and verification of the physical modeling results and conclusions. The

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demonstration will first utilize a scaled, electrically-heated integrated test facility at INL, followed by a demonstration within nuclear systems. The Dynamic Energy Transport and Integration Laboratory is currently being installed within the INL Energy Systems Laboratory to demonstrate an integrated system operation in a lab setting. The Dynamic Energy Transport and Integration Laboratory will utilize controllable electric heaters to demonstrate simultaneous, coordinated, and efficient transient distribution of electricity and heat for power generation, energy storage, and industrial end uses (Frick, Duenas, et al. 2019). The overall facility will provide a demonstration of real-time integration with the electrical grid, renewable energy inputs, thermal and electrical energy storage, and energy delivery to an end user, as shown in Figure 11. As such, an integrated energy network can be emulated with hardware-in-the-loop to improve our understanding of how to optimize energy flows while maintaining system stability and efficient operation of all assets in the system. Further, such a system will provide insight into the performance of new control algorithms, human factor needs, and cybersecurity requirements that will be present in integrated energy systems.

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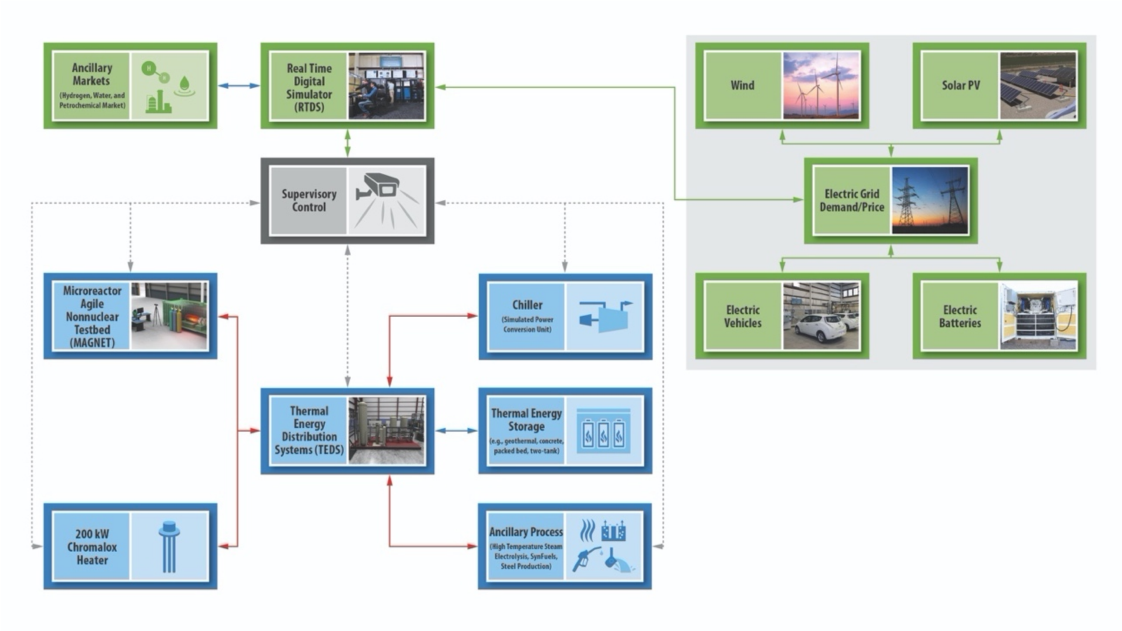

(a)

(b)

Figure 11. System configuration of the INL Dynamic Energy Transport and Integration Laboratory: (a) Overall planned configuration of all components; and (b) Rendering of key laboratory facilities. The Thermal Energy Distribution System (TEDS) and MAGNET facilities are currently under construction.

Source: INL. Used with permissions.

Serving as the backbone of the installation is the TEDS (Stoots et al. 2019), shown in Figure 12. This system is designed to be a "plug-and-play" network of valves, pipes, and heat exchangers that allows the mass movement of thermal energy between connected subsystems. TEDS is currently designed to utilize the commercially available heat transfer fluid Therminol-66. Therminol-66 operating conditions range from -3˚ C to 343˚ C, while vapor pressure remains low across the operating band. With this large operational band, different systems can be attached to the TEDS without the need to swap to a different fluid. The system is designed to support the emulation of energy input from nuclear or coal generators, which typically have outlet temperatures on the order of 300˚ C from the main system steam generators.

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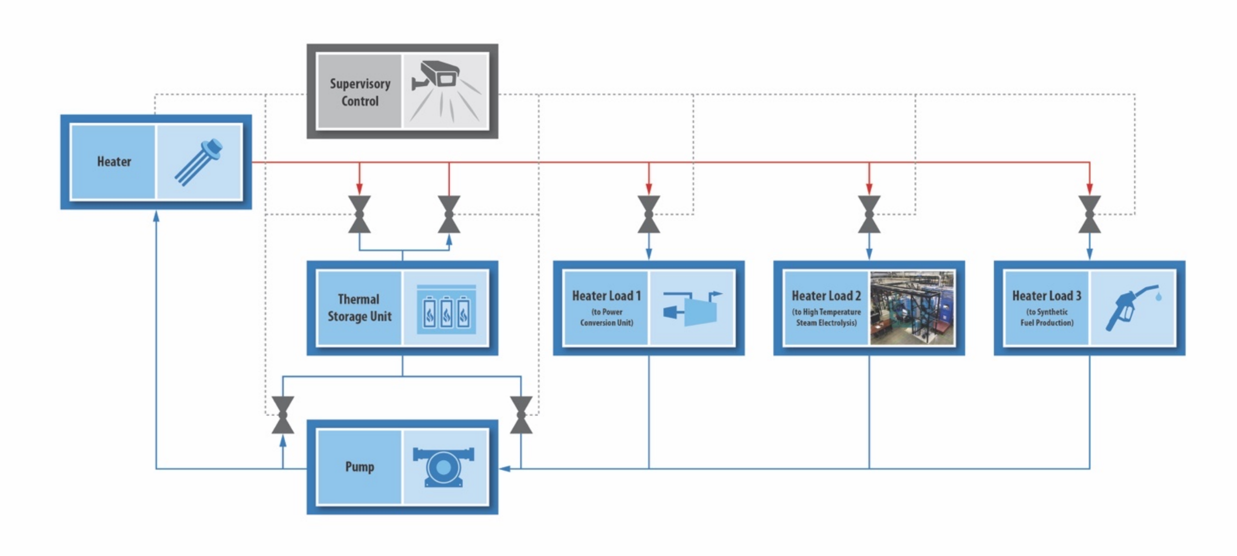

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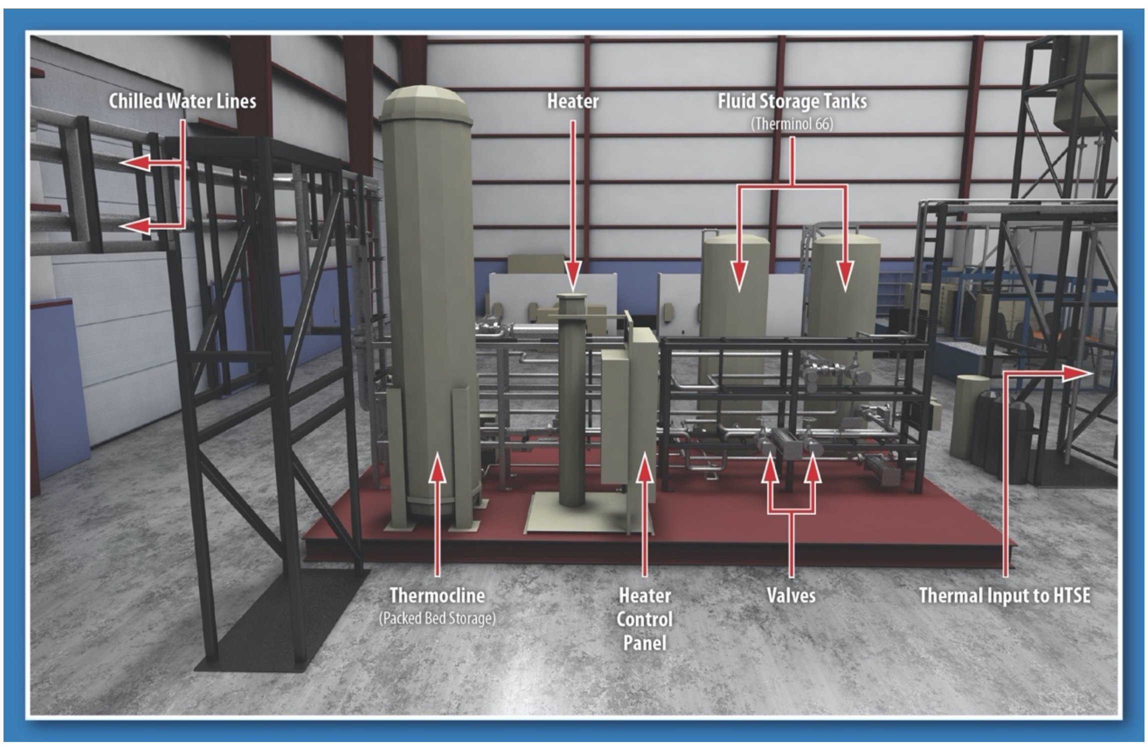

(b)

Figure 12. Simplified system configuration for the INL TEDS, showing: (a) Flow paths; and (b) Rendering of hardware components. TEDS hardware is currently being installed and will be operational in 2020.

Source: INL. Used with permissions.

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The initial ancillary product end user is HTSE hydrogen production facility. The current facility is a 25-kWe HTSE system (O'Brien et al. 2020), but this will be replaced by a larger scale system (~150-kWe) in the near future. This coupling will enable system control to be verified, while simultaneously allowing for system dynamics and characteristic times scales of heat up and cool down to be quantified. Additional heat loads to be tested in the initial phase of TEDS operation include a single-tank packed bed thermocline and a simulated Rankine cycle power conversion unit.

The broader Dynamic Energy Transport and Integration Laboratory includes several microgrid components, such as the digital real-time simulator stations that represent power systems in the grid and facilitate real-time connections to other geographically diverse facilities, wind energy input, solar photovoltaic (PV) input, chemical flow batteries, and electric vehicle and battery charging. The digital real-time simulator enables a connection to outside wind farms, such as the National Wind Technology Center at NREL, that uses real-time wind data to offset demand curves. Virtual connection with existing test facilities that emulate the dynamics of a nuclear reactor primary, such as the NuScale Integral System Test facility at Oregon State University, is also being assessed. Additionally, there exists hardware-in-the-loop that provides realistic time delays and thermal time constants that the system must adhere to. Several additional flanges were added to TEDS to support interconnection with additional thermal energy providers and end users to increase the functionality of TEDS as a plug-and-play type of system. Electrically heated nuclear reactor emulation systems and thermal energy distribution infrastructure are expected to be installed in 2020.

5.3 Case Studies and LWR Demonstration Projects

Leveraging the vast knowledge base and simulation toolsets available from the DOE-NE Integrated Energy Systems and LWR Sustainability programs (INL n.d.), INL has been a lead partner on several cost-shared projects with nuclear utilities to evaluate the potential for nonelectric application of existing nuclear plants in the U.S. Utility partners include Arizona Public Service (APS), Exelon, Energy Harbor, and Xcel Energy. Each of the utility partners are considering implementing flexible operations at their currently-operating nuclear stations, specifically via product flexibility, to provide an alternative revenue stream for their plants (Wald 2019). In general, these utilities are exploring a phased approach to flexible operations, initially using in-front-of-the-meter electrical integration to support additional processes (e.g., water purification and hydrogen production), with the goal of eventually incorporating higher-efficiency processes through a combination of thermal and electrical integration if the economic case is strong. A summary of these activities is available in Table 1.

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Table 1. U.S. LWR (Current Fleet) IES Case Study Synopsis

Utility	Product Stream	Technology	Market	Volatility Driver	Coupling
APS	Water	Reverse osmosis	Regulated	Solar and water scarcity	Electrical and physical water lines
Energy Harbor/Xcel/ Arizona Public Service	Hydrogen	Low-temperature electrolysis	Regulated (Energy Harbor), Deregulated (APS, Xcel)	Wind and natural gas	Electrical
Exelon	Hydrogen	HTSE	Deregulated	Wind and natural gas	Electrical and thermal
Exelon	Hydrogen	Low-temperature electrolysis	Deregulated	Wind and natural gas	Electrical

As seen in Table 1, an emphasis has been placed on hydrogen production as an option for nuclear plant flexibility in these initial U.S. case studies. Hydrogen, as a basic feedstock for several large energy markets, could provide an additional source of revenue to enhance the value of existing nuclear plants and to further enhance their ability to respond to varying demand. To this end, utilities are implementing demonstration projects for both low temperature and high temperature electrolysis technologies. Low-temperature electrolysis takes water molecules as an input and applies a current across an electrolytic cell to split the water molecules into pure oxygen and hydrogen. HTSE follows a similar process but operates at much higher temperatures (650˚C-800˚C), thus achieving higher efficiencies. Both processes are currently under consideration for demonstration and pilot application within the nuclear industry. Low-temperature electrolysis is easier to configure with a nuclear power plant since it only requires electrical energy, while HTSE has the potential to produce hydrogen at a price that is more economically competitive. A detailed synopsis of the energy requirements for both is available in Table 2.

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Table 2. Breakdown of Hydrogen Production Technology Energy Requirements

Hydrogen Production Technology	Electrical vs. Thermal Requirements	Electric Ramp Rate Limit	Steam[3] Ramp Limit	Fixed demand needed for hot standby mode[4]
Low-Temperature Electrolysis	100% electrical, 0% thermal	100% can be ramped instantaneously	N/A	0% assuming PEM electrolysis
HTSE	85%–95% electrical, 5%–15% thermal	80-90% can be ramped instantaneously, remainder is used as topping heat	Fixed steam flow in current designs	10%–20% electrical energy as topping heat; all thermal energy used for feedstock preheating

In addition to hydrogen production technologies, water treatment via reverse osmosis is also considered for utilities with limited regional water supply. An in-depth look at each of the four case studies is presented below.

5.3.1 APS

APS is the operating owner of the Palo Verde Generating Station in the arid southwest region of the United States that has recently seen a boom in solar installations. Palo Verde Generating Station, the largest nuclear plant in the United States, is home to three PWRs. Palo Verde Generating Station uses mechanical draft evaporative cooling towers that provide for steam cycle waste heat rejection. The Palo Verde Generating Station cooling water is provided via a contract with local municipalities to utilize reclaimed municipal wastewater. In the U.S. Southwest, water resources are limited, and the effluent is becoming increasingly more valuable to these municipalities as scarcity of the natural water resources increases concurrent with population growth in the area. As a result, there is a steep escalation in the annual cost of effluent. This results in increased plant cooling costs, leading APS to seek alternative sources of water to use for facility cooling needs.

APS has been researching this issue in cooperation with researchers at INL to evaluate the potential for using a portion of the electricity from Palo Verde Generating Station to desalinate brackish groundwater using reverse osmosis. Addition of reverse osmosis could help the plant to manage the increasing penetration of solar PV in the region while simultaneously reducing the cost of cooling water. Reverse osmosis requires only electrical integration and can be cycled on and off at will as electricity prices fluctuate. This desalinated water, devoid of harsh minerals that would

[3] Flexibility in steam delivery depends on the operating power level and turbine design. Variation of steam flow to electric and nonelectric applications may be limited to less than 3% per hour at some PWR plants if the reactor is between 90% and 100% of its thermal power rating. Limitations to the rate of change in steam flow between the turbine and some ancillary process, such as HTSE, while maintaining constant reactor thermal power, needs to be investigated for the specific plant and turbine set and thus is not reported here. Maximum diversion of steam from the turbine to coupled processes without shutting down portions of the plant secondary depends on the plant and component designs.

[4] Hot standby is when the process is producing zero product but is capable of going to 100% product production almost instantaneously.

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foul heat exchangers, can then be used to cool the plant, with excess fresh water potentially being sold to the public. By desalinating groundwater, APS can potentially reduce the amount of reclaimed wastewater that must be purchased from local municipalities.

Utilizing the RAVEN/HERON/Modelica toolset, a regional water market was constructed for the Phoenix west valley alongside reverse osmosis and Palo Verde water train process models. Several analyses have been carried out using these tools. The conclusions were unexpected, highlighting the possibility of using discharged brine from a large reverse osmosis plant to be diluted into the cooling water and subsequently disposed using Palo Verde Generating Station evaporation ponds. This would lead to a decreased cost to generate potable water due to the decreased waste management cost at the reverse osmosis. Moreover, the analysis also showed possible benefits to Palo Verde Generating Station due to reduction in the costs of water procurement.

The technoeconomic analysis framework developed at INL allowed identification of this business opportunity with a possible differential net present value of ~$100 million if all municipalities in the vicinity participated (Epiney et al. 2019).

5.3.2 Energy Harbor/APS/Xcel

The principle objective of the project awarded to the tri-utility consortium of Energy Harbor, APS, and Xcel Energy is to carry out the planning, design, installation, testing, demonstration, and evaluation of integrated energy technologies connected to an LWR power plant, with a focus on a scalable hydrogen generation pilot plant. The project will install a low-temperature electrolysis hydrogen generation pilot plant unit at the Davis-Besse Nuclear Power Station in Ohio (Boardman et al. 2019). The financial security of the Davis-Besse plant has recently been challenged by falling natural gas and renewable energy prices. Owing to its geographical location, large transportation network, and proximity to large industrial users in America's heartland, Davis-Besse was selected as the pilot nuclear demonstration facility for low-temperature electrolysis hydrogen production. The project, which is supported by a cost-share award from DOE, aims to install a 2-MWe low-temperature electrolysis unit to produce hydrogen by splitting water molecules into H_2 and O_2. This initial demonstration is expected to operate from January 2021 to January 2023 (Henry 2020). Energy Harbor would utilize the clean hydrogen produced as a secondary revenue stream for the nuclear facility while still supporting the grid at its maximum capacity at times of high electricity demand. Hydrogen, as a base product of many petrochemical industries, would be marketed to the surrounding refineries, fertilizer plants, and other agricultural production facilities. The expected result is to have a fully functional operating hydrogen generation skid that has been integrated into the normal operating routine of a nuclear power plant. In addition, accumulated operating data will highlight the technical feasibility and economic viability of this integrated system.

The project will also include technical and economic assessments for APS and Xcel Energy, which operate nuclear power facilities in different electricity markets in the United States. These assessments will support the technical and financial feasibility of integrated system operations for hydrogen generation. This information, along with pre-front-end engineering design input from the collaborating utilities, will support the development of an investor-grade report summarizing the business case for undertaking similar projects to implement hydrogen generation at other LWR power plants. Results from the system demonstration will ultimately be available to other nuclear power utilities to support the large-scale commercialization of the integrated energy system technology at the 100s-MWe scale.

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If the initial demonstration is successful, Energy Harbor is considering the potential for an increased investment into larger systems that may include a thermal integration component to support high-temperature electrolysis. This initial demonstration will help utilities understand the benefits, challenges, and regulatory and marketplace requirements for the multimarket operation of such systems. A larger-scale hydrogen production system could supply additional clean hydrogen to the various customers mentioned earlier at an even lower cost point.

5.3.3 Exelon

In addition to the regional cases with APS and Energy Harbor, wind resources coupled with transmission network constraints across the U.S. Midwest are causing variable pricing scenarios for nuclear generating stations operated by the Exelon Corporation. As an initial response, several Exelon plants have begun operating with “advanced nuclear dispatch,” varying power output from the plant to avoid the sale of electricity at a loss. This operational mode is limited by U.S. Nuclear Regulatory Commission regulations and turbine ramp limits. Exelon is also considering extending their flexibility via alternative products. Hydrogen production, using excess energy from Exelon plants, could support the needs of the petrochemical, steel manufacturing, and agricultural industries throughout the Midwest.

A cost-share project led by Exelon Corporation in collaboration with DOE national laboratories will demonstrate an end-to-end integrated grid-scale carbon-free H_2 production, storage, and utilization pilot plant at an Exelon-owned nuclear generating facility, providing the necessary data to further reduce the technical and financial risk associated with commercial integrated energy system deployment. Via a partnership between INL, NREL, Argonne National Laboratory, Exelon, and Fuel Cell Energy, this project was initiated by a technoeconomic analysis of the viability of retrofitting existing PWRs to produce hydrogen (H_2) via HTSE. These analyses indicate that such integration would allow nuclear facilities to support the growing hydrogen market. The use of excess or low-price electricity for hydrogen production essentially provides an economic floor to the sale of electricity by the nuclear facility, leading to a paradigm shift in the interaction between the nuclear plant and the electricity market. The nuclear plant would sell electricity to the market only when prices are sufficiently high to compensate for revenue that would be lost by halting hydrogen production. In this, many nuclear plants could effectively operate in the electricity market as a peaking plant.

To accommodate such an integration, a detailed analysis of the HTSE process operation, requirements, and flexibility was conducted. The technical analysis includes proposed nuclear system control scheme modifications to allow for the dynamic operation of the HTSE via both thermal and electrical connection to the nuclear plant. High-fidelity Modelica simulations showcase the viability of such control schemes.

From the detailed analysis of the nuclear integration and the HTSE process design, a comprehensive cost estimation was conducted in the commercially accepted Aspen Process Economic Analysis and the Hydrogen Analysis Production models to elucidate capital and operational costs associated with the production, compression, and distribution of hydrogen from a nuclear facility. Alongside this costing analysis, market analyses were conducted by NREL and ANL on the electric and hydrogen markets, respectively, in the PJM interconnect (i.e., the Pennsylvania, Jersey, Maryland Power Pool), the regional transmission organization in which the Exelon nuclear plants operate.

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Utilizing the electricity data market projections in the PJM interconnect from NREL and hydrogen demand/pricing projections from ANL, a five-variable sweep over component capacities, discount rates, and hydrogen pricing was completed using RAVEN and its resource dispatch plugin HERON. Each combination of variables was evaluated over a 17-year timespan, from 2026 to 2042 (inclusive), to determine the most economically advantageous solution.

Results suggest that positive gain is achievable at all projected hydrogen market pricing levels and at all discount rates. However, exact component sizing and net returns vary based on these values, and, if incorrect sizing is selected, major net losses could occur. Overall, the results of the Exelon study advocate that, through market diversification, existing nuclear plants have the potential to substantially increase current profit margins, increase market penetration, and ultimately solidify their place as a mainstay in energy production in the U.S. Midwest. The complete results of the study are available in the report by Frick et al. (Frick, Talbot, et al. 2019).

Exelon is now moving forward to demonstrate hydrogen production, first using an electrically integrated low-temperature electrolysis, at an Exelon-owned and operated plant via a follow-on cost-share project with the DOE. This project will install a 1-MW low-temperature electrolysis unit at an Exelon plant (specific plant to be announced) and will evaluate market opportunities and regulatory requirements related to the participation of integrated hydrogen production and nuclear plant facilities in organized power markets. This will be accomplished by demonstrating dynamic control and operation of the electrolyzer and assessing the economics of dynamic participation combined with the revenue streams from hydrogen production. The main objective of this project is to demonstrate that hydrogen can be economically produced at large scale using nuclear energy. This demonstration will also verify the proposed operating scheme by testing the response characteristics of a commercially scalable hydrogen electrolysis unit and the ability to support grid regulation while producing hydrogen for local users. This demonstration will pave the way to potential future demonstration of large-scale, thermally integrated HTSE.

5.4 Future Work: Advanced Reactor Applications

The LWR industry community was instrumental in defining the initial pilot case studies focused on the use of excess energy from currently operating LWRs to support the production of nonelectric commodities, specifically focusing on water desalination and hydrogen production, and near-term, high-value opportunities. As the LWR studies move to demonstration for hydrogen production at Exelon and Energy Harbor plants, DOE and national laboratories will continue to support that work to ensure success. In addition, the DOE-NE Integrated Energy System program is moving forward to assess the potential for integrated energy systems that utilize advanced reactor technologies to support a wide range of industrial and chemical manufacturing processes.

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6 Agency for Natural Resources and Energy, Ministry of Economy, Trade, and Industry of Japan, and Japan Atomic Energy Agency: Japan's Current Efforts for Nuclear Innovation

Prepared by Takeshi Nagasawa, the Agency for Natural Resources and Energy (ANRE), Ministry of Economy, Trade and Industry of Japan (METI), and Hideki Kamide and Taiju Shibata, Sector of Fast Reactor and Advanced Reactor Research and Development within Japan Atomic Energy Agency (JAEA).

The ANRE is one of the external bureaus of the Ministry of Economy, Trade and Industry. The ANRE is responsible for Japan's Energy policies including nuclear, renewable, and natural resources.

JAEA is Japan's sole comprehensive research and development institute in the field of nuclear energy. In the area of advanced reactor development, JAEA is implementing research and development on fast reactors, high-temperature gas-cooled reactors (HTGRs), and related fuel cycle technologies, in order to attain further enhancement of future energy sustainability, safety, economic competitiveness, and flexibility.

6.1 Necessity of Nuclear Innovation and the Launch of the Nuclear Energy x Innovation Promotion Initiative

Nuclear power is an essential, economically efficient, carbon-free, and base load power source, as described in the Fifth Strategic Energy Plan issued by the Japanese government in 2018. Toward 2050 in the Plan, nuclear power is described as one of the viable energy source options for decarbonization, contributing to mitigating the risks of climate change specified in the Paris Agreement on Climate Change (UNFCCC 2015). Meanwhile, recent trends, such as the rapid expansion of renewable energy and new energy demands for the production of hydrogen and the utilization of process heat, are increasing the necessity of innovative nuclear technologies. In other words, ensuring flexibility to meet various societal needs in an integrated energy system is a long-term challenge and opportunity for nuclear technology development.

Under such circumstances, the Japanese government launched the Nuclear Energy x Innovation Promotion initiative in Fiscal Year 2019, aiming for innovation in nuclear technology. This initiative has a feature whereby it induces technological innovation led by the private sector and that it makes maximum use of the facilities and knowledge resources of the national nuclear research laboratory, the JAEA. In the Nuclear Energy x Innovation Promotion initiative, various nuclear power systems and safety improvement technologies are currently evolving, including SMRs and other nuclear power systems aimed at nonelectric production and use (e.g., hydrogen production) and harmonized combination with renewable energy. The JAEA has several test reactors and related post-irradiation test facilities, important numerical simulation tools, a knowledge database on nuclear system designs, and operational experiences in advanced reactors (https://www.jaea.go.jp/04/o-arai/en/index.html). JAEA will play an essential role in promoting nuclear innovation.

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6.2 Innovation for Flexible Use of Nuclear Power in JAEA

The flexibility of nuclear technology is one of the significant capabilities for advanced reactors when we consider their commercialization. The expanded flexibility concept was shown by the Electric Power Research Institute (EPRI) (Sowder 2019), with the definition of flexibility sub-criteria and attributes for evaluating advanced reactors as follows: (1) Operational flexibility (Maneuverability, Compatibility with Hybrid Systems, Island Mode Operation); (2) Deployment flexibility (Scalability, Siting, Constructability); and (3) Product flexibility (Electricity, Process Heat, Radioisotopes).

JAEA has several research and development activities aiming at innovation that will provide further flexibility, including a sodium-cooled fast reactor (SFR) and an HTGR. These activities are as follows:

1. Development of an innovative design evaluation code system for SFR and other advanced reactors

2. Codes and standards for maintenance of innovative reactors

3. Fast neutron irradiation using the experimental fast reactor, Joyo

4. Demonstration of higher safety performance of HTGR and the capability of its application to hydrogen production.

The details of these activities and how they contribute to improving the flexibility (i.e., operational flexibility, deployment flexibility, and product flexibility) of advanced reactors, such as SFR and HTGR, are explained below.

6.2.1 Development of an Innovative Design Evaluation Code System for SFR and Other Advanced Reactors

JAEA is developing a numerical simulation and design estimation system, named ARKADIA, which covers the whole plant life cycle for advanced reactors.

The ARKADIA system supports innovative plant design with higher safety and reliability through multilevel and Multiphysics simulations and a knowledge base that incorporate reactor design, operational experience, basic experiments, and numerical simulations. Part of the system was recently developed to simulate core behavior of SFRs, incorporating thermal hydraulics, neutronics, and deformation interactions of core structures. The ARKADIA contributes to the evaluations and design improvements for the safety of advanced reactors, which are the essential factors for their deployment flexibility. A safety evaluation code, named SPECTRA, was recently developed as a part of ARKADIA. Figure 13 shows physical models of the SPECTRA.

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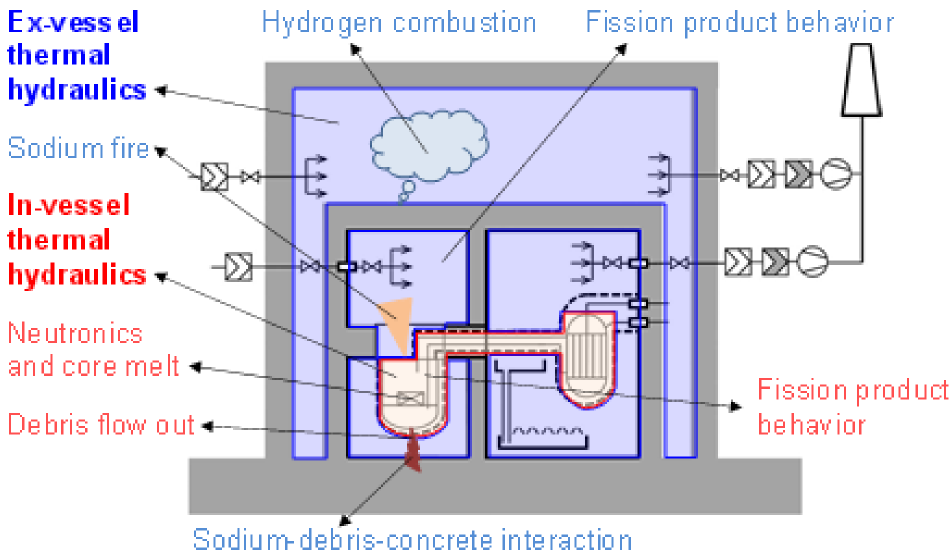

Figure 13. Physical models to be integrated into SPECTRA

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Maintenance is also a significant issue for the safety and economics of an innovative power plant. Development of ARKADIA will consider the mechanisms of plant damage, including thermal shock, thermal fatigue, and so on, using the Multiphysics simulation system, which provides feedback on the plant design before construction to develop an optimum balance between design and maintenance. Such thermal shock and thermal fatigue are key issues of the operational flexibility of advanced reactors which are operated at higher temperatures than LWRs.

6.2.2 Codes and Standards for Maintenance of Innovative Reactors

Codes and standards are important for establishing maintenance procedures in securing a high level of safety in innovative reactors through appropriate inspections. Good maintenance through adequate inspections can contribute to not only flexible operation of the reactors, but can also lead to simple designs with higher deployment flexibility. For example, excess inspection requirement may need large space around the weld lines and result in large or complex geometry of the components. Reliability of design and inspection requirement can be optimized in the component design based on the codes and standards of maintenance procedures. A resultant simple design enables factory manufacturing, and construction at a site.

JAEA contributes to the development of codes and standards through the Japan Society of Mechanical Engineers. Recently, a new code based on the “leak-before-break” concept entered the final stage for approval. It will contribute to standardizing necessary and sufficient inspection strategies for the proper maintenance of an SFR plant. It will further contribute to simple reactor designs and easy operation aiming for higher flexibility.

6.2.3 Fast Neutron Irradiation With the Experimental Fast Reactor, Joyo

Irradiation experiments are key to the development of advanced reactors, especially for the development of core materials used for those reactors. The reactor core must have an adequate safety margin for the operational flexibility and development flexibility. The irradiation

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experiment for the core material is significant to confirm the influence of neutron irradiation on the fuel integrity so as to cover wide range of plant operation conditions. JAEA operates the experimental fast reactor, Joyo. Many irradiation experiments have been conducted in Joyo using higher fast neutron flux. Various measurement techniques were also developed (e.g., online monitoring during irradiation and also high-resolution x-ray computed tomography for irradiated fuel subassemblies as a nondestructive post-irradiation examination).

JAEA is preparing for the restart of Joyo. JAEA submitted the amendment of permission for a change in reactor installation license to the Nuclear Regulation Authority of Japan in October 2018, and it is currently under review.

6.2.4 Demonstration of Higher Safety Performance of HTGR and the Potential for Application to Hydrogen Production

JAEA has been developing an SMR HTGR because of its inherent safety characteristics, compelling economics, and superior operational, deployment, and product flexibility. As for the product flexibility, HTGRs, due to their high temperatures, can be used in multiple heat applications, including power generation, hydrogen production, supplying process heat, sea water desalination, and so on. The overall utilization of reactor thermal power can exceed 80%. Regarding operational flexibility, the HTGR gas turbine and hydrogen cogeneration system has an excellent ability to adjust to the conditions and support power quality of an electric grid with a large input of VRE. As for deployment flexibility, HTGRs can be built close to industrial facilities and residential sites due to their excellent safety features. Inland installation is possible by adopting a dry cooling tower.

Toward the commercialization of HTGRs, JAEA is planning to:

- Demonstrate the safety of HTGRs and develop technologies for connecting hydrogen production and helium gas turbine systems to HTGRs by using the High-Temperature Engineering Test Reactor in Oarai, JAEA.

- Develop a steam generation system and technology for connecting to HTGRs and enhance reactor core performance through international cooperation.

With the successful development of HTGR by JAEA, it is expected that private companies will do the following things:

- Demonstrate the economic viability and reliability of HTGRs and validate business models using a demonstration reactor to be developed through international cooperation

- Commercialize the hydrogen production and helium gas turbine systems coupled to HTGRs in Japan.

The key facility of HTGR development is the High-Temperature Engineering Test Reactor, the only nuclear reactor in the world that can supply 950^{o} C of reactor outlet coolant temperature. The High-Temperature Engineering Test Reactor has been stopped since Great East Japan Earthquake in 2011. In June of 2020, JAEA obtained the permission of changes to reactor installation of the High-Temperature Engineering Test Reactor toward restart by Japan's Nuclear Regulatory

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Authority in conformity with the New Regulatory Requirements. The restart of the High-Temperature Engineering Test Reactor will occur in early 2021, and the High-Temperature Engineering Test Reactor safety demonstration tests (loss of forced cooling test and loss of forced cooling test without vessel cooling) under the Organization for Economic Co-operation and Development/Nuclear Energy Agency framework will be carried out immediately after the restart.

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7 Massachusetts Institute of Technology (MIT): Coupling Heat Storage to Base Load Nuclear Reactors

Prepared by Charles Forsberg, MIT, a university in Boston, Massachusetts, USA.

The coupling of base load nuclear power plants to large-scale heat storage enables a new dimension for nuclear flexibility to enable nuclear plants to provide economic variable electricity to the grid. The economics of a low-carbon world are different than a world built on fossil fuels. The capital costs of fossil power plants, furnaces, and other power conversion systems are low relative to the cost of fossil fuels. The cost of fossil fuel storage is low. These characteristics make it economic to operate these systems at part-load to provide economic variable electricity, mechanical work, and heat to the customer.

Nuclear, wind, and solar have high capital costs and low operating costs. Unlike fossil fuel systems, operating these energy production technologies at half their nominal full capacity approximately doubles the cost of energy. The nominal base load capacity depends upon the technology (EIA 2020). In the United States, the capacity factor is more than 90% for nuclear, 34% for wind, and about 25% for PV. Nuclear plants are shut down for refueling and maintenance. Wind capacity depends upon wind speed with time. PV capacity factors are lower because there is no sun at night and cloud cover. The fuel costs of nuclear plants are low so if operate at 45% capacity the cost of energy almost doubles. Wind and solar have low operating costs; thus, operating them at half nominal capacity doubles energy costs. Energy storage systems, coupled with low-carbon generation, offer the potential to minimize the cost of energy in a low-carbon world by enabling these technologies to operate each at near their nominal full capacity while providing variable energy as needed to the customer. Storage can also support systems with mixtures of fossil, nuclear, wind, and solar.

There are three classes of large-scale energy storage technologies: (1) work (electricity) storage: batteries, hydro pumped storage, and so on; (2) heat storage; and (3) chemical storage (hydrogen, and so on). Electricity storage couples best to the electricity grid and electricity-generating technologies, such as wind and PV. Heat storage technologies couple to heat generating technologies such as nuclear, concentrated solar power (CSP), fossil fuels with carbon capture and sequestration, and geothermal. Hydrogen storage couples to different hydrogen production technologies that may be driven by electrical and thermal energy input and has the capability for seasonal energy storage.

MIT, INL, and Exelon have conducted recent workshops (Forsberg 2018; Forsberg, Sabharwall, and Gougar 2019) that examined proposed heat storage systems coupled to nuclear reactors with storage capacities from a few hundred MWh to 100 GWh. Heat storage is less expensive than electricity storage because low-cost materials (crushed rock, liquid salts, and so on) are used. If very low-cost heat storage coupled to nuclear reactors can be developed and deployed, it would benefit nuclear, wind, and solar by allowing these technologies to be operated in their most economic mode at full capacity. Large scale heat storage was originally developed for CSP systems to enable these systems to provide electricity to the grid after the sun sets. Current CSP systems

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have heat storage capacities of up to several GWh of heat. This chapter describes heat storage systems, heat storage technologies, and integrated heat/hydrogen storage systems.

7.1 Heat Storage Systems

The nuclear heat storage system is shown in Figure 14. The same system design can be used for any heat generating technology. To minimize the cost of energy, the reactor operates at full capacity. When electricity demand is high, resulting in high prices, reactor heat is sent to the turbine to produce electricity. When demand is low, resulting in low electricity prices, a majority of the heat is diverted to heat storage. When peak demand exceeds the base load reactor electricity output, combined heat from the reactor and heat storage is sent to the turbine-generator for electricity production, supported by either oversizing the turbine generator or building a separate peaking turbine-generator for peak power output. At times of very low (or negative) electricity prices, grid electricity can be converted into stored heat using resistance heaters coupled to the heat storage system. Hence, the power plant system can both sell and buy electricity. If stored heat is insufficient to meet peak demand, combustion of natural gas or low-carbon biofuels and hydrogen can provide heat to support peak electricity production.

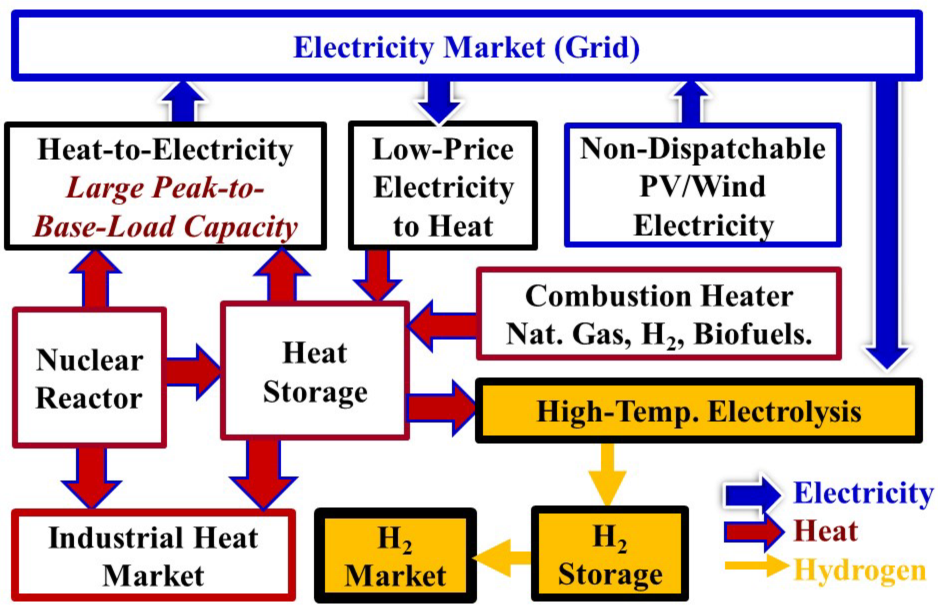

Figure 14. Base load nuclear, wind, and solar with heat storage to provide variable heat, electricity, and hydrogen

Source: MIT. Used with permissions.

The system design enables economic, larger-scale use of wind and PV. First, large amounts of wind and PV collapse the price of electricity at times of high output and, thus, revenue. There is excess electricity production. This system can absorb excess electricity by converting it to stored heat and setting a minimum price for electricity to support solar and wind. Second, the system provides assured generating capacity at times of low wind and solar output at a lower cost than using electricity storage backed up with gas turbines when that storage is depleted.

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The system supports cogeneration of electricity and heat for industry. Cogeneration has major implications for the electricity grid because it directly links the industrial heat market to electricity markets. Some industrial processes can operate flexibly or vary heat demand, freeing up heat for electricity production when needed and consuming added heat at times of low electricity demand. Coupling the industrial sector with the electricity sector via storage adds an additional dimension to balancing energy production with demand.

Energy can also be stored in the form of hydrogen. Hydrogen can be stored underground in the same facilities used for seasonal natural gas storage; thus, hydrogen enables seasonal storage of energy. The leading candidate for nuclear hydrogen production is high-temperature (steam) electrolysis of water a process that requires heat and electricity. Hydrogen production facilities are capital intensive, not just due to the production process but also the compressors, pipelines, and associated facilities—all with large economies of scale. Hence, it is uneconomic to operate such facilities at low capacity factors. This may require that plants producing hydrogen operate more than 80% of the time (Boardman et al. 2019). The high-temperature electrolysis plant is embedded into a system that includes nuclear and renewable generators and heat storage. At times of low electricity prices, electricity from the grid, or electricity produced by the nuclear reactor, can be used for electrolysis while heat from the nuclear plant is directed to storage and the high-temperature electrolysis plant for hydrogen production. At times of high electricity prices, heat from the reactor and heat storage produce peak electricity with no hydrogen production.

This nuclear heat-storage hydrogen system has three characteristics. First, large-scale hydrogen storage, supporting flexibility on an hourly to seasonal basis, is inexpensive when using the same underground storage facilities used for natural gas. Hence, stopping hydrogen production due to increased electricity demand does not disrupt the hydrogen supply to the customer. Second, the system design allows excess low-price wind and solar electricity, when available, to produce higher-value hydrogen while excess heat from the nuclear plant is directed to storage for later use. Third, it enables the nuclear plant to operate at full capacity as a peaking unit for electricity production while producing hydrogen for as much as 80% of the time. This enables the nuclear plant to provide electricity to address seasonal peaks in electricity demand.

7.2 Heat Storage Technologies

There is no single optimum or best heat storage technology. Different types of nuclear plants deliver heat at different temperatures and use different coolants. The heat storage technology must match the reactor type. In addition, different markets may require different heat storage technologies. If heat storage is use on a daily basis, as might happen in a system with a large PV capacity, the storage technology will be used several hundred times per year that creates a large economic incentive for efficient storage. If heat storage is used to store excess energy from the weekend at times of low demand for use during the weekdays at times of high demand, the storage system will be used, at most, 52 times per year. There are fewer storage cycles per year to pay for the capital cost of the storage system. In such an application, the economics will prefer a storage system with very low capital costs even if it is somewhat less efficient.

7.2.1 Liquid Salts

The primary heat storage materials used in high-temperature CSP systems are nitrate salts where the most common salt is solar salt with a composition of 60 wt% $NaNO_3$- 40 wt% KNO_3. In these

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systems, there are cold and hot nitrate salt storage tanks. Cold salt is sent through the CSP system, is heated, and is sent to the hot salt storage tank. Sensible heat of storage is obtained by varying salt temperatures from 290° C to 565 °C. Hot salt is sent to a steam generator to produce steam that is used to produce electricity with the resultant cold salt returned to the cold salt storage tank. The largest CSP nitrate-salt storage system sizes are measured in gigawatt-hours of heat. Nitrate salts can be used to move heat to industrial customers.

Similar nitrate-salt storage system designs are proposed for SFRs, fluoride-salt-cooled high-temperature reactors with solid fuel and liquid salt coolants, molten salt reactors (MSRs) with fuel dissolved in the salt and fusion machines with liquid salt blankets. In each of these cases the nitrate salt replaces the intermediate heat transfer loop that separates the low-pressure reactor from the high-pressure power cycle. Because the nitrate salt replaces other fluids in the intermediate loop with hot salt, there is no efficiency loss by adding storage to these reactors—salt after being heated goes directly to storage, just like in a CSP system.

7.2.2 Heat Transfer Oils

Lower-temperature CSP systems use heat transfer oils, such as Therminol-66. These systems have operating temperatures below 400°C—the upper limit for these oils. These heat storage systems are compatible with existing LWRs with peak temperatures of ~300° C.

7.2.3 Crushed Rock and Cement

The costs of liquid salt and heat-transfer oil heat-storage systems can be reduced with the use of a lower-cost filler material in the tank partly replacing salt or oil for heat storage. Both crushed rock and special high-temperature cements are being considered as fill materials. Cements can be formed into specific shapes, such as parallel plates with narrow channels in the storage tanks to minimize the inventory of heat transfer fluid. Crushed rock is the lowest-cost fill material but has a higher void volume.

Westinghouse is examining a system for LWRs where steam is used to heat oil that, in turn, transfers its heat to concrete in prefabricated boxes filled with closely packed cement plates with small cooling channels between the plates. This minimizes the inventory of the more expensive heat transfer oil. At times of high electricity demand, the oil transfers heat back to the steam cycle.

Korean researchers (Amuda and Field 2019) are examining a similar system for LWRs that uses crushed rock as the heat storage material. There would be multiple tanks of crushed rock with heat-transfer oil only in tanks where heat is being transferred from the steam cycle to the crushed rock or from the crushed rock back to the steam cycle. This reduces the inventory of expensive heat-transfer oil. Roundtrip efficiencies can approach 80%; that is, if a MWh is generated without storage, 0.8 megawatt hours of electricity is generated from the stored heat. The Korean design proposes that the storage system be built as a large barge (60 m by 450 m) with multiple tanks with a heat storage capacity of 20 GWh of electricity. The barge, the size of a supertanker, would be delivered to coastal nuclear power sites where it would be floated into a dry dock at the reactor site. Hot-oil heat transfer also allows easily coupling to industrial heat customers.

Germany (Odenthal, Klasing, and Bauer 2018) is examining nitrate salt heat storage in single tanks filled with crushed rock with lower-density hot salt on top of cold salt. The single tank reduces

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costs relative to the use of separate hot and cold salt tanks. The crushed rock is a heat storage medium and helps prevent mixing of hot and cold nitrate salt.

Third-generation systems, where only limited work has been done (Forsberg 2020), store heat in crushed rock in insulated and covered trenches up to 60 meters wide, 20 meters high, and 1 kilometer long. For systems coupled to LWRs using oil as a heat transfer medium, every 10 meters of crushed rock provides about a GWh of heat storage, assuming a 200° C hot-to-cold temperature swing. When excess energy is available, some of the steam from the reactor heats oil rather than being sent to the turbine-generator to produce electricity. The hot oil is sprayed over sections of crushed rock to heat the rock as it flows down to the oil pan under the crushed rock. The oil is collected and cycled back to the reactor to be reheated. At times of high electricity demand, cold oil is sprayed on the hot rock, flows through the rock, is collected by the oil pan, and is used to convert water into steam. The steam is sent to a peaking steam turbine-generator to produce electricity. There is a parallel system for nitrate salts that operates at higher temperatures. Costs are minimized by three features. Crushed rock is the cheapest heat storage material. Flowing the salt or oil over the rock rather that filling all the rock void spaces minimizes the inventory of heat transfer fluid. The large storage system size minimizes the surface-to-volume ratio and, thus, the cost of insulation and liners.

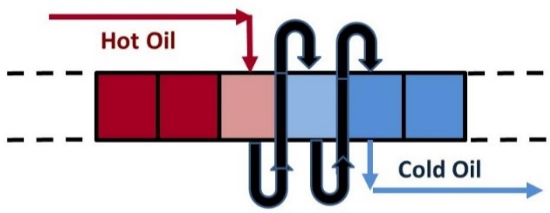

Figure 15. Sequential heating of crushed rock bed with hot oil

Source: MIT. Used with permissions.

There is other ongoing work using crushed rock for GWh heat storage systems because of its low cost. Siemens (Kosowatz 2019) is developing a hot rock heat storage system where air is heated by electric resistance heaters at times of low electricity prices and blown through the crushed rock to heat it to 650° C. At times of high electricity prices, cold air is blown through the hot rock to produce hot air for a steam boiler.

7.2.4 Cast Iron With Cladding

Sensible heat can be stored in solid tightly packed hexagonal assemblies 10–20 meters high made of cast iron with a stainless-steel cladding chosen for chemical compatibility to match the coolant—sodium, salt, lead, or helium. Coolant flows between the solid assemblies. This option places an upper limit on the cost of heat storage associated with any coolant—water, salt, sodium, and helium. It is compatible with any reactor coolant with the appropriate choice of clad. It may be particularly attractive for SFRs with its low-pressure secondary loop by enabling storage in the secondary sodium loop. This system minimizes flammable sodium in the storage system, and the cast iron is cheaper than sodium.

The DOE goal for the capital cost of heat storage systems is \$15/kWh of heat. The commercial nitrate salt storage system costs are near \$20/kWh. The projected costs for second-generation

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nitrate-salt crushed-rock heat storage systems are near $10/kWh, whereas predicted capital costs for some of the third-generation systems are only a few dollars per kWh in sizes to 100 GWh to enable weekend/weekday storage. Today, commercial heat storage system costs per unit of electricity are a factor of three to four less than electricity storage technologies. Advanced heat storage technologies have the potential to be an order of magnitude lower in cost than electric storage technologies reflecting lower cost materials of construction (i.e., crushed rock and thermal salts versus lithium, cobalt, carbon, or steel) and higher operating efficiency.

7.2.5 Hydrogen

The synergistic combination of two energy storage technologies (heat and hydrogen) would enable nuclear plants to address subhourly, hourly, and seasonal mismatches between demand and energy production. This includes integration of nuclear and renewable systems to enable high capacity factors for all low carbon-generating technologies to minimize total energy costs. The central question is whether the future size of hydrogen markets is sufficiently large to achieve this goal.

Hydrogen generation provides an approach to store energy in a chemical form, offering different benefits relative to heat or electricity storage. Massive quantities of hydrogen are used in fertilizer and liquid fuels production. In a low-carbon world, hydrogen may replace coal as a chemical reducing agent in the production of steel (Millner et al. 2017) and be used to produce biofuels. In these roles, hydrogen is used because of its chemical properties—not primarily as an energy source. Hydrogen may also be used as a fuel for transport vehicles, peaking gas turbines, and to produce very high temperature heat for industrial processes.

Recent assessments (Miller et al. 2020) indicate hydrogen may become 10% to 30% of total energy demand in a low-carbon economy. Equally important is that this scale of operations is not dependent upon a single hydrogen market or technology. It is credible that the combination of heat and hydrogen storage can address subhourly to seasonal storage requirements at the required scale.

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

Prepared by Jordan Cox, Maxwell Brown, and Caroline Hughes, NREL, a laboratory operated under the DOE laboratory complex.

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

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

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

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

The U.S. version of ReEDS consists of 134 regions where the power balance constraint must hold (i.e., generation plus net transmission losses must equal load) and 356 subregions with unique characteristics and supply curves for wind, PV, and CSP capacity. The 134 balancing areas also face system reliability constraints, such as operating reserve and planning reserve requirements to ensure grid reliability and adequate capacity exists to meet peak demand, respectively. Technology-specific curtailment rates are computed in a submodule that accounts for the availability of a resource, and technology-specific capacity credit (the potential contribution to the planning reserve margin) is computed in a submodule that computes a technology's availability in peak net load hours (Zhou, Cole, and Frew 2018). Figure 16 shows the U.S. regions as represented in ReEDS. Another version of ReEDS has been modified to represent India; both the U.S. and India versions are publicly available.[5]

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

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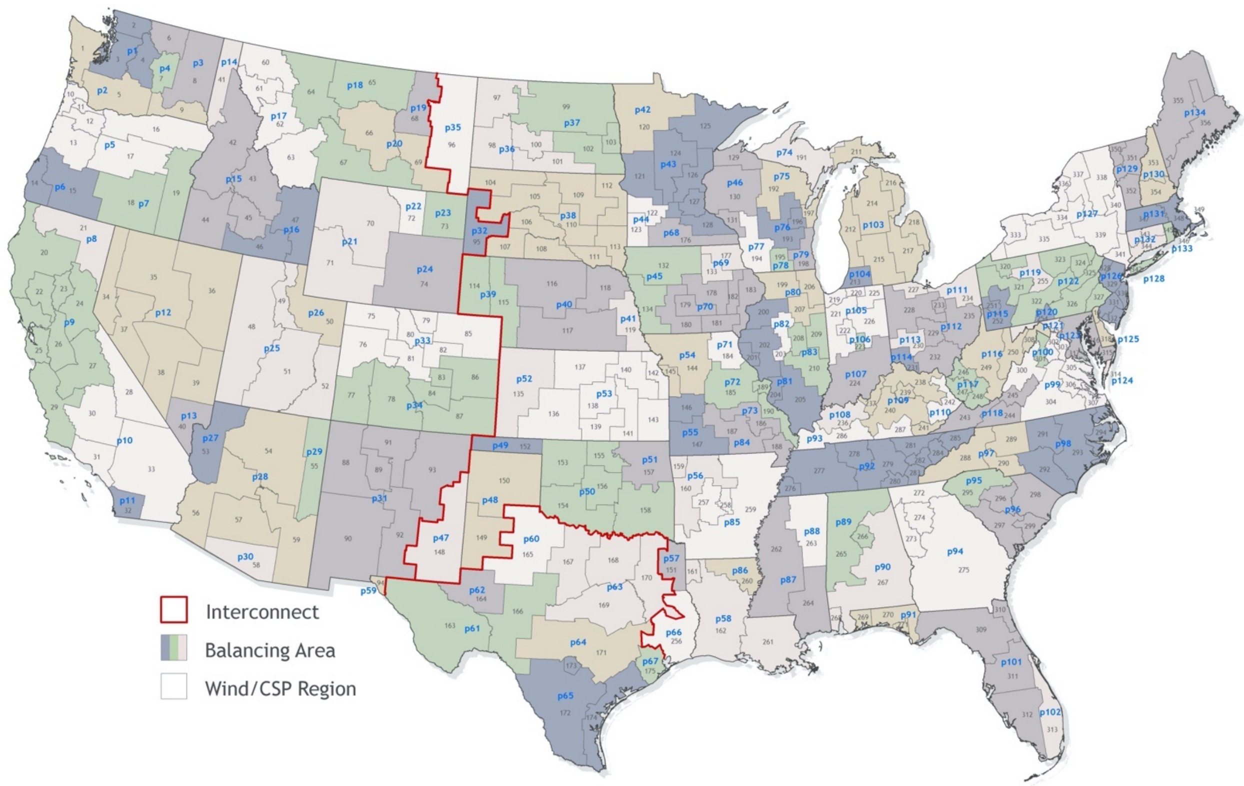

Figure 16. ReEDS map of the United States with balancing area

Source: (Brown et al. 2020a)

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

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

Key members of the U.S. nuclear industry, led by the DOE LWR Sustainability program, are researching both technical and economic barriers for existing LWRs to operate beyond their initial 40-year operating licenses. Some reactors have renewed their license to operate up to 60 and 80 years (McCarthy 2017). The baseline scenario for ReEDS incorporates plant-specific and exogenously imposed retirement rates of 60–80 years for nuclear plants, but there is another option

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for assuming nuclear reactors are allowed to operate up to 80 years. Nuclear reactors can still close for economic reasons—as suggested by ReEDS when endogenous retirements are enabled. Reactors that have announced their closure are forced to close in the ReEDS model. Results from these two scenarios are provided in Table 3. The system levelized cost of energy is the overall system costs divided by total power generated and is expressed in terms of U.S. dollars ($) per unit of energy (MWh).

Table 3. ReEDS Standard Scenario Mid-Scenario 2050 Nuclear Capacity (Cole et al. 2019)

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

The scenarios summarized in Table 3 are "business-as-usual" type scenarios and, therefore, do not include potential futures such as innovations in nuclear flexibility, the availability of SMRs, the availability of integrated energy systems, or policy changes that might impact nuclear generation. However, the purpose of this example is not to predict the overall nuclear capacity, but rather to set a baseline for examining the value of nuclear flexibility for the power system. In this scenario, the impact of allowing plant life changes from the reference assumptions to 80 years when economically viable as evaluated by ReEDS is significant to overall nuclear generation.

8.2 ReEDS Analysis of Nuclear Flexibility: Description of Scenarios

For the Flexible Nuclear Campaign, NREL used the ReEDS tool to examine some of the effects of nuclear flexibility within the context of the U.S. power system. A main focus of the Campaign is to demonstrate how flexible nuclear energy might complement and enable high contributions of VRE; hence, scenarios were chosen that examine both high VRE and highly flexible nuclear scenarios, and, most importantly, the impact of nuclear flexibility (both existing capabilities and future innovation) on overall deployment. In the following subsections, the cases examined are described in detail. A summary of scenarios explored is also provided in Table 4.

A few caveats are important to note about this ReEDS analysis as uniquely related to nuclear energy. ReEDS is a U.S. focused and entirely economic based optimization and analysis tool (with technology-specific physical constraints)[6]. The costs of nuclear in the U.S. are higher than many other countries (Wittenstein et al. 2015). The costs for this work were chosen to include both international experience and some of the costs projected for SMRs, but the analysis is only

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

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

8.2.1 Base Scenarios

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

At $3,000/kW and above, the capacity and annual generation of nuclear energy does not change in the ReEDS model. At the lower costs of $2,000/kW and $1,500/kW there is significant buildout of nuclear power. These scenarios will be used to further examine the impact of nuclear innovation, high RE contribution, and emissions policy on nuclear deployment. Note that costs below $3,000/kW are low for the United States but have been achieved in other countries (MITEI et al. 2018). Future work should examine the feasibility of these cost reductions ($6,200/kw down to $3,000/kW and below) in advanced economies (Gogan and Ingersoll 2018; MITEI et al. 2018), and should examine a broader scenario space to identify opportunities for nuclear power to be deployed economically at capital costs higher than those seen here. Table 4 summarizes system parameters of the base scenarios where only the capital cost of nuclear energy is changed and demonstrates how nuclear costs significantly affect the overall electric system. For example, due to nuclear energy's high capacity factor, low-cost nuclear energy reduces the overall system nameplate capacity while maintaining overall energy generation.

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

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Table 4. Varying Capital Expenditures (CapEx) of Nuclear Energy Within the United States and With an 80-Year Nuclear Lifetime

CapEx of New Nuclear	No Change	Baseline	Low-Cost	Very Low-Cost
2050 Total System Capacity (TWe)	1.75	1.75	1.75[7]	1.71
2050 Total Annual System Demand (TWh)	5.27e3			
2050 Installed Nuclear Capacity (GWe)	89.3		105.2	107.0
2050 Generation (TWh)	713.5		840.2	854.9
Nuclear % of Generating Capacity	5.1%		6.0%	6.3%
Nuclear % of Generation	13.5%		15.9%	16.2%
System Levelized Cost of Energy ($/MWh)	47.2		46.6	46.0
2050 GHG Emissions (Million Metric Ton)	884		891	893[8]

8.2.2 *Flexible Nuclear, High VRE Penetration, and Emissions Limits*

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

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

To simulate high VRE contribution, the Annual Technology Baseline scenario with low VRE prices was used (NREL 2019a). Table 5 summarizes some of the OCC of VRE used for this analysis for the base and low cost (high penetration) VRE scenarios. There are additional

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

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

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technologies than those listed in Table 5 and more information can be found in the Annual Technology Baseline; but the technologies listed here are provided for reference. Low VRE costs resulted in significant deployment of VRE capacity and was paired with flexible nuclear innovations to examine how the addition of flexibility would impact the U.S. electricity system under high VRE penetration.

Table 5. Base and Low Overnight Capital Cost for Select VRE Used in ReEDS Analysis (NREL 2019a)

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

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

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

The metrics examined in this study were power system capacity (GW) and annual generation (TWh), nuclear capacity (GW) and annual generation (GWh), percentage contribution from nuclear both in capacity and generation, system average cost per MWh (referred to as levelized cost of energy in $/MWh), overall system costs[9] and savings over the base case ($), and 2050 emissions (MMton). A summary of the parameters for the scenarios discussed here is given in Table 6.

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

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Table 6. Summary of Scenarios

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

8.3 Results

The results of the ReEDS simulations are displayed in Table 7 for the scenarios described previously. Where appropriate, comparison values between the scenarios examined here and the base scenarios are included in the table. An important note for the calculation is that the energy system savings are based on a discount rate for a future value. Changing the discount rate or analyzing the value only for 2050 would significantly increase the numerical value of the system cost and system savings. Additionally, for both low emissions scenarios, the Savings over Base Scenario are negative, meaning the emissions cap incurs additional power sector costs when replacing all emitting technologies with non-emitting ones. This calculation ignores any external costs that may be incurred by emissions. Table 7 provides a graphical representation of these results in terms of nuclear electrical generation capacity (GWe) and nuclear annual electricity generation (TWh).

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Table 7. 2050 Results for Capacity, Generation, Percentage, and Cost for Nuclear and Renewable Energy

Scenarios	Cost	Flex	High VRE	High VRE+ Flex	Cap
Total System Capacity (TWe)	Low-Cost	1.713	2.032	2.054	2.11
	Very Low-Cost	1.710	2.053	2.044	1.93
Nuclear Capacity (GWe)	Low-Cost	104.8	89.3	89.6	135.2
	Very Low-Cost	107.4	90.6	99.6	214.2
Nuclear Generation (TWh)	Low-Cost	836.9	714.5	708.8	998.2
	Very Low-Cost	857.0	722.9	791.3	1626
Nuclear Capacity %	Low-Cost	6.12	4.39	4.36	6.41
	Very Low-Cost	6.28	4.41	4.87	11.10
Nuclear Generation %	Low-Cost	15.8	13.5	13.4	18.8
	Very Low-Cost	16.2	13.6	14.9	30.7
System Levelized Cost of Energy ($/MWh)	Low-Cost	45.9	43.3	43.0	53.4
	Very Low-Cost	45.8	43.0	42.9	49.0
2050 Annual System[10] Costs (Billion USD)	Low-Cost	243.27	229.49	227.9	283.02
	Very Low-Cost	242.74	227.9	227.37	259.7
2050 Annual Savings Over Base Scenario (Billion USD)	Low-Cost	6.89	20.67	22.26	-32.86
	Very Low-Cost	7.42	22.26	22.79	-9.54
2050 GHG Emissions (Million Metric Ton/yr)	Low-Cost	889	519	501	121
	Very Low-Cost	889	509	506	121

[10] 2050 system costs and savings are the annual system costs and savings for the year 2050, but in 2004 adjusted U.S. dollars based on a 5%–7% adjusted discount rate. For more information, see the ReEDS documentation on how future costs are adjusted (Brown et al. 2020a).

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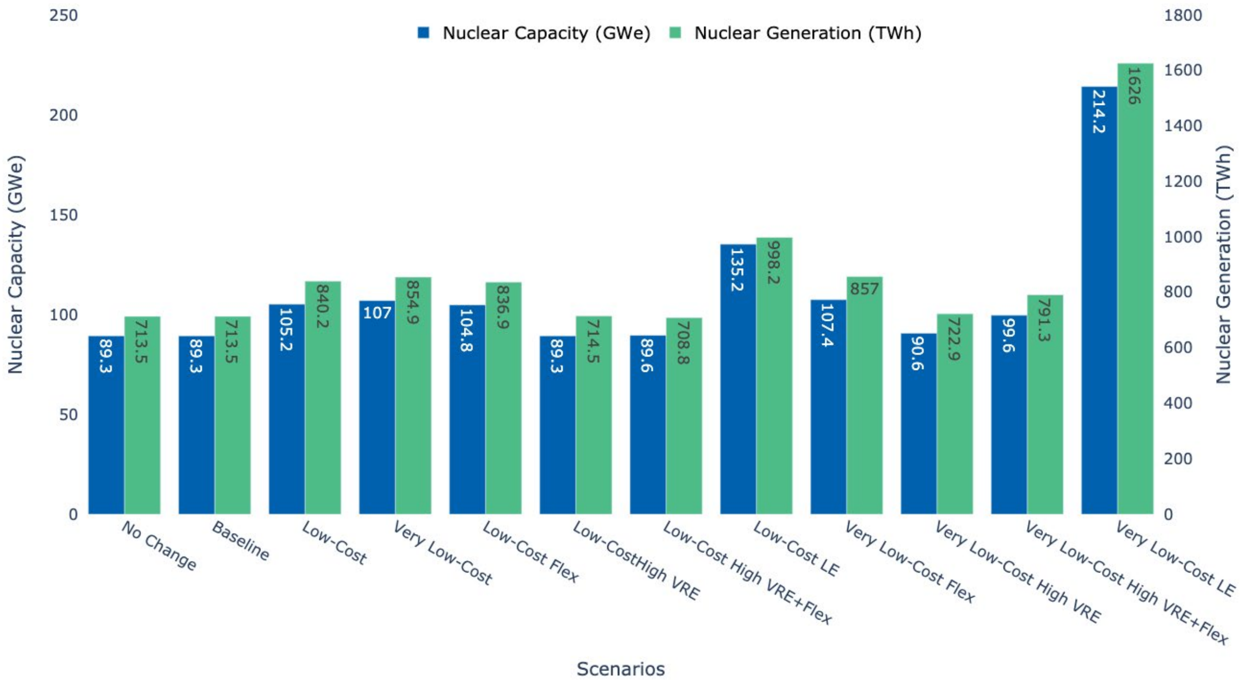

Figure 17. Nuclear capacity calculated with ReEDS in 2050 based on the given scenarios in Table 4 and Table 6

Source: NREL. Used with permissions.

8.4 Discussion

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

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

- In the low-emissions scenario, the availability of low-cost nuclear energy significantly decreases the overall electricity cost versus a low-emissions scenario with no low-cost nuclear. The results indicate that an emission-constrained system decreases from an average price of $53.4/MWh down to $49.0/MWh with the addition of nuclear flexibility. While this difference may seem small, when multiplied by the annual generation in TWh, this results in a change in the present value of system cost of $23.32 billion due to the availability of low-cost nuclear. In terms of nuclear capacity, this emission constrained scenario results in an increase in nuclear

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capacity by 40 GW in the low-cost scenario and approximately 120 GW in the very low-cost scenario. This is also for the baseline VRE costs scenario. This simulation did not include the impact of flexible nuclear energy on top of low-cost nuclear energy; this is a next step for future analysis.

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

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

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9 Tokyo Institute of Technology: What Findings From the MIT-Japan Joint Study on the Future of Nuclear Power in a Low-Carbon World Tell Us About Flexibility

Prepared by Akira Omoto, Tokyo Institute of Technology, a university in Tokyo, Japan.

An MIT-Japan study was carried out between early 2015 to early 2018 and resulted in the final report MIT-ANP TR171 (MITEI et al. 2018), released in September 2017.

The key messages of this report, which remain valid today, are:

1. Heat storage technologies can be coupled with nuclear reactors to provide reliable dispatchable electricity and are enabling technologies that support larger-scale use and sustained delivery of variable renewables;

2. It is vitally important to decarbonize the nonelectricity sectors by using nuclear energy, including heat storage and hybrid operation of nuclear power, for example, by Nuclear Air-Brayton Combined Cycle; and

3. Changes are needed in regulatory and other policies.

The study, which used MIT's GenX code as modeling tool, also revealed that decarbonization without using nuclear energy would result in unaffordable electricity prices and proposed an integrated energy network for intensive decarbonization (see Figure 18 and Figure 19).

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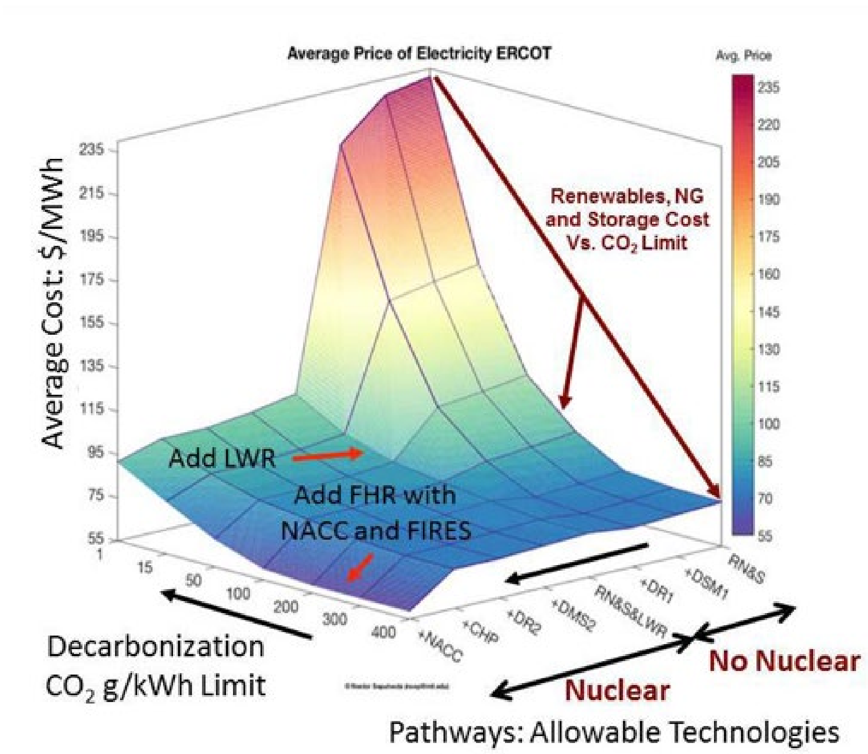

Figure 18. Cost of decarbonization with different technology portfolios as predicted by MIT study on decarbonization

Source: MIT. Used with permissions.

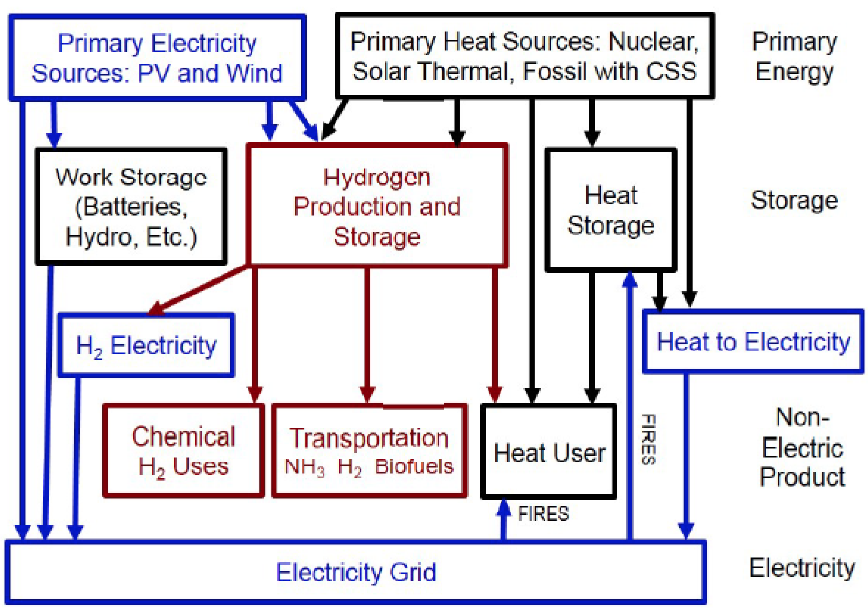

Figure 19. Hybrid energy systems energy flows to enable electricity and hydrogen production, heat and electrical storage, and chemical processing

Source: MIT. Used with permissions.

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GenX was used to model the electric sector of different independent system operators (specifically, the Texas electricity grid that has high-grade wind and solar resources) in the United States in 2050. The details of the assumptions and data can be found in the report and a report by Sepulveda (Sepulveda 2016). The results of similar study in different jurisdictions and used data are available in MIT's report (MITEI et al. 2018), released in September 2018.

The study was conceived in the middle of 2014 by the government (DOE/METI) and academia (MIT/Titech) to vitalize the future of civilian nuclear energy. From among the candidate topics, the topic of integration of nuclear and renewables was chosen, and a Statement of Work was agreed upon in late 2014. Participating researchers, besides MIT and the Tokyo Institute of Technology (Titech), were the University of Tokyo, the JAEA, and so on.

Continuation of the MIT-Japan study was suspended in 2018 due to financial reasons. On the part of Japan, a limited scope study is currently being carried out by Toshiba/University of Tokyo/Titech on the topic of viability of LWR heat storage to find an appropriate level of LWR heat storage as a function of the share of variable renewables in the grid, economic viability of the system, and supporting approaches for storage.

Given the current situation that: (a) energy accounts for ~70% of GHG emission; and (b) the aggregated results of Nationally Determined Contribution falls far short of the goal set out by the Paris Agreement as a global action plan to limit global warming to well below 2° C and to aim to limit to 1.5° C (UNEP 2019), it is clear that clean nuclear energy needs to expand significantly and go beyond just producing electricity.

As for nuclear energy's relationship with variable renewables, the public may think that nuclear is not compatible with solar or wind; however, both nuclear and variable renewables are important to reduce GHG emission, and both are capital-intensive, meaning high capacity factor is necessary for economics. The MIT-Japan report points out that both are compatible, and nuclear power can help electricity production from solar or wind, while the capacity factor of nuclear is maintained. For example, cases of curtailment of electricity supply from solar power (when its supply is beyond demand) is reduced if nuclear reactors reduce electricity generation then and a part of their heat is stored or used for hydrogen production. In this chapter, "variable" means, in the case of PV, changes of electricity supply by clouds, nights and seasons, whereas "dispatchable" means that supply is controllable, depending on demand situation, from load dispatching center to vary supply from controllable power source such as nuclear or fossil power plants.

Also, a comparative study of selected European countries shows that countries with a high share of dispatchable energy (nuclear and hydro) translates to low electricity prices and low value in terms of gCO_2/kWh. Energy policy and institutional arrangements play an important role in securing dispatchable energy. What matters is how to achieve decarbonization with a minimum burden to society, a consideration that was a driving force behind the MIT-Japan study and still is valid today.

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10 U.K. Nuclear Innovation and Research Office: Experience of Flexible Nuclear and the Road to Net Zero

Prepared by Dr. Philip Rogers, Mr. Gareth Peel (U.K. Nuclear Innovation and Research Office), and Dr. Daisy Ray (U.K. Department for Business, Energy and Industrial Strategy).

In 2019, the United Kingdom was the first major economy to legislate for net zero GHG emissions by 2050. Net zero refers to achieving a balance between the amount of GHG emissions produced and the amount removed from the atmosphere. There are two contributing actions that work in tandem to achieve net zero: Reducing existing emissions and actively removing GHGs. In short, the pathway to 2050 will require total decarbonization of the U.K. energy system, and any remaining emissions must be compensated for with carbon removal activities, such as direct air capture and changes to land use and lifestyles. This has provided the impetus to consider how low carbon technologies could be deployed to deliver on changing energy usage profiles and an overall scale up in demand. The U.K. Committee on Climate Change (CCC) has shown the scale of the challenge in Figure 20.

The four highest-emitting sectors are transportation, energy supply (generating electricity from burning fuels such as coal, oil, and natural gas), business (commercial use of electricity), and residential (heating homes). Together, these account for around 84% of emissions in 2018 (BEIS 2020).

The United Kingdom's overall energy usage is around 1,700 TWh (BEIS 2019b), and, by 2050, this is anticipated to increase by around 40%–50%, with electricity demand doubling from 300 TWh today (Stark et al. 2019a), Currently, 53% of the U.K. electricity supply is low carbon, with 21% from VRE, 20% from nuclear, and 10% from bioenergy and hydropower (BEIS 2019b). This energy mix has generally not required nuclear to operate flexibly; however, recently, in a period of very low demand, one of the U.K. nuclear power stations was reduced in power output to support balancing of the electricity grid.

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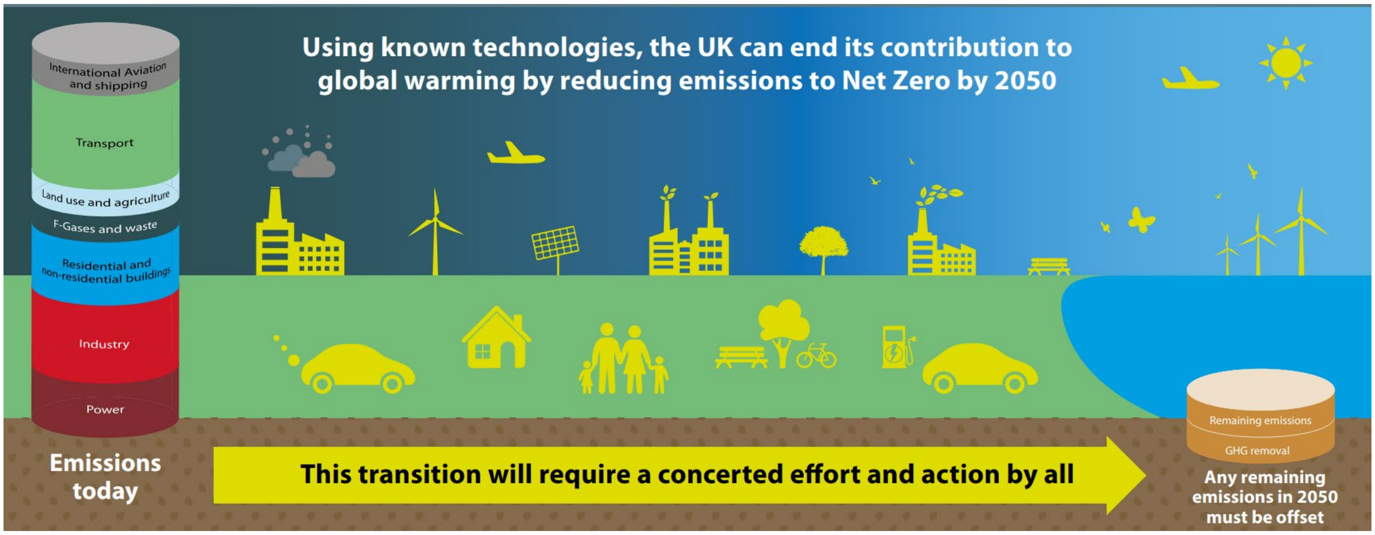

Figure 20. CCC report key message

Source: CCC.

Figure 21 highlights anticipated decarbonization pathways from nuclear energy to a range of sectors; many of these are distributed or mobile carbon emitters that are challenging to decarbonize. Recent modeling outputs on the U.K. energy system indicate nuclear energy applied for these purposes is advantageous toward achieving the lowest-cost net zero energy system. In doing so, this may also provide synergies with the need for a more flexible supply of electricity and other energy vectors (hydrogen and heat) in commercially attractive ways. Whole-system decarbonization therefore provides an opportunity for nuclear energy to work with established technologies in new ways.

The United Kingdom has a long history of civil nuclear research, development, operations, and decommissioning, having commercially operated a fleet of Generation II Magnox reactors, Generation III advanced gas reactors and a Generation III PWR. Deployment of these reactor fleets in the United Kingdom have resulted in experience of civil nuclear, including an element of flexible operation, dating back to the first commercial civil nuclear reactor fleet in the 1950s.

Alongside base load generation, the United Kingdom has historically used the output of civil nuclear reactors for:

- Complementary siting of industrial facilities reliant on a secure source of electricity
- Energy storage systems, such as pumped storage, located nearby to nuclear power stations
- District heating for an industrial site collocated with a nuclear power station.

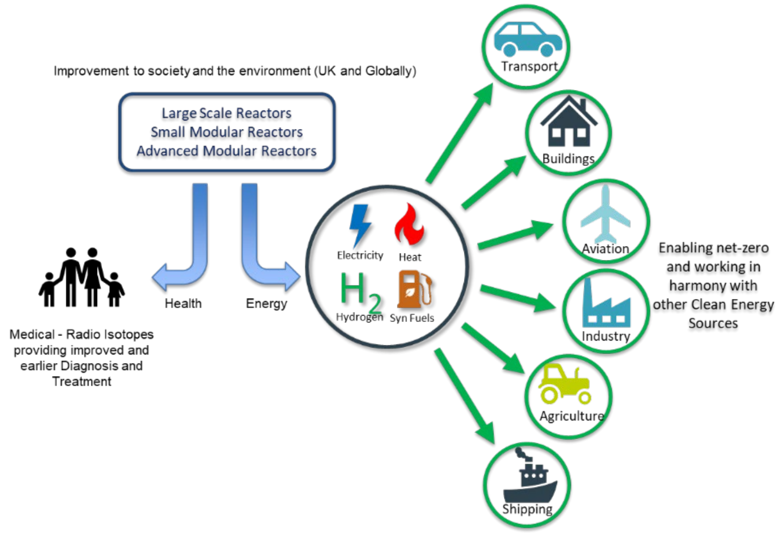

Figure 21. The flexible potential of civil nuclear

Source: U.K. BEIS. Used with permissions.

10.1 Flexible Nuclear in the United Kingdom

Civil nuclear power generation in the United Kingdom goes back to 1956 when HRH Queen Elizabeth II opened the new power station at Calder Hall in Cumbria, the world's first commercial civil nuclear power station. This marked the start of civil nuclear generation in the United Kingdom that, to date, has seen the deployment of three different reactor types: the Magnox fleet of 26 reactors across 11 sites (now retired), the advanced gas reactor fleet of 14 reactors across 7 sites, and the single PWR at Sizewell B.

The operating statistics for these technology types have been exceptional, and nuclear continues to be one of the largest contributors to clean electricity production in the United Kingdom. Through the latter half of the last century, the United Kingdom's nuclear generating capacity steadily increased (see Figure 22) peaking at 12.7GWe in 1994, which at the time was around 17% of total installed capacity (Roberts and Clark 2018).

For the most part, the United Kingdom's nuclear power stations have operated at full power, providing base load electricity and during the 1950's and 1960's synergies between energy supply from nuclear, storage and usage were exploited to maximize the output of the U.K. nuclear fleet. This chapter explores some of the approaches taken.

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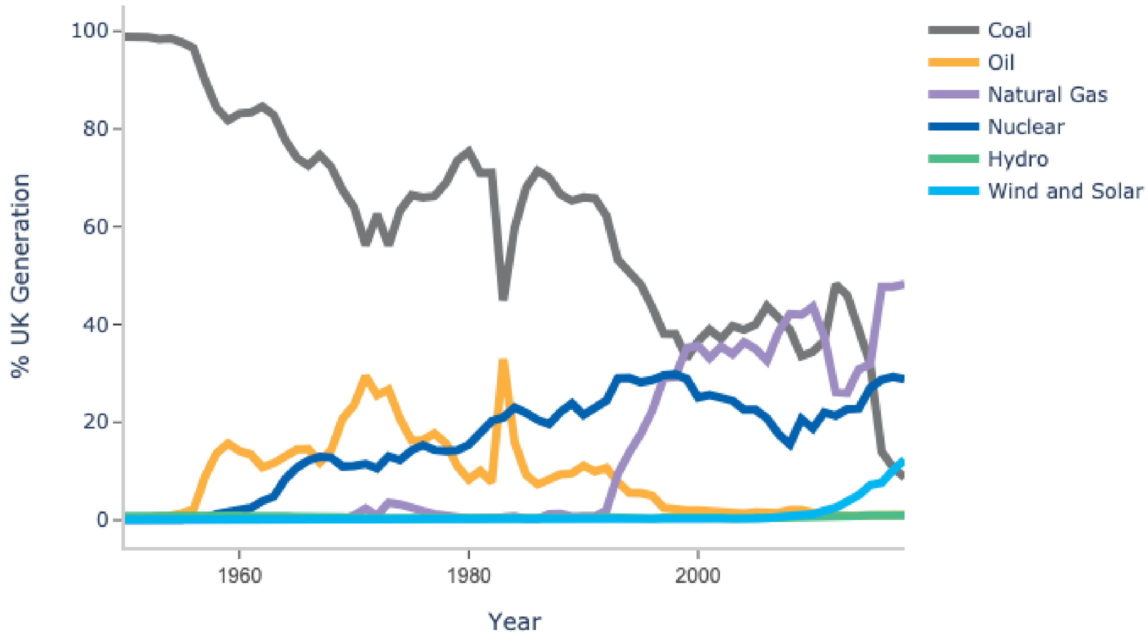

Figure 22. U.K. electrical output by fuel source

Source: (BEIS 2019c)

10.1.1 Major Energy User Local to Nuclear Plant

The Wylfa nuclear power station was the last of the U.K. Magnox stations. Its two reactors operated between 1971 and 2015 and delivered a combined output of 980 MWe. The plant was built on the island of Anglesey, located in far northwest Wales, remote from significant urban or industrial development. To stimulate growth of the island economy and provide local jobs, an aluminum smelting plant was constructed concurrently within 15 miles of the power station to capitalize on the new, local and reliable energy resource. During operation, the aluminum plant drew 255 MWe of power from the Wylfa plant over a dedicated high-capacity electric cable. Anglesey Aluminum operated successfully from 1971 to 2009, employing 540 workers and adding to the direct local economic benefits of the Wylfa site.

The challenge for the Anglesey Aluminum plant was that once the Wylfa plant was scheduled for closure, the contract for power provision could not be renegotiated, and with no alternative realistic source of local electricity, the aluminum works closed in 2009.

10.1.2 Energy Storage Systems

The United Kingdom has two pumped water energy storage plants, both in North Wales: Ffestiniog and Dinorwig. Both plants are within reach of the two now-decommissioned nuclear stations; Wylfa and Trawsfynnyd. Articles from the period refer to the strategic intent to exploit the synergies between pumped storage and the local nuclear power stations (Lovins 1973). The energy storage plants started operating in 1963 and 1982, respectively, and they remain operational today (Electric Mountain n.d.).

Pumped water energy storage systems utilize excess power to the grid during periods of low demand (assumed to be at night) to pump water to a raised reservoir. Water is then released at

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periods of high electricity demand (during the evening for example) using gravity to reverse the pumps to become turbines. At Ffestiniog, the capacity is 360 MW via two sets of pump/turbines and 1.7 GW via six pumps/turbines at Dinorwig, the latter having an operational duration of 5 hours from a full top reservoir.

10.1.3 District Heating

The use of civil nuclear power to drive local district heating dates to the operation of the very first civil nuclear reactor at Calder Hall. For over 40 years, the Calder Hall reactors on the Sellafield site provided steam to meet the site demands for industrial process heat and space heating over a local heat network.

The use of the reactors for industrial heat applications was integral to the design of Calder Hall, which operated until the decommissioning of the reactors in 2003. In 1998, a 168 MWe replacement gas plant was constructed on the periphery of the site to meet the continuing demand for energy. This outlines the value and scale of the reactor's contribution to supporting the site with electrical and heat energy cogeneration.

10.2 Historical Lessons

The lessons to be drawn from previous activities to leverage synergies between nuclear and non-nuclear technologies focus on strategic planning of energy assets to balance local and national energy systems and the regional considerations to enable local benefits. The pumped storage assets of Ffestiniog and Dinorwig both remain significant national assets, albeit now focused on energy storage more generally, including for balancing of the U.K. VRE supply.

The operational success of Anglesey Aluminum partnered with the Wylfa power station and the long-term supply of district and process heat to the Sellafield site from the Calder Hall reactors demonstrate that parallel thinking to maximize local energy provision can be successful and support heavy industry, enduring local jobs and wider economic benefits. However, long-term security of supply issues needs to be considered, as does siting and regulation. This is relevant to the current thinking in the United Kingdom on the decarbonization of industrial clusters.

The U.K. government has undertaken studies into the most energy-dense industrial regions, or clusters (BEIS 2019a), which showed that the demands of these areas are substantial in terms of electricity and industrial heat. Significant benefits can be achieved through local and regional strategy planning of energy supply and industrial energy usage. Through understanding the lessons from the United Kingdom's previous experience (as noted in Chapter 10.1), there is an opportunity for industrial clusters to leverage nuclear energy for decarbonization at a regional level. SMRs (both Generation III and Generation IV high temperature) may also present opportunities for more flexible siting to support these regional decarbonization efforts.

10.3 Modeling our Future Net Zero Energy System

Today, governments have the challenge of enabling our future energy needs to be met via the most cost-effective route. There are numerous predictive tools to support related decision-making, all of which use different inputs and derive their solutions dependent on an array of selection criteria including economic, technical (including technology maturity), and social/political criteria. They are also based on the limitations in thinking and data availability.

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Since the United Kingdom legislated for Net Zero GHG emissions by 2050, the range of potential future energy scenarios being modeled has taken on a new focus. This chapter describes some of the outcomes relevant to flexibility.

10.3.1 The CCC Report

The CCC report (Stark et al. 2019b) uses the Energy System Modeling Environment software, amongst other tools (Stark et al. 2019a), to predict a number of scenarios for the United Kingdom's future energy system requirements in 2050 and the potential routes to deliver net zero. The Energy System Modeling Environment model is a cost optimization model that takes into consideration emission intensity, resource availability, technology development rates, and system capacity and flexibility. For CCC work, the inputs are set specifically by the CCC members and their advisors.

A number of energy system scenarios are modeled based on a wide range of low-carbon technologies, lifestyle changes, and land use shifts. Prior to 2019, the United Kingdom was targeting 80% reduction in emissions by 2050, from 1990 baseline levels. Analysis showed that there would be relatively high confidence of achieving this target with reasonable changes to the energy system. However, to deliver on a 100% emissions reduction target (net zero), a broad range of speculative measures and technologies (or assumptions about foreseeable technologies) need to be introduced. An example of a speculative assumption would be that very high (i.e., 99%) capture rates from carbon capture and storage technology can be delivered.

The report outlines a need to double U.K. electricity generation between 2019 and 2050, primarily due to electrification of transport and heating. It projects that this equates to a fourfold increase in low-carbon electricity, with an equal requirement for of 30–60 GWe flexible and base load generation. This is in addition to the extensive building of renewable power infrastructure. The CCC outlines the importance of flexibility highlighting how the commercial case for future energy generating assets can be supported by the project, either in its own right or by partnering with flexible energy conversion systems.

10.3.2 Energy Systems Catapult

The Energy Systems Catapult has analyzed the potential future pathways to realizing a net zero energy system. The most recent work, (McKinnon, Milne, and Thirkill 2020), centers on two main deployment scenarios: (1) Clockwork, a centralized approach where national-level decision-making drives the development of the energy systems; and (2) Patchwork, a decentralized approach where local and regional decision-making results in variability of approach across the nation.

Given a set of input parameters, the model finds the least-cost energy mix in 2050 and generates the potential energy system assets that would be required. An output is provided in 5-year intervals to provide the user with an indication of what could be low-regret decisions on technology investment and deployment in the near, medium, and longer term.

Nuclear is modeled as several discrete technologies, that is, large-scale nuclear and SMRs (both Generation III and Generation IV in the form of HTGR). The economic, siting, and technical attributes of these different asset types are all considered including cogeneration and flexibility. At the time of writing, the Energy System Modeling Environment model was subject to further updates to include the explicit production of hydrogen from high-temperature heat.

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Figure 23 and Figure 24 provide the predicted energy mix in 2050 based on each of the scenarios, with the Clockwork scenario showing a higher level of nuclear deployment due to national programs that deliver reduced costs through project delivery learning. Under the Patchwork scenario, the higher proportion of energy provided from VRE places a very high demand on interseasonal and intraday storage, with hydrogen turbines providing peak electricity demands. The hydrogen supply is mainly from electrolysis using both curtailed and dedicated renewable supply.

The Energy Systems Catapult findings place a high value on flexibility and underline the potential of nuclear to meet a range of different energy needs, especially district heating and electricity. As part of a sensitivity study on nuclear deployment, HTGRs partnered with thermo-chemical hydrogen production appear cost-competitive generating hydrogen up to around one-third of the predicted 2050 demand, or 50–100 TWh (McKinnon, Milne, and Thirkill 2020).

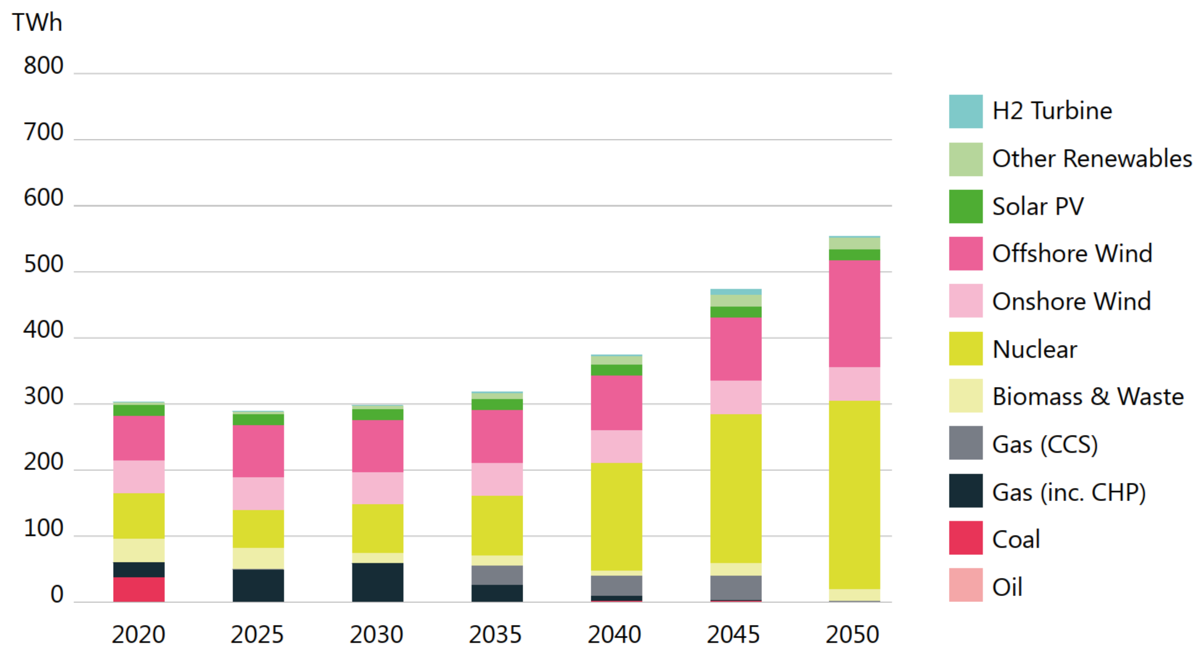

Figure 23. Energy Systems Catapult Clockwork prediction of least-cost electricity generating mix in 2050

Source: Energy Systems Catapult.

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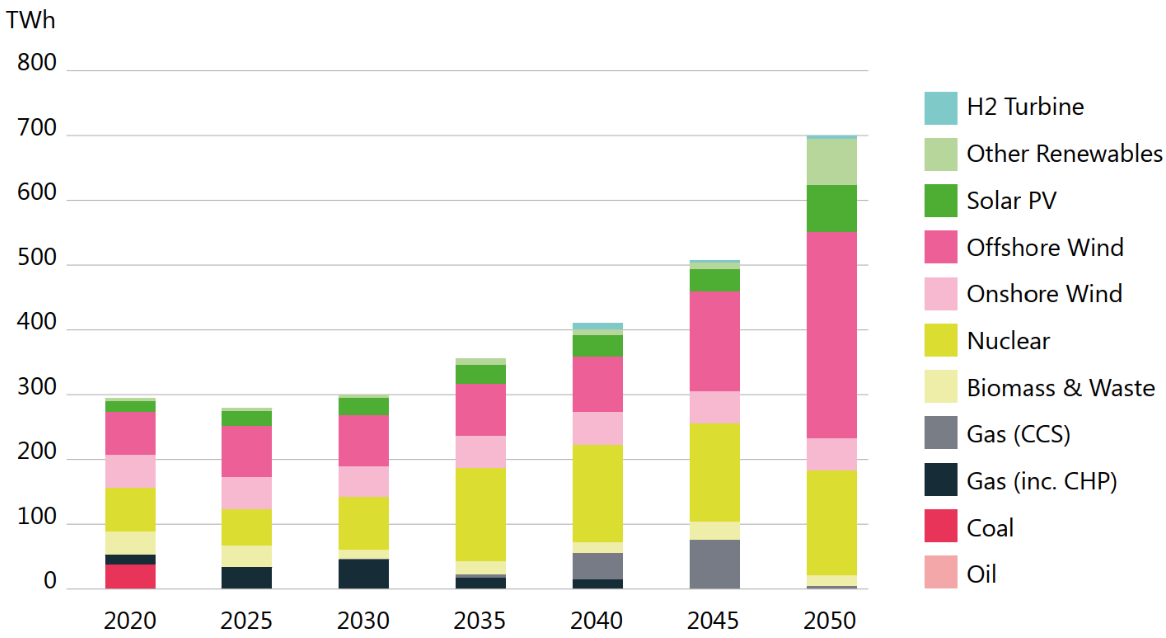

Figure 24. Energy Systems Catapult Patchwork prediction of least-cost electricity generating mix in 2050

Source: Energy Systems Catapult.

10.4 The Future of Nuclear in the United Kingdom

Work in the United Kingdom on achieving net zero has shown the importance of system thinking and the optionality provided by flexible supply and management of energy. Delivering flexibility has synergies with a future hydrogen economy through cogeneration and larger energy storage systems.

These systems could be driven by civil nuclear reactors alongside a range of other low-carbon energy sources with the role of nuclear as part of a flexible hydrogen economy becoming much more widely explored. This has been the subject of recent modeling efforts on the U.K. energy system, and the U.K. National Nuclear Laboratory is currently leading a broad scope of work to develop the United Kingdom's knowledge base on the techno-economics of hydrogen from nuclear energy.

In particular, electricity and in the future high-temperature heat from nuclear power stations could be suitable for partnering with a range of hydrogen production technologies. There are similarities with the pumped storage systems deployed in the United Kingdom, historically, as hydrogen is proposed as a chemical energy storage medium to support interseasonal and intraday balancing of electricity supply and demand. In planning the future energy system there is learning to be taken from approaches taken in the past.

Cooperation between energy supply technologies and local and national energy demands require collaboration between technology providers and regional groups, operating under market frameworks set at a government level. This not only drives the need for cost-competitive solutions

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but also highlights the importance of flexibility of plant output to maximize revenues through several product lines, for example electricity, hydrogen, and heat markets.

The picture for flexibility and its role in energy supply, storage, and hydrogen production in the United Kingdom is currently emerging and the precise technologies and deployment models that will comprise a future decarbonized energy system is uncertain. Commercial drivers will determine, for example, whether reactors will be deployed to deliver a single product from a dedicated system, or many; however, flexibility of energy supply from the project and the versatility of reactor technologies and the associated energy conversion systems will be crucial.

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11 Électricité de France: The Contribution of French Nuclear Fleet to the Flexibility of the Electric System

Prepared by Stéphane Feutry and Antoine Herzog of Électricité de France (EDF), a French electric utility company.

French electricity generation is characterized by a very high share of zero-carbon production. With 495 TWh generated in 2019 (NREL 2019a) out of 538 TWh, nuclear and renewable energies (hydro, wind, solar, bioenergy) represent 92% of the total electricity generated. With a positive balance of 56 TWh in 2019, France is also a major exporter of electricity in Europe. The demonstrated flexibility of French nuclear power plants, which today account for about three-quarters of the zero-carbon production, clearly shows the way for the complementarity of variable renewables and nuclear in a decarbonized economy.

11.1 Nuclear Flexibility Already Utilized in France

The nuclear reactors in service in France have a considerable amount of built-in flexibility. French nuclear reactors are designed to be able to reduce output from 100% to 20% of rated capacity twice a day in under 30 minutes, depending on the type of reactor. Thus, they have a ramp up/down ability of 30–40 MW per minute (about 3% of the nominal capacity), which can be compared to normal ramp-up abilities of gas combustion turbines (7–12 MW/min, 5%–8% of the nominal capacity) or combined gas cycles (15–40 MW/min, 3-7% of the nominal capacity) and is adequate to meet the needs. To keep pace with fluctuating demand, a major load variation program is agreed upon in advance with the grid operator.

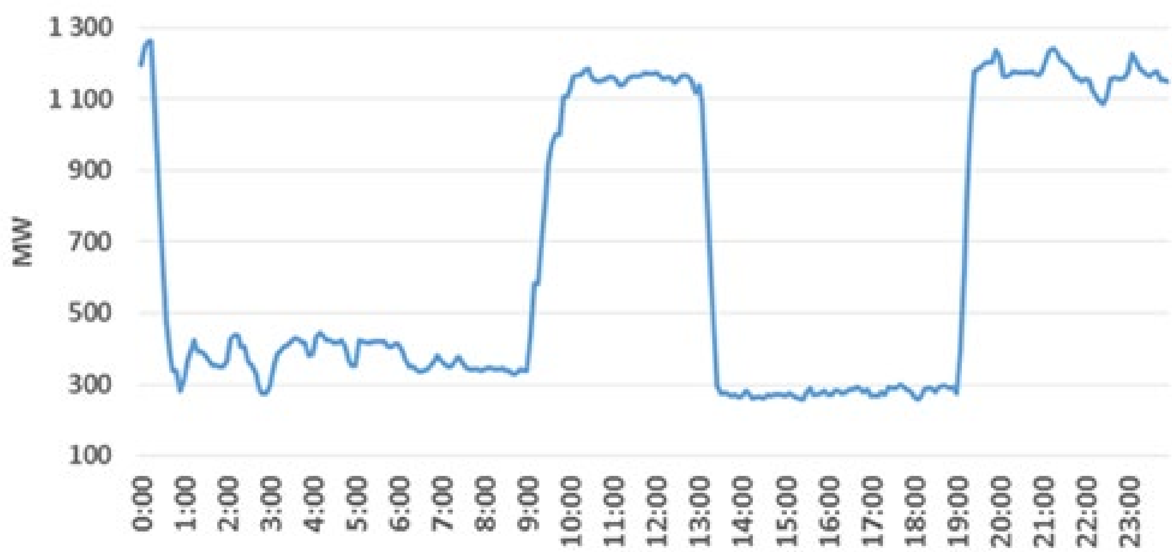

Figure 25. Example of power variations over 1 day, Golfech 2 nuclear power plant, 1,300 MW

Source: Jun Zeng, EDF. All rights reserved.

Figure 25 shows electric capacity delivered by Reactor 2 at the Golfech nuclear power plant in the southwest of France over 1 day on May 3, 2020. Output was cut sharply twice, in the middle of the night and in the afternoon, with variations from 1,250 MW to 300 MW within half an hour.

This flexibility is amplified by the fleet effect. At the beginning of 2020, France's 58 nuclear reactors had a combined net capacity of 63 GWe operated by EDF. These reactors could, on average, ramp up to 21 GWe within 30 minutes. This is a significant modulation capacity, as nuclear reactors supply an average of about 50 GWe over the year. The nuclear fleet also contributes to power system stability as nuclear reactors can make minor automatic load variations to control grid frequency.

The nuclear fleet also provides seasonal fluctuations. Since nuclear fuel can be considered a finite life stock, both short-term nuclear flexibility and medium-term fuel management can be jointly optimized so that nuclear power plants are available when needed. The number of refueling outages scheduled simultaneously thus fluctuates greatly over the year, with more than 15 reactors out of 58 shut down for refueling at the same time during the summer, when demand is lowest.

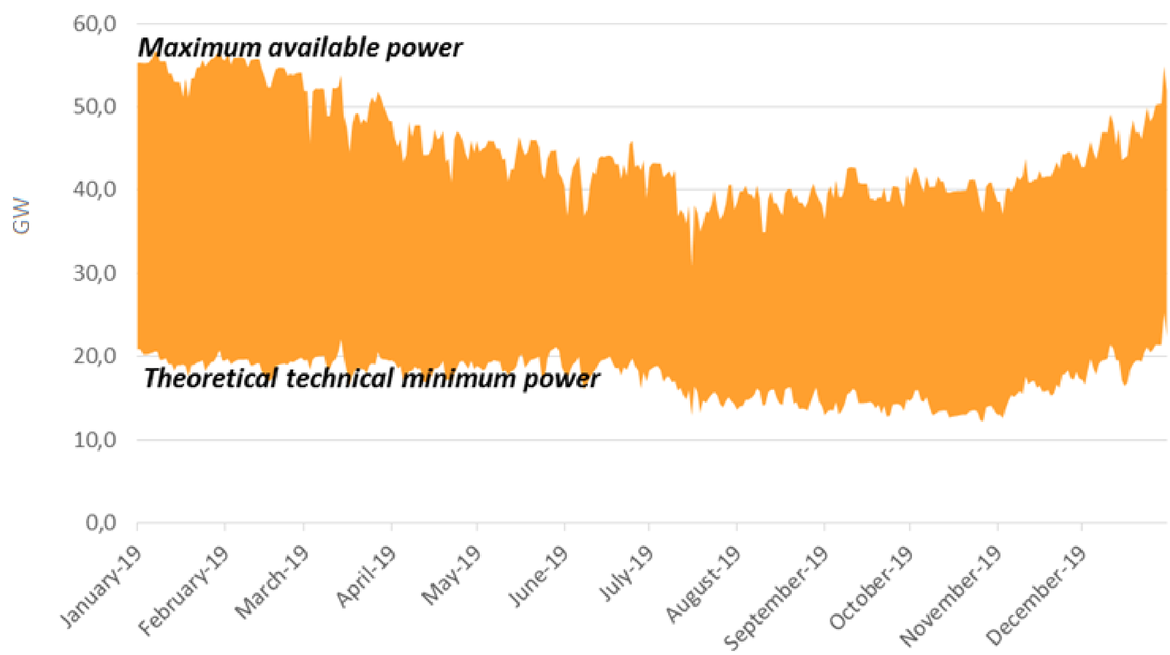

Figure 26. Maximum available power and technical minimum power of the EDF nuclear fleet in 2019

Source: Jun Zeng, EDF. All rights reserved.

11.2 Today's Flexibility Reflects the Success of the French Nuclear Program

In the space of 25 years, between 1974 and 1999, EDF built and commissioned 58 reactors, which now have an average age of 35 years. Thanks to standardization and series effects, nuclear has been and is still very cost-competitive. The favorable economics of French nuclear reactors meant that it was cost-effective to run the plants beyond base load generation to provide load-following

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power. Nuclear accounts for the largest share of the French power mix, which implies a modulation requirement to keep up with daily fluctuations in demand: a low overnight and a peak at around 7 p.m. in winter and around 1 p.m. in summer, with an average supply of up to 60 GWe in winter and 40 GWe in summer.

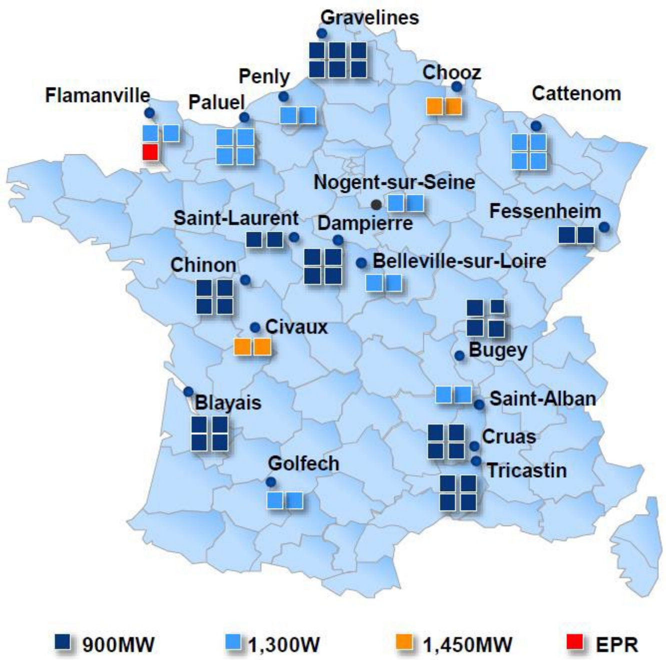

Figure 27. Nuclear power reactors in France

All French nuclear reactors are PWRs operated by EDF and were supplied by the same vendor.

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11.3 Complementarity of Variable Renewables and Flexible Nuclear Is a Pillar of Decarbonized Power Generation

Electrifying end uses and unleashing energy savings across all sectors are keys to fighting climate change and decarbonizing the energy sector. Because of the resulting surge in demand for zero-carbon electricity, the complementarity of renewables and flexible nuclear is a pillar of the energy transition. Today, it already makes good economic sense, as it leads to competitive prices for consumers: in France, electricity prices for household consumers are 18% lower than the European Union average. Moreover, with CO_2 emissions representing 49g/kWh in 2018, less than one-fifth of the European average, France already has low-carbon electricity.

France is fully committed to a zero-carbon energy objective for 2050. According to the French low-carbon strategy, electricity consumption should reach around 600 TWh in 2050, a 30% increase from the current level, mainly due to electrification of end uses. The French transition energy law sets a 50/50 goal in 2035 for nuclear and renewables generation in the electricity mix, which will require far greater flexibility. Given the strong increase in renewable production and the future closure of French nuclear reactors at the end of their lifespan (today scheduled between 50 and 60 years), the successful balance between renewables and nuclear energy implies a need for new reactors being commissioned in the coming decades.

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Accommodating a growing share of variable renewable energies (wind, solar PV) will be a challenge for the power system. Rising to that challenge will require not only strengthening the grid but also adding zero-carbon backup to maintain electricity quality and the supply-demand balance. Thus, nuclear will, over the long term, be a proven source of operational flexibility, along with other sources being developed (e.g., batteries, vehicle-to-grid, demand-side management, other dispatchable low-carbon sources). Tapping this potential will require skills and expertise both in design engineering and operations, to guarantee that reactor operations meet all safety standards.

A question often raised relates to the impact of flexibility on operating performance. For instance, whether additional maintenance is required and/or plant availability is affected. Studies conducted by EDF found that the impact exists but is not significant. If the level of flexibility required increases in the coming decades, then market design will have to be adapted to maintain an adequate level of remuneration of flexibility with future market conditions.

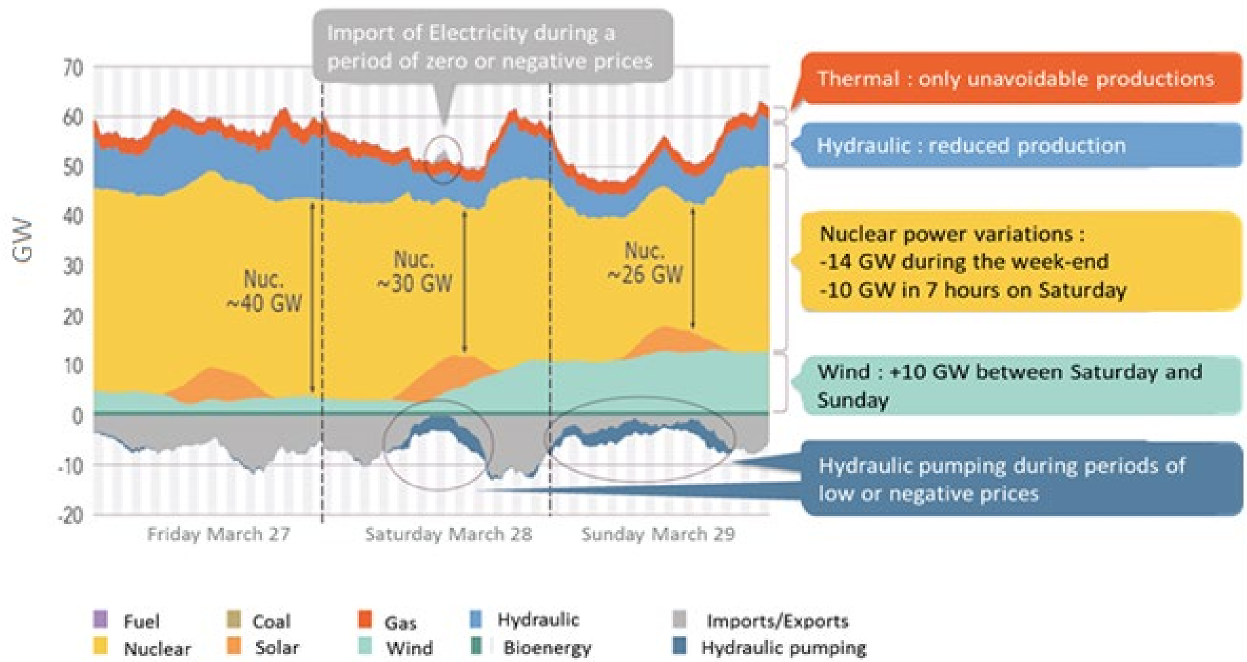

Figure 28. Different metrics recorded between March 27 and March 29, 2020

Source: Jun Zeng, EDF. All rights reserved.

During the 3 days, nuclear power ramps down from 40 GW to 30 GW in a few hours, and then to 26 GW when power demand and exports are low and solar and wind productions are high. Imports and hydraulic pumping take place when prices are low or negative.

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11.4 Innovations That Have Made Flexible Nuclear Possible in France Can Be Widely Replicated

Innovation has allowed EDF to operate its nuclear plants in a flexible manner and to develop supporting technical skills for nuclear operators. Key areas of innovation are design modifications, extended safety studies, and control room operation, which requires well-trained personnel.

Enhanced Design: The design of French nuclear power plants has evolved to include features not found in standard PWRs. These modifications have primarily involved using different types of rods and changing their position in the core depending on power levels. The use of special "gray rods" composed of materials that absorb fewer neutrons than standard control rods makes it possible to modulate chain reactions more precisely.

Extended safety studies: Safety studies have been extended to consider a wide power range. Dedicated specifications, validated by the French Nuclear Safety Authority, are applied to flexible operation.

Well-trained operators: Control room operators receive specific training in this mode of operation on full-scope simulators that are exact physical replicas of control room equipment. Assistance tools have also been developed over the past 15 years.

What has been accomplished in France can be duplicated elsewhere in the world. Developing new reactors with these operating procedures integrated as early as the design phase will be key to controlling the economic impact of this flexibility. The costs associated with new nuclear will determine where this powerful source of zero-carbon flexibility fits in the merit order relative to other tools that will be available moving forward.

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12 Exelon: Nuclear Cycling at Exelon Generation

Prepared by David Throne, Exelon Corporation. Exelon is a U.S. energy company that provides energy services at the generation, transmission, and distribution levels.

In 2015, Exelon recognized a need to respond to grid conditions such as transmission congestion and power prices, which could become negative due to congestion. The Advanced Nuclear Dispatch program was created as the solution. Advanced Nuclear Dispatch is a real-time system in which the Exelon Constellation Market Operations Center can monitor conditions and provide a dispatch signal to selected sites in the nuclear fleet to lower power. The results have been positive with notable savings being generated along with reduced costs. A vast majority of the savings and reduced costs from cycling, approximately 90%, comes from the effect on forward market cost savings. Forward prices are stabilized and are not as low as they would have been due to cycling the selected units.

The Advanced Nuclear Dispatch process physically works through a signal sent to the selected site via Exelon's Generation Manager computer system. The site receives the signal on a computer in the Main Control Room, operators confirm the dispatch signal with the Constellation Generation Dispatcher, and then a Nuclear Regulatory Commission-licensed Senior Reactor Operator at the site authorizes the load reduction. Reduced power is maintained until a dispatch signal to raise load is received.

Table 8. Summary of Sample Ramping Scenario

Sample Only							
Generator	Actual MW	ISO Calc Setpoint	Deviation MW's	Minimum MWe	Maximum MWe	Up Ramp Rate	Down Ramp Rate
Byron 1	1,203	1,205	-2	845	1,205	0.6	4
Byron 2	1,177	1,180	-3	820	1,180	0.6	4

Advanced planning is one key to a successful program. Operators practice load-following maneuvers in the simulator, briefs are prepared in advance of each shift, and reactivity maneuver documents are created ahead of time. Capability limits for load reduction and recovery are calculated by the station and provided to the Market Operations Center via the Generation Manager computer system so capabilities are clearly understood.

Other load cycling programs include congestion relief, which is an independent system operator initiative to resolve constraints on the transmission system. Day-ahead scheduling is utility-initiated to minimize financial losses due to negative pricing in the day-ahead market. Day-ahead scheduling uses a fixed MW hourly output scheduled, communicated and agreed to by the Market Operations Center and the station in advance when next-day pricing dictates use of the process.

In summary, nuclear load cycling has proven to be a safe and successful method to eliminate localized negative pricing in real time and day ahead conditions while increasing nuclear plant profitability. Operator standards and fundamentals are reinforced through training, procedure development and adherence, and effective communication during Advanced Nuclear Dispatch

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dispatches. Nuclear units are only cycled within their technical capabilities for reductions and recovery rates, and measures are in place to avoid cycling units up and down repeatedly in the same day. The shift manager, a Nuclear Regulatory Commission Senior Reactor Operator license holder, authorizes all power maneuvers requested by the Market Operations Center to assure nuclear safety. Preplanning, good communication, and technical knowledge as to why cycling is required have helped make the program a success.

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13 Generation IV International Forum: Delivering Next-Generation Nuclear Systems

Prepared by Hideki Kamide, Chairman of the Generation IV International Forum (GIF), a multinational co-operative.

GIF is a multinational co-operative endeavor organized to foster the research and development needed to accelerate the deployment of the next generation of nuclear systems.

Since its creation in 2000, GIF has identified the following six nuclear energy systems as being the most promising to meet its objectives, assuming a deployment horizon beyond 2030 (Petti et al. 2014):

- SFR
- Very high temperature reactor
- Gas-cooled fast reactor
- MSR
- Lead-cooled fast reactor
- Supercritical water-cooled reactor.

These concepts fit within the Generation IV systems depicted in Figure 29.These nuclear systems meet stringent criteria in sustainability, economics, safety and reliability, proliferation resistance and physical protection. While all six systems are certainly capable of producing electricity, they have been developed from the onset considering potential applications for their nuclear heat, particularly those systems capable of outlet temperatures ranging 700°–950° C (i.e., very high temperature reactor, gas-cooled fast reactor, lead-cooled fast reactor, and MSR), and ~550° C (SFR). Nuclear heat can be used to support hydrogen production or to provide industrial process heat to chemical processing facilities, such as petroleum refineries.

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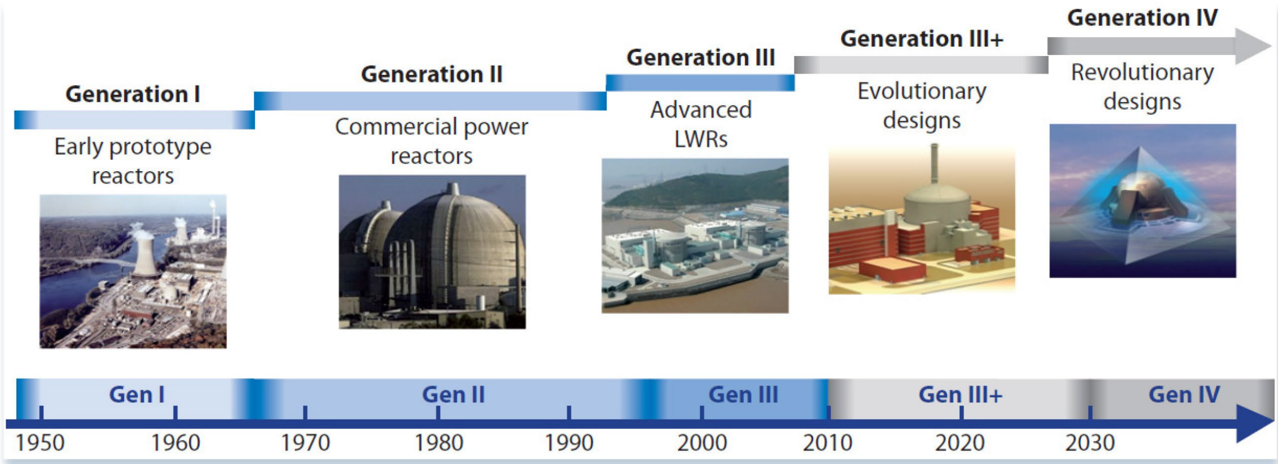

Figure 29. The four generations of reactor designs

Source: (Stanculescu 2019)

In addition to these core drivers, GIF is also increasingly recognizing the need to take into account flexibility capabilities as a specific requirement for future nuclear systems. As recommended by its Senior International Advisory Panel, GIF is progressing toward a system approach to flexibility in a broad sense, addressing operational flexibility (maneuverability, compatibility with hybrid systems, island mode operation, diversified fuel use), deployment flexibility (scalability, siting, constructability), and product flexibility (electricity, process heat).

This context was integrated into the recent update of the GIF research and development outlook (EMWG 2018) and is now taking place through a number of initiatives at the level of the GIF cross-cutting working groups (in particular for economics) and as part of the definition of research and development priorities of the six systems.

13.1 Economic Perspectives on the Flexibility of Gen-IV Systems

The GIF Economic Modeling Working Group is currently working on market issues related to the deployment of Gen IV systems (EMWG 2018); especially considering the increasing penetration of variable renewable electricity production and the importance of capital cost reductions for the future competitiveness of nuclear power.

Together with the GIF Senior International Advisory Panel, the Economic Modeling Working Group is monitoring the work being done elsewhere on the integration of renewable and nuclear energy systems to inform the research and development activities of the six GIF systems. This work resulted in the publication in 2018 of a first position paper (Bredimas 2011) with two key recommendations for GIF research and development activities:

- While flexibility is not directly identified in the original GIF goals, the six GIF systems need to ensure that flexibility aspects are an integral part of their future research and development priorities.
- Specific opportunities for cross-cutting research and development should also be encouraged. This typically includes topics such as advanced materials resistant to thermal

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fatigue, advanced instrumentation and control for dynamic balancing of electrical and thermal outputs, as well as efficient and flexible energy conversion systems such as the supercritical CO_2 Brayton cycle.

In addition, the Senior International Advisory Panel has further identified three strategic issues that need to be addressed in order to better integrate Gen-IV systems in future energy markets:

- Enhanced maneuverability to operate in electricity mixes that include an increasing share of intermittent energy sources. Although flexible operation may likely result in reduced revenues when participating in current liberalized electricity (energy only) markets, designers of Generation IV advanced reactors recognize that enhanced flexibility may be an essential feature in the electricity markets of the future that may value reliability, resiliency, capacity, and other ancillary services.

- Enhanced flexibility of energy products (e.g., power, heat, hydrogen, and so on). Generation IV advanced reactors are to be designed with the capability to deliver a variety of energy products, such as heat or hydrogen, in addition to traditional power. This will be beneficial from a system cost perspective while increasing the overall reliability and resilience of the energy systems and optimizing the business case for Gen IV technologies.

- Enhanced reliability of nuclear reactor operation with energy storage options. These solutions could improve the balance between base load and variable generation. Further work is needed to be assess the economic and technical implications of energy storage components.

13.2 Technical Flexibility Capabilities of Gen-IV Systems

Building on the economic and strategy assessments of Gen IV system flexibility, developers of the six system concepts are working to identify key technical areas to focus their research and development efforts. A dedicated technical workshop was organized in May 2019 in Vancouver in the margins of the 10th Clean Energy Ministerial to discuss research and development needs. A number of important findings are be highlighted in the following subsections.

13.2.1 Operational Flexibility

Overall, Gen-IV systems are expected to have load-following capabilities at least similar LWRs that implement flexibility features. However, important differences remain among the six systems.

Some Gen-IV systems, and, in particular, MSR concepts with liquid fuel, are inherently flexible. The main limitation in terms of operational flexibility would be imposed by the steam cycle. Other Gen-IV concepts, such as SFR and lead-cooled fast reactors, have in the past provided ancillary services to the grid (e.g., Phénix and Superphénix SFR reactors in France) but face technical constraints for load-following. This constraint is partly due to the fact that these reactors were initially designed without requirements for operational flexibility. In that respect, a number of research and development priorities have been identified to address this issue. For SFR, this includes:

- Redesigning the inner vessel to minimize thermal gradients

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- Insertion of a backpressure to avoid changes in the level of the sodium coolant free surface
- Diversification of generated energy products generated to maintain the reactor operating at full nominal power.

13.2.2 Deployment Flexibility

Gen IV systems may face, in general, fewer siting constraints than traditional LWRs. For instance, due to their intrinsic safety features, some advanced concepts may have a smaller emergency planning zone requirements. Furthermore, the higher thermal efficiency of Gen IV systems reduces the need for an ultimate heat sink on a per-unit electricity generated basis. They can be designed for a large power range, which also supports greater deployment flexibility, as these systems can be tailored to the needs of a specific market.

In terms of construction, higher modularity and advanced manufacturing processes will also foster deployment flexibility.

13.2.3 Product Flexibility

Gen-IV systems are expected to have superior capabilities compared to LWRs in terms of product flexibility due to their higher outlet temperature. All Gen-IV systems exhibit higher reactor outlet temperatures compared to LWRs and are ideal for a wide range of process heat applications. In particular, there is a large existing and near-term market for steam at temperatures lower than 600° C. For instance, in Europe, the process heat market represents 100 GWth today, and about 50% is found in the temperature range up to 550° C (primarily in the chemical industry and for refineries) ("Cost and Performance Requirements for Flexible Advanced Nuclear Plants in Future U.S. Power Markets" 2020). In the longer term, very high temperature reactors could also offer promising opportunities for temperatures higher than 950° C (such as steelmaking, cement, and, potentially, hydrogen production) but will require additional research, particularly related to material science.

In addition to specific research and development activities, the construction of first reactor prototypes and the industrial demonstration of coupling with nonelectric applications, in particular industrial heat and hydrogen production, remain the key near-term objectives for the commercial deployment of these Gen-IV systems.

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14 Energy for Humanity: Economic Requirements for the Expanded Role of Nuclear Energy in De-Risking the Energy Transition in the Electricity and Fuels Sectors

By Eric Ingersoll and Kirsty Gogan, LucidCatalyst (Cambridge, Massachusetts, USA) and Energy for Humanity (London, United Kingdom). With contributions from John Herter, Andrew Foss, and Romana Vysatova of LucidCatalyst.

In 2019, several clean-energy nongovernmental organizations helped conceive and co-founded the Flexible Nuclear Campaign, because it was time to explore the expanded role that nuclear energy can play in de-risking countries' energy transitions by exploring additional paths to significantly reduced emissions. This chapter describes three ways to broaden the role that nuclear energy can play in clean energy transitions.

The first is an expanded role in electricity production through the design of nuclear configurations—using a combination of flexible operations and thermal energy storage— intended to complement renewables in future grids. The key here is providing guidance to designers of advanced nuclear systems about features and capital costs that will make their designs more valuable and competitive in future electricity markets.

The second is enabling nuclear energy to contribute to energy transitions beyond electricity production—in the primary energy sectors making up three-quarters of energy consumption currently served by oil and gas—by providing hydrogen that can be used directly or as a feedstock for synthetic fuels.

The third is redefining the deployment paradigm for nuclear energy based on a high-volume, low-cost, rapidly-deployable, commercially-attractive manufacturing model—in order to expand nuclear's role in all energy sectors with the goal of significantly reducing emissions and ensuring clean affordable energy for all.

These concepts show how the nuclear industry can apply commitment and creativity, combined with technical and business innovation, to deliver the scale and rates of deployment needed to provide large-scale and timely contributions toward clean energy transitions, just as the renewables industry learned to do. This chapter is an effort to open a broad and rigorous discussion of what it would take for this to occur.

14.1 Enhancing the Value of Nuclear Energy to the Electric Grid: Design and Capital Cost Targets for Flexible Advanced Nuclear Plants

In the United States, competitive power markets are experiencing extended periods of very low power prices, driven primarily by large supplies of low-cost natural gas. At the same, growth in demand for electricity has stagnated in many areas of the United States, driven by deindustrialization and efficiency improvements. These power market conditions would normally discourage new entrants; however, federal government incentives, state policies, and corporate

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purchases of renewable energy are driving significant deployment of wind and solar, further depressing wholesale power prices. Remarkably, in spite of these conditions, there are now more companies developing advanced reactors than at any other time before. However, reactor developers today must design for very different future market conditions than nuclear plants have seen in the past.

In this new environment, it is critical for advanced reactor designers to have clear signals from the market about what plants need to cost to be attractive investments, and what performance characteristics will create the most value for plant owners. Many advanced reactor designs, especially their balance-of-plant, are still in the conceptual design stage and therefore have large scope for reducing CapEx by making intelligent design choices and applying target cost design methods. Designers face critical questions such as: What is the maximum allowable CapEx for which plants can be built once they are commercially available? Further, how flexible should the reactor be? How much is that flexibility worth? How much effort and/or cost should be expended to deliver flexible performance and how much value can that create for the plant owner?

LucidCatalyst used the PLEXOS® electricity production cost modeling software to estimate the revenues earned by a generic high-temperature advanced nuclear plant in deregulated power markets in 2034 (LucidCatalyst 2020). These revenues (which included the opportunity to receive capacity payments that are seen in today's markets) were then analyzed in a power plant financial model to determine the maximum allowable CapEx for which a plant must be delivered to meet a market rate of return. The goal was to provide advanced reactor developers information about the CapEx targets they need to achieve by the time their reactors are to be commercially available. The team also analyzed the value of flexible operation, as several advanced nuclear plants are being designed with similar ramping and load-following capabilities as combined-cycle natural gas plants (LucidCatalyst 2020).

LucidCatalyst modeled two different future scenarios—each containing different resource mixes. The first is a baseline low renewables scenario, which presumes a continuation (and eventual expiration) of existing renewables policy. The second is a high renewables scenario that has the same resource mix as an NREL ReEDS scenario, which assumes low renewables and natural gas costs (thus high penetration of both resource types). These scenarios were modeled across four deregulated U.S. power markets: ISO-NE, PJM, MISO, and CAISO.

The PLEXOS modeling revealed that the average allowable CapEx across all scenarios and independent system operators is $3,234/kW (reflecting a range from $1,965/kW to $4,503/kW, depending on the power market, resource mix, and capacity payment amount). Each modeled scenario also included a run with a 12-hour, co-located thermal energy storage system. The additional energy revenues earned from higher prices and extra capacity payments earned from doubling the effective capacity of the plant, enabled an increase in the allowable CapEx for the nuclear + storage plant which ranged from $613/kW to $1,891/kW across the modeled scenarios and independent system operators. The table below provides the maximum allowable CapEx for each modeled scenario and power market.

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Table 9. Maximum Allowable CapEx by Independent System Operator and Scenario ($/kW)

	Low RE w/out ESS	Low RE with ESS	High RE w/out ESS	High RE with ESS
ISO-NE				
Low Capacity Price Case ($50/kW-yr)	$2,289	$2,962	$1,965	$2,788
Mid Capacity Price Case ($75/kW-yr)	$2,566	$3,515	$2,242	$3,341
High Capacity Price Case ($100/kW-yr)	$2,843	$4,068	$2,519	$3,894
PJM				
Low Capacity Price Case ($50/kW-yr)	$2,358	$2,988	$2,186	$3,038
Mid Capacity Price Case ($75/kW-yr)	$2,634	$3,541	$2,462	$3,591
High Capacity Price Case ($100/kW-yr)	$2,911	$4,095	$2,739	$4,144
MISO				
Low Capacity Price Case ($50/kW-yr)	$2,244	$2,857	$2,000	$2,654
Mid Capacity Price Case ($75/kW-yr)	$2,521	$3,410	$2,276	$3,207
High Capacity Price Case ($100/kW-yr)	$2,797	$3,963	$2,553	$3,760
CAISO				
Low Capacity Price Case ($50/kW-yr)	$2,187	$3,397	$1,968	$3,306
Mid Capacity Price Case ($75/kW-yr)	$2,464	$3,950	$2,244	$3,859
High Capacity Price Case ($100/kW-yr)	$2,740	$4,503	$2,521	$4,412

LucidCatalyst performed additional sensitivity analyses to assess the impact of other factors on maximum allowable CapEx, including a scenario with a large fleet of advanced nuclear plants with energy storage systems. As expected, due to lower operating costs, advanced nuclear plants set lower energy clearing prices and thus decreased the allowable CapEx thresholds.

Table 10. Annual Average Market Prices for ISO-NE, PJM, MISO, and CAISO

		Average Annual Energy Price
ISO-NE	High RE Future (Without Flexible Adv. Nuclear)	$26.32/MWh
	Fleet Deployment of Flexible Adv. Nuclear	$22.64/MWh
PJM	High RE Future (Without Flexible Adv. Nuclear)	$27.03/MWh
	Fleet Deployment of Flexible Adv. Nuclear	$22.67/MWh
MISO	High RE Future (Without Flexible Adv. Nuclear)	$26.13/MWh
	Fleet Deployment of Flexible Adv. Nuclear	$24.70/MWh
CAISO	High RE Future (Without Flexible Adv. Nuclear)	$38.06/MWh
	Fleet Deployment of Flexible Adv. Nuclear	$29.61/MWh

Because advanced nuclear plants can operate as base load resources as well as load following, they can supply a large fraction of firm power without raising the overall cost of electricity. These findings motivate independent system operators, public utility commissioners, policymakers, utilities, and other stakeholders to investigate the potential roles that these products could play in future grids and to continue supporting advanced nuclear commercialization efforts. This should also encourage organizations responsible for national and international energy modeling to include flexible, advanced nuclear with thermal energy storage in their projections for future energy systems. Figure 30 shows installed capacity for PJM across the range of scenarios, and Figure 31 shows generation. This illustrates the potential effectiveness of advanced reactor plants with energy storage to operate flexibly and cost-effectively while reducing emissions.

The CapEx thresholds highlighted in this report are relatively low compared to conventional nuclear new build plants in North America and the European Union. That said, they are well within the range of those reported by third-party cost studies (Energy Innovations Reform Project 2017) and advanced nuclear developers themselves. This range is also well within the costs being achieved in countries with continuous new build nuclear programs (Energy Technologies Institute 2018). Designers should integrate these cost requirements into their plant designs and consider whether adding thermal storage makes sense in their target markets.

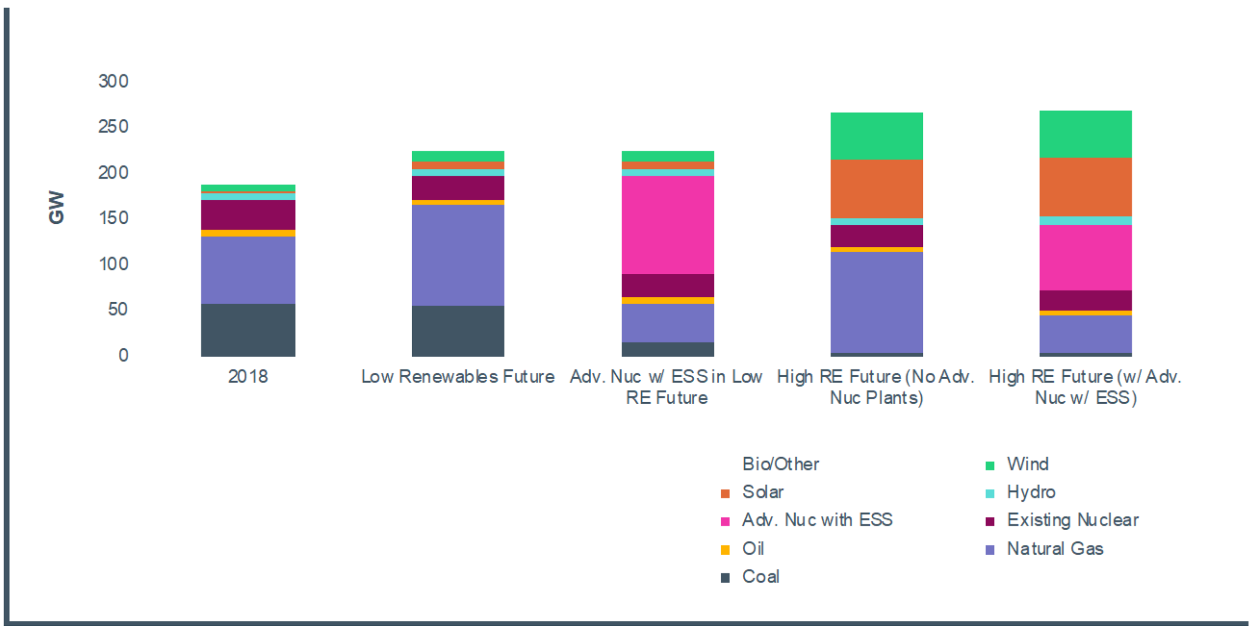

Figure 30. PJM installed capacity

Source: LucidCatalyst.

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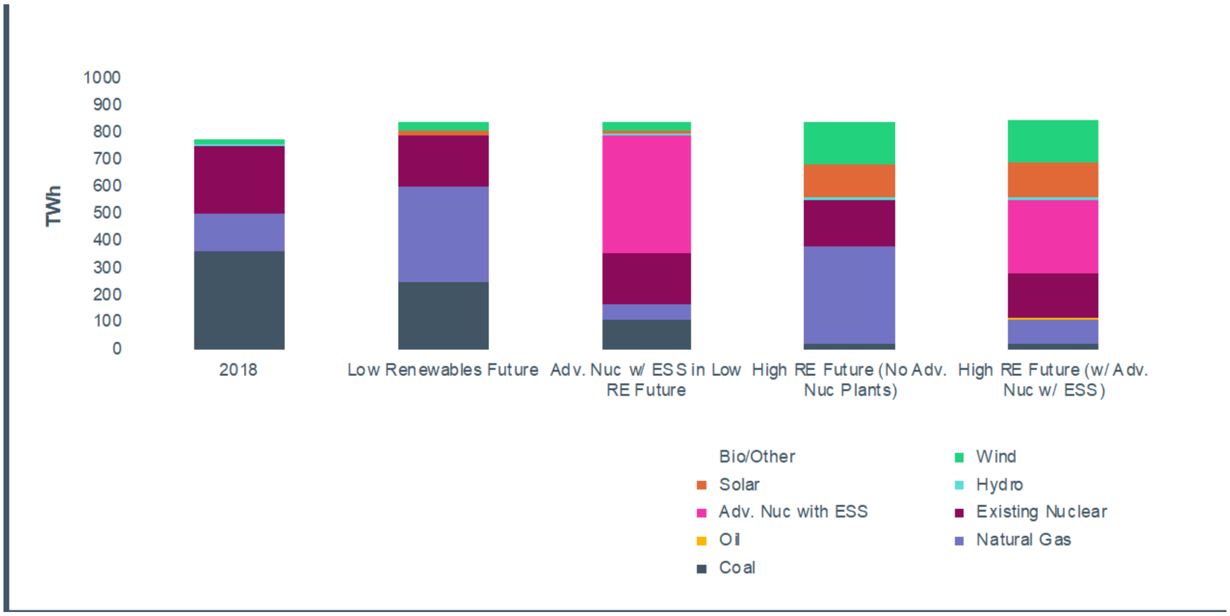

Figure 31. PJM generation

Source: LucidCatalyst.

14.2 Nuclear Energy is Well-Suited to Emissions-Free Hydrogen Production

Despite progress on driving down emissions in the power sector, credible projections indicate that fossil fuels will continue to supply the bulk of global energy by mid-century. This assumes extensive deployment of electrification, efficiency, renewables, and other clean technologies (BP 2019; DNV GL 2019; EIA 2019b; IEA 2019c). The *IEA World Energy Outlook 2019's Stated Policies Scenario* assumes substantial electrification of transport sectors and significant long-term growth of renewable energy (IEA 2019c). Nevertheless, IEA projects that fossil fuels (coal, oil, and gas) will supply approximately 75% of primary energy by 2050[11] (IEA 2019c).

At the same time, three billion people will lack access to electricity in 2050, up from the 840 million people today who lack access to sufficient electricity (Sustainable Energy for All 2019). To avoid this outcome, growth in energy access will need to be better represented in global climate mitigation strategies (IEA World Energy Outlook 2019).

[11] In the IEA Stated Policies Scenario, energy demand rises by 1% per year to 2040. Low-carbon sources, led by solar PV, supply more than half of this growth, while natural gas, boosted by rising trade in liquefied natural gas, accounts for another third. Oil demand flattens out in the 2030s, and coal use edges lower. Some parts of the energy sector, led by electricity, undergo rapid transformations. Some countries, notably those with net zero aspirations, go far in reshaping all aspects of their supply and consumption. However, the momentum behind clean energy technologies is not enough to offset the effects of an expanding global economy and growing population. The rise in emissions slows but, with no peak before 2040, the world falls far short of shared sustainability goals.

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Failing to achieve net zero emissions and providing basic access to electricity for large numbers of people will have severe global consequences. New solutions are required, especially for fuels use, both liquid and gas.

In light of this, numerous recent studies have examined emissions-free hydrogen production as a decarbonization tool, with estimated production costs from various clean electricity sources indicating this to be a potentially promising opportunity (Glenk and Reichelstein 2019; IEA 2019b; IRENA 2018).

By 2050, clean hydrogen produced using nuclear and/or renewable energy could help avoid half of cumulative future carbon emissions from a large fraction of otherwise locked-in fossil fuels. However, this depends upon very low-cost clean hydrogen being available in the near term.

Drawing on the IEA World Energy Outlook 2019's Stated Policies Scenario, it is possible to identify the most relevant sectors for hydrogen substitution. These are: natural gas for nonelectricity uses, oil for transportation, and oil for other uses (IEA 2019c).

The vehicles, machinery, heating systems, and other applications in these sectors could consume drop-in synthetic fuels from hydrogen rather than conventional fossil fuels. All coal consumption and natural gas for electricity generation are excluded from this analysis because these sectors could be decarbonized in a relatively straightforward manner with other clean electricity sources rather than synthetic fuels.

Fossil fuel consumption for IEA World Energy Outlook 2019's Stated Policies Scenario sectors considered (natural gas for nonelectricity uses, oil for transportation, and oil for other uses) (IEA 2019c) are expected to be responsible for nearly 20 GT of CO_2 emissions in 2050 (55% of total CO_2 emissions from fossil fuel consumption). Emissions from the included sectors rise faster in the IEA Stated Policies scenario than those from the excluded sectors (coal for all uses and natural gas for electricity). Cumulatively, over the period from 2020 to 2050, the included sectors are predicted to emit 525 GT of CO_2 (IEA 2019c).

The sectors addressed are, by definition, difficult to abate, because emissions are not being eliminated by the stated policies assumed in the IEA analysis. The strategies outlined therefore are intended to drive emissions reduction in parts of the economy for which viable solutions are currently not foreseen to be available by mid-century. These strategies should therefore be seen as complementary and needed for net zero emissions by mid-century.

14.2.1 Target Costs for Hydrogen as a Feedstock for Synthetic Fuels

To achieve the scale and pace of emissions reduction required, we assume that zero- and carbon-neutral fuels substitutes need to achieve price and performance parity with fossil fuels. This is also necessary to enable energy access and continued economic growth, and to reduce the risks associated with the need for political support, government subsidies, and behavior change if prices are not competitive.

The rapid decrease in hydrogen costs from nuclear plants would allow for faster substitution of large amounts of fossil fuel consumption in the IEA World Energy Outlook 2019's Stated Policies Scenario sectors addressed in this report. Based on hydrogen cost and market size data analyzed,

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more than half of fossil fuel consumption in these sectors could be decarbonized by 2030, and all of it by 2050.

As shown in Figure 32, emissions-free hydrogen production using nuclear technology can be cost-competitive with other zero-CO_2 production methods and has the potential to be cost competitive with steam methane reforming of low-cost natural gas, which is the cheapest pathway to making hydrogen today (Allen et al. 1986; BloombergNEF 2020; Boardman et al. 2019; Gogan and Ingersoll 2018; Hydrogen Council 2020; IEA 2019b; NREL 2019b; M. Ruth et al. 2017; Yan 2017). Even current first-of-a-kind U.S. and EU conventional LWR are not optimized for low-cost construction can produce clean hydrogen at costs comparable to wind and solar resources with good capacity factors.

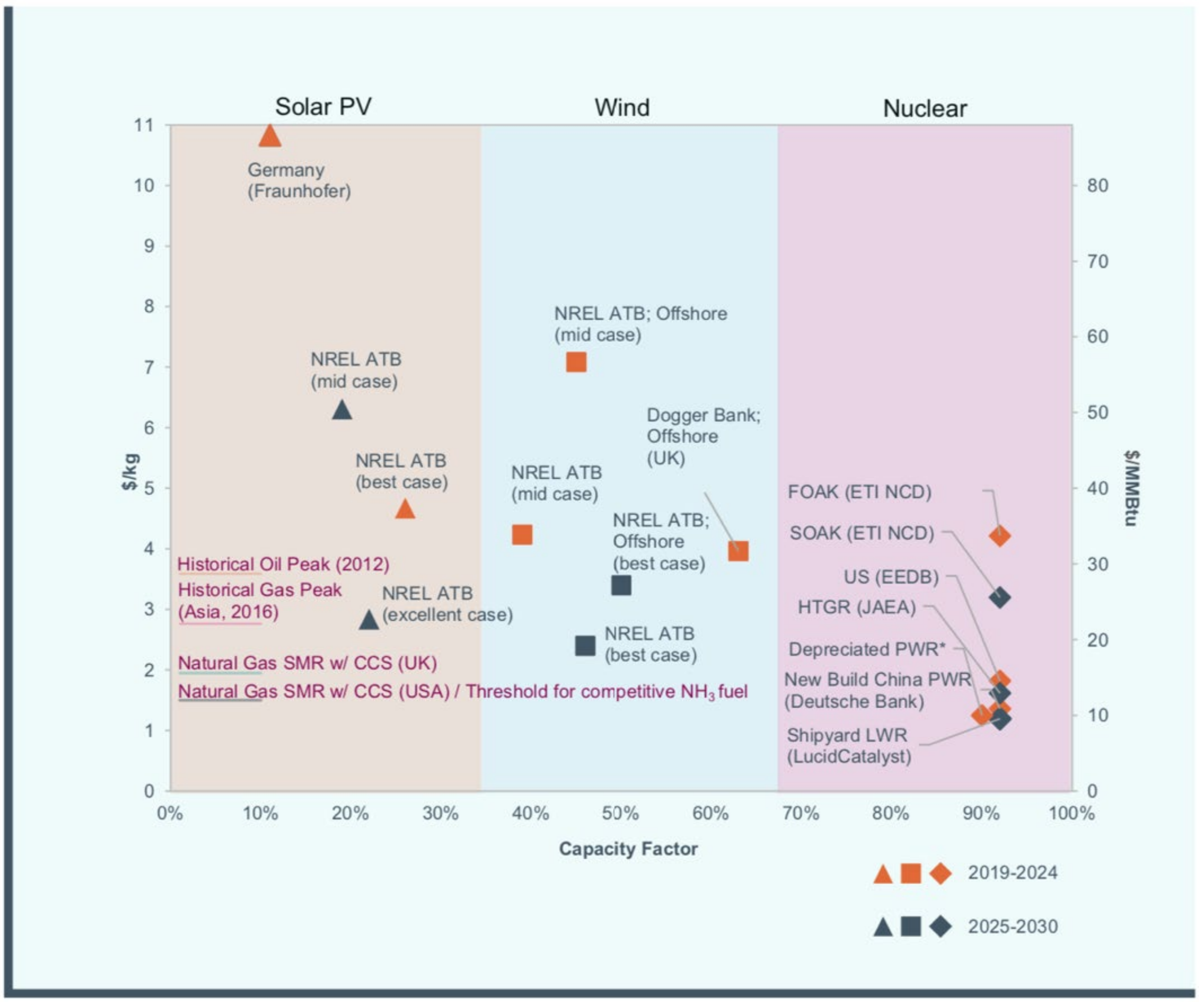

Figure 32. 2018–2030 hydrogen production costs

Source: (LucidCatalyst 2020)

Nuclear energy has particular attributes well-suited to the production of hydrogen. Electricity and heat production at very high capacity factors enables large-scale production of relatively low-cost,

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zero-CO_2 hydrogen (Boardman et al. 2019).[12] High power density also enables a relatively tiny environmental footprint. Nuclear production of hydrogen offers additional flexibility in how nuclear energy supports grid demand, assuming that the coupled hydrogen plant can be operated in a flexible manner as well.

Hydrogen can be produced with grid electricity or surplus energy from clean sources like renewables and nuclear. However, future zero-carbon fuels markets are so large that they will also need to be addressed by large, dedicated zero-carbon hydrogen production facilities. This is because the ultimate size of the zero-carbon hydrogen market—if expanded to produce synthetic substitutes for fossil fuels—could be far larger than the global electricity market. Therefore, the emphasis here is primarily on cost and scalability potential of hydrogen production from large, dedicated projects.

Low-cost hydrogen (below $1.50/kg) can enable large-scale production of carbon neutral fuels such as Jet A fuel for aviation, and ammonia to replace bunker fuel in marine shipping and peaker gas plants as well as other uses. Low-cost hydrogen requires low-cost, high capacity factor energy, as well as low-cost and highly efficient electrolyzers. Reaching aggressive cost targets is helped by using advanced high temperature electrolysis as well as thermochemical, heat driven processes.

Due to its ability to produce electricity and high-temperature steam reliably at capacity factors over 90%, nuclear technology is well suited to produce large volumes of low-cost hydrogen at a global market scale. Production from nuclear technology is highly advanced. Decades of research, including whole programs in national laboratories, both with conventional (light water) and advanced reactors, has shown the transformative and near-term potential for low-cost, high-volume clean hydrogen production. Recent analyses and planned LWR-generated hydrogen demonstrations in the United States are summarized in Chapter 5.

14.2.2 Transformative Nuclear Project Delivery Models for Low-Cost and Large-Scale Deployment for Power, Hydrogen, and Fuels

The nuclear industry as it is configured today is unlikely to be able to deliver the scale of plants necessary within the required timeframe to make a substantial contribution to synthetic fuels production. To drive a massive increase in clean hydrogen production, the nuclear industry will need to transform project delivery and deployment models in order to scale up and deliver the products needed for clean heat, fuels, and power. These would be achievable with the application of the same intensity of focus on cost reduction, performance improvements, and deployment rates that have enabled renewable technologies to begin transforming the global energy system.

Steep, near-term cost reduction is achievable by shifting from traditional construction projects to high productivity manufacturing environments, such as shipyard-manufactured plants or floating production storage and offloading vessel (in Figure 34) or a Hydrogen Gigafactory model (defined

[12] "Affordable clean hydrogen can be produced using energy from the nuclear power plant. The DOE target for the levelized cost of hydrogen production (i.e., <$2.00/kg H_2) can be met and exceeded. The analysis indicates an LWR electricity/hybrid plant can also outperform conventional natural-gas steam reforming under specific operating conditions and clean energy allowances. The economic evaluation indicates H_2 can be produced for around $1.50/kg, based on the financial parameters invoked for a publicly bonded capital project" (Boardman et al. 2019).

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below and pictured in Figure 35). Moving from traditional construction to high productivity manufacturing will dramatically lower the cost of clean hydrogen and synthetic fuels production using high temperature advanced reactors. Leading shipyards already have extensive manufacturing capacity, which can produce designed-for-purpose hydrogen production facilities. Existing global shipyard capacity combined with new and/or upgraded capacity could deliver sufficient synfuel floating production storage and offloading vessels to fully replace fossil fuels in the difficult-to-decarbonize sectors identified in this chapter.

These new delivery models achieve hydrogen costs that enable cost-competitive synfuels at large scale as early as 2030. Achievable hydrogen production costs for 2030–2050 are shown in Figure 33.

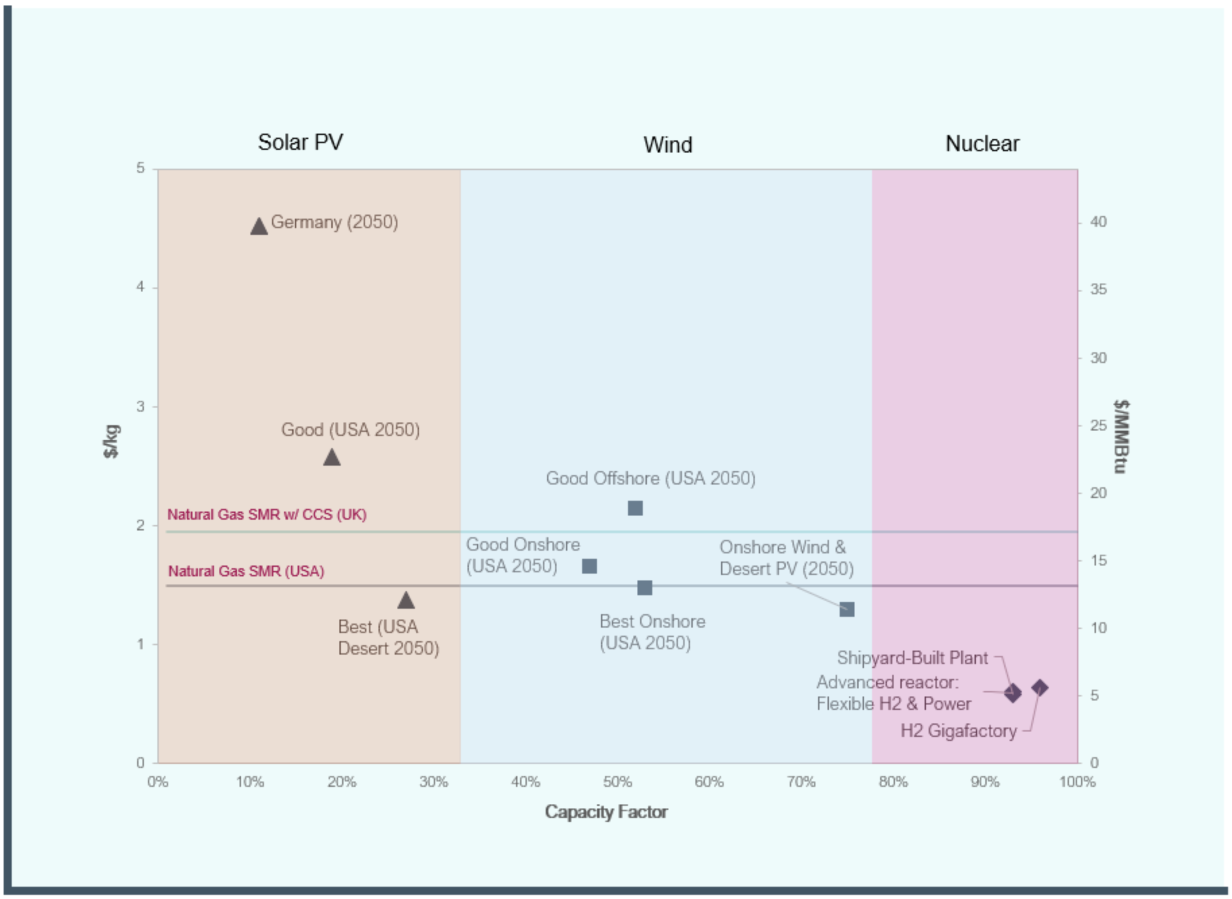

Figure 33. Hydrogen production costs 2030–2050

Source: LucidCatalyst.

Figure 34 and Figure 35 show a conceptual shipyard manufactured floating production storage and offloading vessel with the potential to produce hydrogen, power, ammonia, and desalination moored close to shore. Not shown are the pipelines and underwater transmission cables sending products to shore.

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Figure 34. Shipyard-manufactured hydrogen, ammonia, and desalination facility

Source: LucidCatalyst.

The production of fuels which are transportable commodity with a global market enables a new business model for nuclear energy. As the product changes from local electricity to global fuels deliveries, the siting and scale of operations are transformed. Offshore deployment increases siting opportunities and reduces costs, further enabling global-scale production of low-cost hydrogen and synthetic fuels in the 2030s and beyond.

The Hydrogen Gigafactory concept (illustrated in Figure 35) is a next generation refinery to be located on brownfield sites, such as large coastal oil and gas refineries. This refinery-scale hydrogen production facility is sized to produce one-tenth of U.K. hydrogen demand in 2050. The Hydrogen Gigafactory delivery model, with its highly integrated, high productivity onsite manufacture, assembly, and installation of key components and compact layout, can deliver large quantities of very low-cost hydrogen. For countries developing such refinery-scale facilities, this represents huge potential to establish world-leading domestic supply chain capability, potential competitive export of synthetic fuels, and affordable decarbonization.

By rethinking nuclear deployment from this cost-reduction perspective and scaling up operations, this chapter defines a path to ultra-low-cost hydrogen at under $1/kg. The rapid achievement of low hydrogen costs via these innovative delivery modes could accelerate deep decarbonization across the difficult-to-decarbonize sectors. By 2050, low-cost clean hydrogen could help avoid substantial global cumulative future carbon emissions from a large fraction of otherwise locked-in fossil fuels.

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Figure 35. 2018–2030 Hydrogen Gigafactory

Source: LucidCatalyst.

Achieving the extent of decarbonization required within 30 years will be a herculean effort. Major constraints, including the extent of capital available for investment in new infrastructure need to be taken into account. The investment required to maintain the anticipated flow of oil (approximately 100 million barrels of oil per day) is $16.8 trillion over the period 2020–2040 (Hureau and Serbutoviez 2020).

By contrast, the innovations described here would require a lower investment than would otherwise be required to replace the oil and gas flows in hard-to-decarbonize sectors from the IEA stated policies scenarios. Figure 36 shows the total investment required for 350 EJ full fuel substitution by 2050, either by floating production storage and offloading vessels,[13] or by renewables (a combination of excellent capacity factor wind and solar) (NREL 2019b) compared to the projected exploration-production investment required to maintain and grow this flow of conventional oil and gas to 2050. In other words, meeting the same energy need for liquid fuels and gas (the 350 EJ identified earlier) through floating production storage and offloading vessels and Gigafactories requires substantially less investment between now and 2050 than continuing to invest in oil and gas production to meet this future requirement. The nuclear case supplies 350 EJ and includes the full cost of hydrogen plus conversion to synthetic fuels, resulting in an investment requirement considerably less than current investment projections to maintain the equivalent flow of oil and gas supply. The implication is that these fossil fuel supplies could be replaced with clean

[13] The floating production storage and offloading vessels investment case assumed a weighted average installed cost over 2030–2050 timescale of 1.3 billion per GW-class floating production storage and offloading vessel, including electrolysers, fuel production equipment, and onboard storage.

substitutes within three decades for less investment than would be required to continue supplying them through conventional oil exploration and production methods.

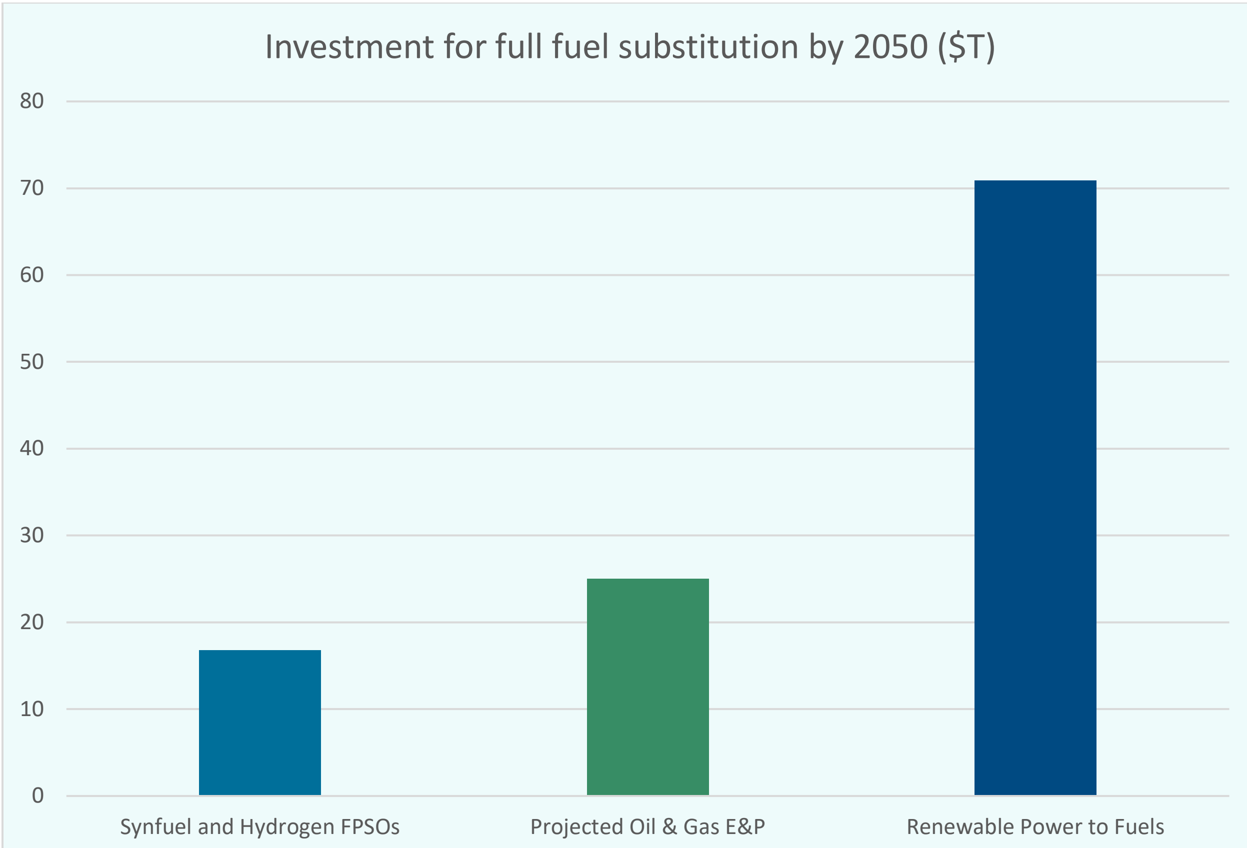

Figure 36. 2018–2030 hydrogen production costs

Source: LucidCatalyst.

Synthetic fuel production cost is a function of the cost of the hydrogen feedstock required. For synthetic fuels to achieve a price range that corresponds to typical cost ranges for standard fuels requires extremely low-cost hydrogen feedstock. Specifically, to achieve ammonia costs that are comparable to fuel oil for ships, requires hydrogen at $1.50/kg or below, and $1.10/kg or below for synthetic hydrocarbons, such as Jet A for aviation fuel. This can be achieved by combining advanced nuclear technologies with innovative delivery and deployment models in designed-for-purpose facilities intended to quickly achieve very low costs and large-scale deployment for rapid, near-term emissions reduction.

Our forthcoming study, *Decarbonizing Prosperity,* shows how scalable, cost-effective hydrogen can be produced in the near term (LucidCatalyst 2020). The study combines key results from techno-economic modeling of clean hydrogen production pathways. Given the high stakes, every effort should be made to realize this potential. For too long, risks associated with nuclear energy have been considered outside of the context of risks with other technologies, and without due consideration to the risks of failing to decarbonize. This chapter is a call to action for leaders to become educated about nuclear power, put risks into context and make informed, evidence-based and outcomes-focused decisions having properly evaluated the alternatives. To facilitate such

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informed decision-making, governments may wish to investigate the cost reduction and scale-up potential of factory-based and shipyard-manufacturing models for clean fuels production.

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15 International Atomic Energy Agency: Member State Experience on Flexible Nuclear Energy and Electricity Generation

Prepared by experts from the Department of Nuclear Energy, IAEA ("IAEA Overview" 2016) (https://www.iaea.org/about/overview)

The IAEA has an important role in providing Member States with guidance and assistance for deploying safe, secure and safeguarded nuclear technology and in formulating national energy strategies and policies. Supporting Member States in the attainment of the United Nations climate change targets and Sustainable Development Goals is thus closely aligned with the statutory objective of the IAEA: to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world. For Member States currently pursuing the nuclear energy option and those interested in deploying new nuclear power plants, the question of how to best integrate nuclear energy systems with other low carbon technologies, requires careful analysis. Nuclear power plants traditionally operated as base load generators may need to operate differently, more flexibly, in systems with large shares of variable renewables such as wind or PV plants.

This chapter summarizes the work and studies carried out by the IAEA in the area of nuclear power plant flexibility. The IAEA technical and economic analysis discussed here draws from the expertise and experience of Member States collected in various publications, technical meetings, workshops and conferences. It covers both the current fleet of reactors in today's electricity markets as well as the way nuclear power plants (including with advanced reactors, such as SMRs and Generation IV reactors) will need to operate in future electricity markets with large shares of variable renewables. Flexibility is key to the successful integration of nuclear and renewables, and the IAEA shows that beyond operational flexibility (i.e., load-following and provision of other system services), product flexibility, (i.e., the ability to produce electricity and nonelectric products such as hydrogen, process heat, or potable water) could be an important lever to decarbonize the entire energy sector. References to all relevant IAEA publications and ongoing activities are provided.

15.1 Flexibility of Nuclear Power Plants in Existing and Future Electricity Systems

The energy landscape is rapidly evolving in response to a worldwide commitment to drastically reduce carbon emissions, to the increased economic competitiveness of some low carbon generating options, as well as to the emergence of breakthrough technologies and applications for the power sector ("Climate Change and Nuclear Power" 2020). In the last decade, the generation share of VRE, wind and solar PV, has constantly increased in most countries, and this trend is expected to continue. The future power sector will likely evolve toward a larger, more complex and more integrated systems that rely mostly on low-carbon technologies, with a limited contribution from fossil-fueled technologies. Future flexibility and ancillary services needs are likely to go well beyond the levels in today's power systems and will be required from all dispatchable technologies, including those traditionally operated as base load, such as nuclear

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power. Load-following needs will be more difficult to forecast in advance, and power adjustments will be required in a shorter timescale and will be much more frequent.

The main driver of this change is the growing share of VRE technologies in the system. In the presence of significant share of VRE, the residual demand (i.e., the demand that must be satisfied by the rest of the system) becomes increasingly volatile and features increased amplitude of load variations and steeper ramps (see Figure 37). This increases the need for system flexibility. The residual load also becomes more unpredictable, being determined more by the uncertain generation from VRE sources (although forecasting methods have improved significantly) than by changes in demand, and loses its well-known daily, weekly, and seasonal patterns. Consequently, more reserve capacity and ancillary services are needed to ensure the power system reliability. In the presence of large shares of VRE, the power system will require and have to compensate the ability to provide firm capacity, flexibility, and other system services in addition to electricity generation; otherwise all thermal power plants will experience a decline in the achievable load factors (see Figure 38). The optimal mix will shift from base load to peaking and mid-merit plants.

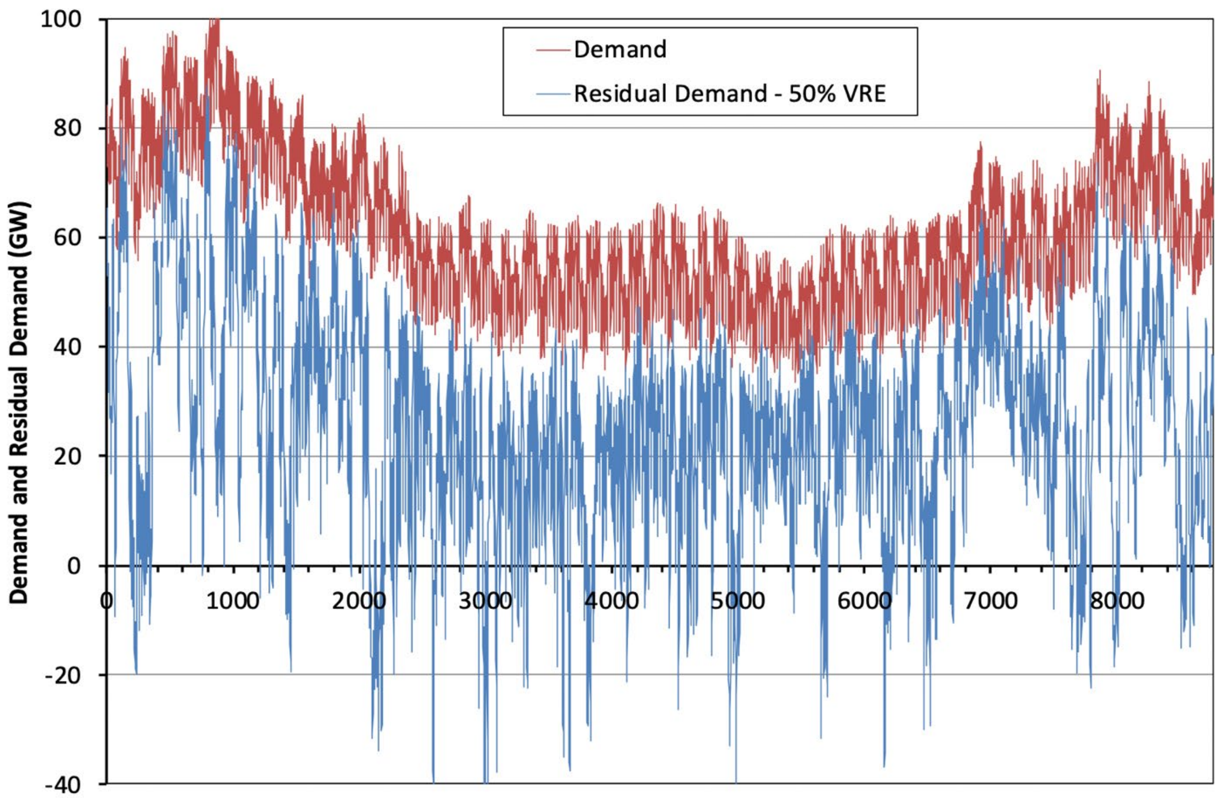

Figure 37. Electricity demand and residual demand at 50% VRE shares

Source: IAEA, adapted from "The Costs of Decarbonization" (NEA 2019).

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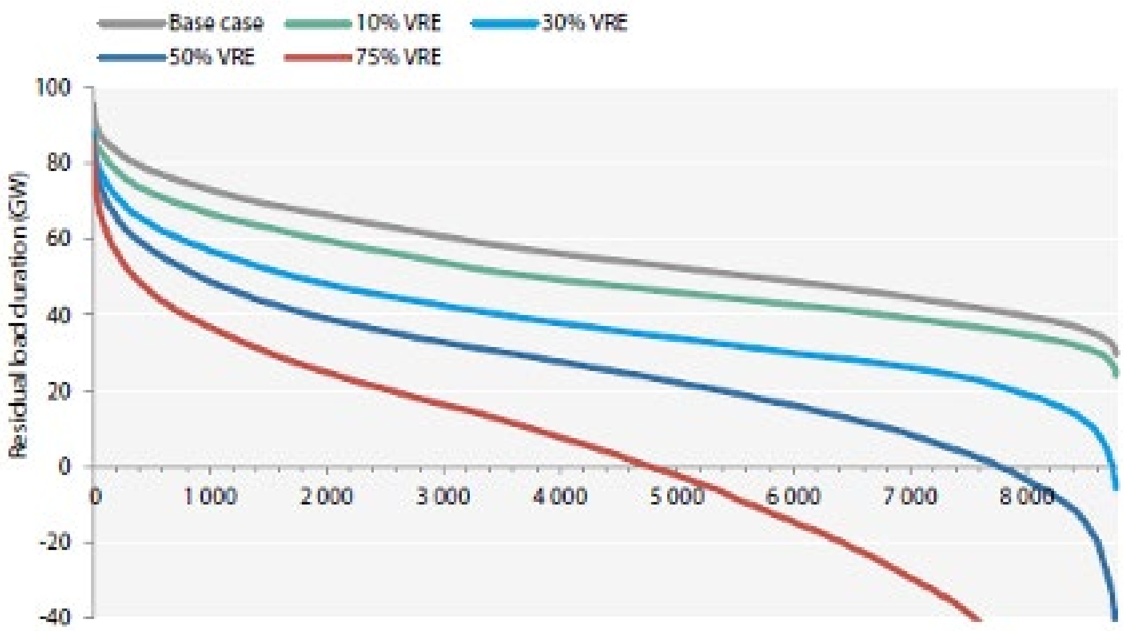

Figure 38. Residual load duration curves at different VRE shares, illustrative cases

Source: IAEA, adapted from "The Costs of Decarbonization" (NEA 2019)

Besides the VRE share in the system, many other factors and new technologies are likely to transform the power system of the future and thus have an impact on the mode of operation and flexibility required from nuclear power. Some of the most promising developments (e.g., advances in storage technologies, development of interconnections, increased level of demand response, and broader integration with the energy sector) help to flatten the residual demand and provide, directly or indirectly, flexibility and other services to the system. This would ease the integration of VRE in the system and increase the role of technologies associated with base load generation, such as nuclear power.

Policy decisions, in particular policies requiring a lower power system carbon intensity level will also have an impact on the future generation mix as well as on the flexibility requirements from nuclear power. A more stringent carbon constraint will limit the amount and role of fossil-fueled plants into the system. Hence, the role of plants that are currently ensuring a large fraction of the flexibility and services to many systems (i.e., natural gas peaking plants) likely would be reduced. All other things being equal, a more stringent carbon constraint will therefore increase the role of nuclear power in the power system as well as its requirements to provide flexibility and other system services.

This is the reason why many scenarios compliant with the Paris Agreement targets see an increasing role for nuclear power (IPCC 2018). There is the potential that nuclear power will likely be operated more flexibly in the future but with lower load factors than today. The combination of power production with nonelectric storable outputs could help shift the output toward the most valuable product. This would provide flexibility and system services and significantly enhance the economics of nuclear power.

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15.1.1 Technical Aspects of Load-Following for Current Reactors

In the early years of nuclear power, some owners/operators of nuclear units considered the potential need for flexible operation, requesting designs having these capabilities, and performing flexible operation tests. They also carried out a limited amount of load following operation. Nevertheless, since that time, the majority of nuclear power plants have operated at base load and have optimized their plant and equipment for operation in that mode. However, some Member States, such as France and Germany, either designed or converted the majority of their nuclear power plants for flexible operation. Plants in those countries operate flexibly (see Chapter 4 for additional information on French flexible operation), and many reactor-years of experience and knowledge of flexible operation have been collected. Furthermore, a few nuclear power plants in other countries have been performing, seasonal, or occasional power maneuvers (IAEA 2018a).

The technical requirements that are requested by the grid system operators are input to assess whether the existing design/facility is capable of meeting those, or what changes to the design/facility need to be implemented. At this stage, several iterations occur between the grid system operator and the plant owner/operator and designer, as well as the grid and nuclear regulators, to agree on what is requested and what can be provided[14] in order to understand the technical aspects of flexible operation for a given plant. Comprehensive understanding and evaluation of a nuclear power plant's design and licensing basis, at that stage, are necessary to: reach an informed decision on the need for and extent of flexible operation; confirm the capacity and capability of the design and configuration for flexible operation; plan and implement design features or modifications to achieve the capabilities needed; and perform flexible operation in a plant safely, reliably, and efficiently.

The impact and extent of technical aspects to consider for load following shown in Table 11 will depend on the magnitude and frequency of power changes magnitudes, power change rates, length and level of extended low power operation, minimum reactor and electrical output power, etc. Even with the same grid requirements, the impacts and technical aspects on the plant will differ depending on the plant location, design, configuration, size, age (including the vintage of technology), fuel type, operations and maintenance practices, effectiveness and extent of existing programs, and so on. (Persson et al. 2012). The identified impacts need to be addressed by a series of technical and administrative controls and solutions for implementation and performance of flexible operation. Based on the experience gained from French and German nuclear power plants, as well as those impacts that can be anticipated on the basis of the latest knowledge and technical fundamentals, there are common technical impacts/issues/solutions (IAEA 2018a).

[14] Some comprehensive plant specifications and procedures have been developed by organizations comprising designers, developers, vendors, and electrical and nuclear industry associations that include the guidance for performance requirements for load following and frequency control, such as the European Utilities Requirement Document and LWR Utility Requirements Document, which may cover most of the technical requirements that are requested by the grid system operators by their local, national or regional grid codes (e.g., European Network Code on Requirements for Generators).

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Table 11. Basic Considerations of Flexibility in Response to Grid Occurrences

Event	Response	Associated Methods or Parameters
Predicted daily demand variation	Load following	Low power period Power change rate Number of occurrences per given time (seasonal, monthly, weekly) Duration at low power for longer period planned demand (extended low power operation) Minimum power for secondary system efficiency
Real time small demand variation	Frequency control	Power change equivalent of frequency disturbance (amplitude, ramp rate, required control type, e.g., local/remote, manual/automatic)
Grid disturbances, large and infrequent power variations	Spinning reserves	Ramp (amplitude, rate, initial power level) Step (amplitude, initial power level) Minimum stable power level, house load capability Instantaneous (a few per cent rated thermal power change, return to full power notice)

For example, any increase in thermal and mechanical cycling as a result of flexible operation could adversely affect evaluation for components with respect to fatigue, wear, erosion/corrosion, ageing, and so on. For systems important to safety, the deviations from the existing component design assumptions and the failure modes and effects that demonstrated insufficient system and design capacity to perform the safety functions throughout the intended lifetime in all operational modes must be reviewed and addressed. Similarly, for systems not important to safety, evaluations must be conducted to ensure that the system changes due to flexible operation preclude the possibility of affecting safety system performance, as well as efficiency and availability. In particular, the operating conditions of secondary system components will change, thus affecting their design assumptions. Even when the extent of cycling is bounded by conservative lifetime assumptions, they must be confirmed, and monitoring must be conducted to ensure that they will remain bounded. The effects of flexibility on the performance of design functions, including surveillance, inspection and maintenance programs need to be described.

15.1.2 Impact of Load-Following on Fuel Performance

Nuclear fuel rods are vital to reactor safety. Fuel rods are designed to ensure that structural integrity is maintained during all modes of operation (IAEA 2016). Indeed, operating experience in nuclear power plants indicates that fuel rods can withstand thermal mechanical loads caused by various modes of reactor flexible operation (such as listed in Table 11) without fuel failures, as far as the fuel rods are used within the operational technical specifications. Flexible operation and related power changes can have a direct impact on fuel integrity through pellet-cladding interaction/stress corrosion cracking phenomena, which could lead to fuel failures in certain conditions. That is, for some anticipated operational occurrences that affect the fuel with small pellet-cladding interaction/stress corrosion cracking margins, the number of pellet-cladding interaction/stress corrosion cracking failures cannot be benign, and a significant radiological source-term may be generated. Taking account of such situations, in some Member States, regulatory requirements are specified to demonstrate that no fuel failures could result from pellet-cladding interaction/stress corrosion cracking under operational states including anticipated operational occurrences power transients. An anticipated operational occurrence event following an extended low power operation is of primary concern.

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Traditionally, nuclear power plants have been operated in a base load mode, producing their maximum rated power whenever online, although they are known to be capable of flexible operation. Since fuel management in the reactor has been optimized for the base load mode, margins to pellet-cladding interaction/stress corrosion cracking fuel failure have become reduced in flexible operation. The nuclear fuel community has developed PCI design verification methodologies to quantify margins to the pellet-cladding interaction/stress corrosion cracking failure under flexible operating conditions, including extended low power operation (Paulin 2016). Based on the quantified margins, operators are able to relax constraints conservatively imposed on reactor operation to better accommodate grid requirements. In other words, when operational limits are re-evaluated, the core can ramp within allowable limits to simultaneously provide flexible generation and preserve fuel integrity.

The IAEA organized a technical meeting in 2019 to share information among Member States on the progress made to understand and mitigate pellet-cladding interaction/stress corrosion cracking. The meeting participants agreed to contribute to an IAEA technical report describing the state of the art of knowledge and experiments on fuel behavior during power maneuvering operation. The publication is in progress.

15.1.3 Economic Study of Flexible Operation

From an economic perspective, operating nuclear power plants at base load is generally considered to be most advantageous. Nuclear units have high upfront capital costs and relatively low fuel and operational costs compared with fossil fuel energy generating units. In competitive markets with individual nuclear plants acting as price takers, revenues from electricity generation are maximized at full load operation. Therefore, operating nuclear power plants in load following mode will certainly affect the economics of plant operation. The plant owner/operator will identify the origins of the costs and the possibility to benefit from providing flexible operation as a value to the grid system operator and the nation's energy policy, at large. Therefore, in economic terms, why and how non-base load operation may add value to the power system, together with the associated costs, need to be evaluated.

The economic analysis calls for a comparison of impacts resulting from flexible operation with those from a base load operation mode. The costs and benefits associated with flexible operation have to be considered in a comprehensive and integrated manner because they may be mutually exclusive at different scales, as well as mutually dependent in specific interfaces. Stakeholders at each scale will be affected differently in different situations. On the one hand, a nuclear operator will have impacts in terms of higher initial installation costs or operations and maintenance costs for flexibility. On the other hand, for a grid system operator, the added flexibility may allow for increased renewable energy resources to be added, and grid reliability and stability are provided or improved; however, the same plant owner/operator might benefit from market structures that pay the plant for the added flexibility. Additionally, governments would be primarily interested in the impacts on the overall economy. Therefore, four distinct levels are considered for which a systematic impact assessment (cost–benefit analysis) can take place (see Figure 39).

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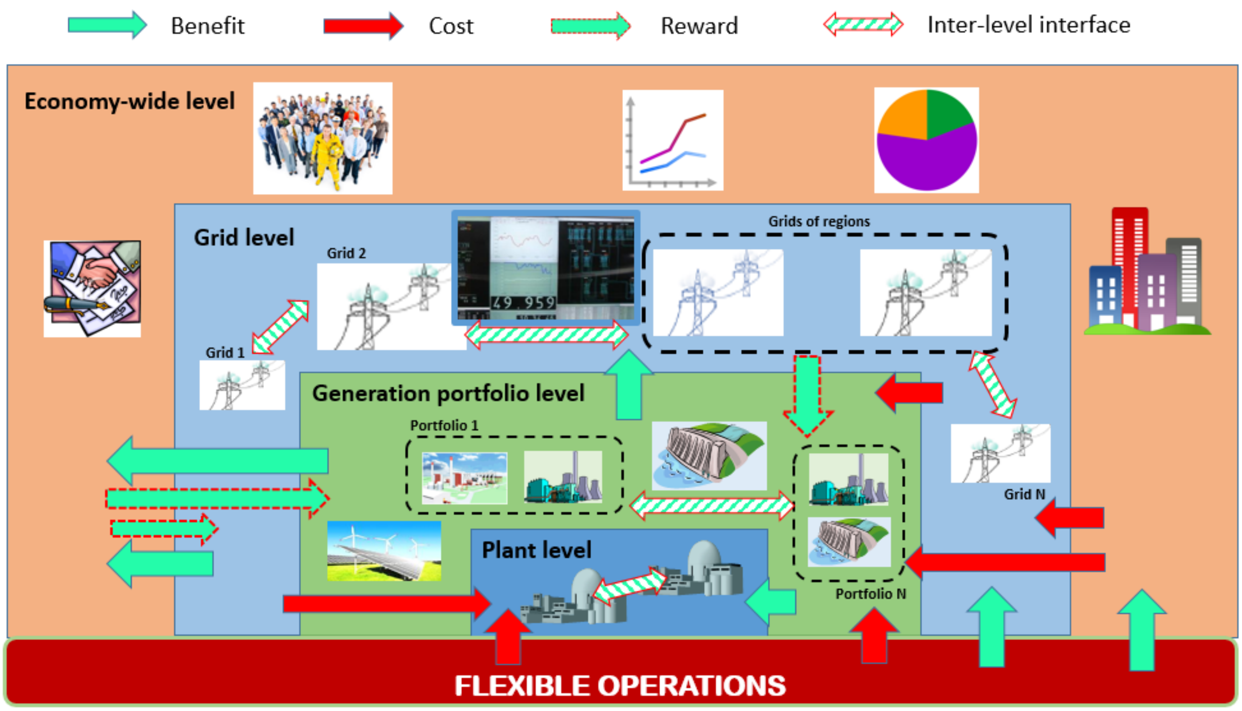

Figure 39. Economic interfaces of flexible operations: impact, value, incentives, regulations at all levels

Source: (IAEA 2018a)

The IAEA has developed a model-based study on economic aspects of nuclear power plant operations (including flexible nuclear) in future power markets with increasing deployment of renewable energy up to 2050, described in (IAEA 2018a). The European Union has been selected for the case study. The latter represents an important case for analysis of flexible operation, given that current and future renewable energy penetration rates, overall energy mix portfolios, grid interconnectivity levels, load profiles and size of the power market vary substantially across the European Union Member States. The analysis was conducted at the level of individual Member States and built upon an application of a dispatching model and an economic model.

The highest requirements for flexible nuclear energy generation in 2050 were identified in regions with high shares of nuclear and renewable energy capacities, as well as with low and medium interconnections. It shall be noted that the same transient budget of upward and downward power generation variation was applied to all flexible nuclear reactors. However, depending on the system flexibility needs, the cycling type varied significantly across the regions. The nuclear fleet in some parts of the European Union is requested in 2050 to provide deep short cycles, while others would perform light frequent cycles to match the residual load. In still other countries, the budget is well balanced across all cycle types: the simulated number of cycles does not exceed the licensed design. Given that the modeling framework did not determine the optimal level of provision of flexibility services for plants, moments of excessive cycling of flexible nuclear power could be observed, if no constraints are put in place (Table 12). It can be concluded that investors and plant operators need to anticipate the load following pattern and its potential effect on life cycle costs.

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Table 12. Maximum Transient Budgets and Requested Flexibility (European Union Average) for 2050 in the IAEA Study

Load cycle depth (% rated thermal power/rated electrical output)	10	20	40	60
Annual budget of load cycles	1,667	1,667	250	200
Simulated number of load cycles	57	63	86	259

Source: IAEA (IAEA 2018a).

Further conclusions of the study could be summarized as the following:

- Although the integration of renewable energy generation may represent the central case for flexible operation of plants in many grid systems, it is not the only driver for flexible operation of nuclear generating units. A lower degree of interconnection among grid components and inflexible energy generation mix provide additional pressure for provision of flexibility services.
- Even with flexible operation within a given set of assumptions, flexibility needs may not be resolved in some regions by 2050.
- Flexible operation is likely to decrease the load factor and to generate less payment for energy delivered when operating at reduced power.
- In the absence of specific market arrangements for flexibility services, it is likely that revenues of plant owners/operators will decrease in comparison to the base load mode, driven mainly by the decrease in load factors of flexibly operated plants.

15.1.4 Cost-Related Implications of Flexible Operation

The deterioration of a plant's profitability is considered to be one of the major economic risks associated with flexible operation. One of the channels through which the profitability of a plant can be affected is linked to the potentially higher plant costs. Besides the loss of revenue due to lower load factors (opportunity cost), the following categories of real costs are likely to be affected when flexible operation, especially if load following, is introduced (for more information, see (IAEA 2018a)):

- Additional capital costs may be incurred by modifying a design to be compatible with flexible requirements, depending on the requirements requested by the grid system operator from a nuclear power plant. For example, to become eligible for operation in a certain degree of flexible modes additional investments may be needed in instrumentation and control systems, in-core monitoring, control rod drive mechanism, and advanced control systems to provide improved monitoring of physical wear, particularly in secondary system components.
- Flexible operation may increase operation and maintenance costs. Additional maintenance and replacement of components may be needed as a result of flexible operations causing an increase in maintenance activities and resources. Wear on components due to excessive use, vibrations, and changes in temperature, can occur in particular in the secondary system

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components. Load following may also induce more frequent maintenance and reduce the availability of power plants in terms of increased outage frequency and/or duration.

- Fuel costs are likely to be affected by the use of fuel in a nonoptimal manner if fuel management in the reactor has been optimized for base load operation. Planned power maneuvering (daily load following, end of cycle coast down to manage timing of refuelling outages, and so on) needs be built into core reload depletion and safety analysis. However, unplanned power maneuvering may alter power distribution and burnup profiles, change core physics parameters, impact fuel utilization efficiency, and necessitate additional analyses, adding costs.

- Some additional staff costs may also be incurred, particularly when some of the operator actions are manual. More importantly, initial and continuing training of personnel for additional or revised monitoring, surveillance and maintenance, for more frequent or brisk plant system interventions (e.g., chemistry control) need to be considered.

15.1.5 Nuclear Power in Current and Future Ancillary Markets

The increased deployment of VRE creates a need for ancillary services to address greater fluctuation in power grids, more network congestion, and to ensure a timely restoration of the grid operation after a blackout. Comparison across Member States having a deregulated power industry highlights, however, a large heterogeneity in terms of current regulatory arrangements, market rules, compensation structures, timescales, and so on. Given that product specifications vary substantially across regions as well, the first standardization/harmonization efforts should first be initiated, for example, in Europe.

Against this background, the question arises to what extent new and evolving ancillary services markets might incentivize nuclear power plants to provide flexibility services. In the presence of decreasing and more volatile wholesale electricity prices, the participation in ancillary markets can, in principle, offer an additional revenue stream for nuclear power plants. But apart from some limited evidence (for example in Germany), little is known about the revenue-related implications of nuclear plants participating in current market-driven and/or required load-follow regimes. The issue of economic opportunities for nuclear power in ancillary services markets will likely become even more pressing in a future electricity system with higher amounts of VRE. The economic opportunities which ancillary services represent will be linked to the way they are procured. Today, they are typically procured in three major ways: via a mandatory response which may or not be compensated, via a long-term bilateral contract and via a market-based procurement mechanism. Policymakers might look at mechanisms to incentivize plant owners to operate in a flexible manner when there are benefits at the grid and economy wide levels.

15.2 Advanced Nuclear Energy Systems and Nonelectric Applications

15.2.1 Flexibility of Advanced Reactors: SMRs and Gen-IV Reactors

The technology development of SMRs for immediate and near-term deployment is progressing globally. At the International Conference on Climate Change and the Role of Nuclear Power, organized by the IAEA in October 2019, the participating Member States expressed that, with a typical output of up to 300 MWeI, SMRs could be the most effective source of CO_2-free electricity to supersede ageing fossil fuel powered plants. The driving forces in the development of such

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reactors are: meeting the need for flexible power generation for a wider range of users and applications; replacing the ageing fossil-fuel fired power plants; enhancing safety performance through inherent and passive safety features; offering lower upfront capital cost affordability; suitability for cogeneration and nonelectric applications; providing options for remote regions with less-developed physical infrastructures; and offering possibilities for synergetic hybrid energy systems that combine nuclear and alternative energy sources, including renewables (IAEA et al. 2018; IAEA 2018b). From this viewpoint, considering increasing shares of intermittent renewable energy on all continents, SMRs are considered a very promising option to provide both base load and flexible operations in synergy with renewables to ensure security of supply with carbon-free energy systems.

Integrating SMRs and renewable energy into a single energy system, coupled through smart grids, enables SMRs to run at high capacity while simultaneously addressing the need for flexibility of generation rates and producing energy services, ancillary services, and low-carbon co-products. These can include electricity, hydrogen, synthetic fuels, hot process gases or steam for merchant or captive use, and transportation fuels (IAEA 2018c). When coupled with variable energy sources such as wind, solar, wave, and tidal energy, SMRs can mitigate fluctuations on a daily and seasonal basis. This would be accomplished by ramping to offset the variation and shifting power over time (i.e., demand-follow). The remaining power variation from the system could be negotiated with the grid regulator.

Figure 40 compares the performance of flexible and modular SMRs based on an equivalent power output. For the modular SMRs, three topologies are considered using 1, 4, and 7 modules, each using 100-MWe modules to produce a total output of 100 MWe, 400 MWe, and 700 MWe. In the flexible case (nonmodular), the equivalent power capacities were used (i.e.,100 MWe, 400 MWe and 700 MWe). The flexibility ranges from 60% to 100% of their rated power. During periods that the wind prevails, the modular SMRs are more efficient than the flexible, single unit reactors in the smoothing of the wind power variability. This results from the modular reactors redirecting their output to other heat applications (i.e., reduce their electrical power output to zero), which was not a permitted operational mode for the single-unit reactors in the study. The flexible reactors must produce as a minimum 60% power, so they tend to overshoot during the periods with wind. This can be clearly seen, for example, in the case of 700 MW, where the virtual power plant output power overreaches 1,200 MW in many cases. The overcapacity condition could also be mitigated by curtailing the wind power; however, this investigation was focused on the potential benefits from SMRs alone in reducing the variability. During gaps in the wind, both the modular and nonmodular SMR types are equally capable of producing full output to fill in the energy gaps.

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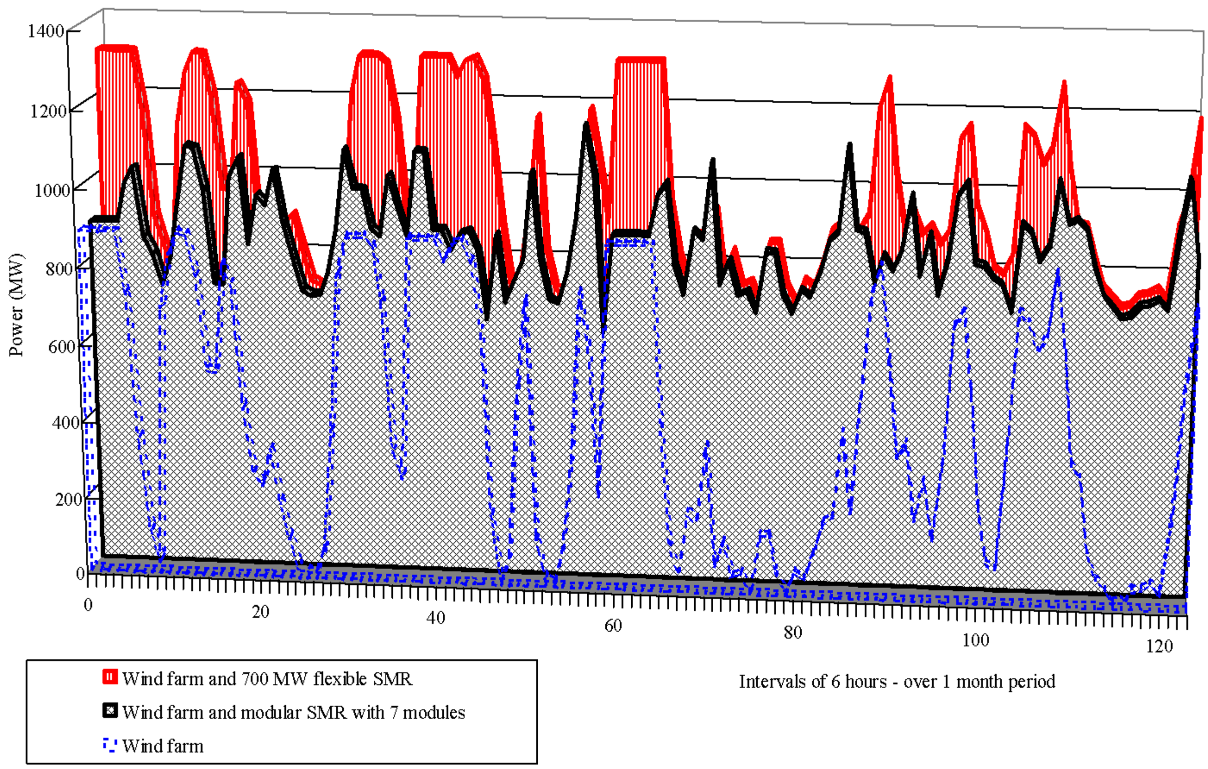

Figure 40. Reduction of electrical variability from the virtual power plant compared to a wind-only system

Source: IAEA.

One of the most promising Gen-IV concepts for flexible operation is expected to be the MSR. Some MSRs are designed to provide significant operational flexibility by relying mainly on their liquid fuel (IAEA 2020). The negative reactivity feedback coefficient characterizing many MSR concepts provides an intrinsic stability of the core. Moreover, this negative feedback coefficient acts very rapidly when the heat is produced directly in the coolant (i.e., when the fuel salt itself is used as coolant). Some MSRs are thus particularly well-adapted to load following of the grid due to their ability to rapidly adjust the power generated to the power extracted, with the salt temperature variations remaining very small. Indeed, as soon as the salt temperature and, consequently, the fuel temperature varies because the power extracted has changed, the quasi-instantaneous variation of the salt density modifies the power generated. Thus, the temperature excursion variation of the salt and, as a result, of the reactor structures, is limited. This property is a valuable asset for a grid whose energy mix gives a larger share to intermittent electricity production sources than a conventional grid. In this way, these MSRs are particularly suitable to coupling with variable renewables. Moreover, the MSR adjustment could be achieved without requiring a control rod system. Additionally, MSRs have the possibility to operate at high temperature (> 600° C), which can more efficiently support nonelectrical applications as discussed next.

15.2.2 Product Flexibility: Nonelectric Applications of Nuclear Energy

Nuclear energy can be used for various industrial applications, such as seawater desalination, hydrogen production, district heating or cooling, the extraction of tertiary oil resources, and

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process heat applications such as cogeneration, coal to liquids conversion, and assistance in the synthesis of chemical feedstock. Production of alternative products offers opportunity to decarbonize not only the electrical system but the whole energy supply. In particular, a large demand for nuclear energy for industrial applications is expected to grow rapidly on account of steadily increasing energy consumption, the finite availability of fossil fuels and increased sensitivity to environmental and climate change impacts of fossil fuel combustion (IAEA 2017; 2019). In 2018, a total of 74 operational nuclear power reactors (15 in Asia and 59 in Europe) were used worldwide to generate 2,122.92 GWh of electrical equivalent heat to support nonelectrical applications of nuclear energy. Of these reactors, 11 supported desalination, 58 supported district heating, and 33 supported industrial process heat applications (IAEA 2019).

Interest in nonelectric applications of nuclear energy continues to grow worldwide. The use of nuclear energy to serve these sectors provides a sustainable route to ensure energy security and combat climate change. The recovery and use of waste heat from nuclear power plants for nonelectric applications can lead to an overall increase in the plant's thermal efficiency and can reduce the environmental impact of this heat when discharged into rivers or other water bodies. Cogeneration using recovered waste heat can offset a significant part of power generation costs (IAEA 2019). For example, the waste heat from high temperature gas-cooled reactors could be used in seawater desalination, resulting in cost credits against the price of the produced water from desalination plants driven by gas or oil-fired power plants. Indeed, nuclear power plants can also provide adequate, cost-effective process heat or steam. This can be used for several other applications, including district heating and cooling.

The use of nuclear energy for hydrogen production can enable the flexible fleet of nuclear reactors to play a main role in the future hydrogen economy and climate change mitigation (IAEA 2018d). Currently operating nuclear power plants can produce hydrogen through advanced low temperature water electrolysis. The economics of this process could be improved by using electricity generated off-peak. Several other hydrogen production technologies have been advancing in recent years, including high temperature electrolysis and thermochemical or electro-thermo-chemical hydrogen production cycles. These technologies can be integrated into high-temperature nuclear reactors expected to be deployed in this decade.

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16 International Energy Agency: Exploring the New Frontiers of Flexibility

Prepared by Brent Wanner and Claudia Pavarini, IEA.

Renewables, particularly wind and solar PV, are expected to make large gains in their share of electricity generation between now and 2040. In the Stated Policies Scenario of the 2019 World Energy Outlook (IEA 2019c), which reflects the impacts of implemented and announced government policies and evolution of the costs of energy technologies, electricity generation from renewables increases rapidly, surpassing coal by 2026. Wind and solar PV together provide over half of the growth in electricity supply, raising their share from 7% in 2018 to 24% in 2040. In the more environmentally ambitious Sustainable Development Scenario, which is consistent with limiting the temperature rise by 2100 to 1.8° C with a 66% probability, the gains by wind and solar PV are even more striking: rising to 40% of the global electricity supply by 2040.

Table 13. Global Electricity Generation by Source and Scenario (Terawatt-hours)

			Stated Policies				Sustainable Development	
	2000	2018	2025	2030	2035	2040	2030	2040
Coal	**5 994**	**10 123**	**10 291**	**10 408**	**10 444**	**10 431**	**5 504**	**2 428**
Of which carbon capture, utilization, and storage	-	-	1	16	43	69	246	994
Gas	**2 750**	**6 122**	**6 984**	**7 529**	**8 165**	**8 899**	**7 043**	**5 584**
Of which carbon capture, utilization, and storage	-	-	-	0	0	1	220	915
Oil	**1 207**	**809**	**724**	**622**	**556**	**490**	**355**	**197**
Nuclear	**2 591**	**2 718**	**2 801**	**3 073**	**3 282**	**3 475**	**3 435**	**4 409**
Renewables	**2 863**	**6 799**	**9 972**	**12 479**	**15 204**	**18 049**	**15 434**	**26 065**
Hydro	2613	4203	4759	5255	5685	6098	5685	6934
Bioenergy	164	636	916	1085	1266	1459	1335	2196
Wind	31	1265	2411	3317	4305	5226	4453	8295
Solar PV	1	592	1730	2562	3551	4705	3513	7208
Geothermal	52	90	125	182	248	316	282	552
CSP	1	12	28	67	124	196	153	805
Marine	1	1	2	10	25	49	14	75
Total	**15 427**	**26 607**	**30 803**	**34 140**	**37 682**	**41 373**	**31 800**	**38 713**

16.1 Power System Flexibility Requirements Will Increase Significantly

The rise in the share of VRE, namely wind and solar PV, in the electricity supply is the main driver for a significant increase in the need for more rapid flexibility—the ability of power systems to respond in a timely way to changes in electricity supply and demand. All regions will need more flexibility relative to the current energy systems and grid. Expressed as peak ramping requirements, flexibility needs will increase much faster than electricity demand. They increase

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fastest in developing economies where almost 90% of the electricity demand growth in this scenario takes place, and particularly in India (Figure 41).

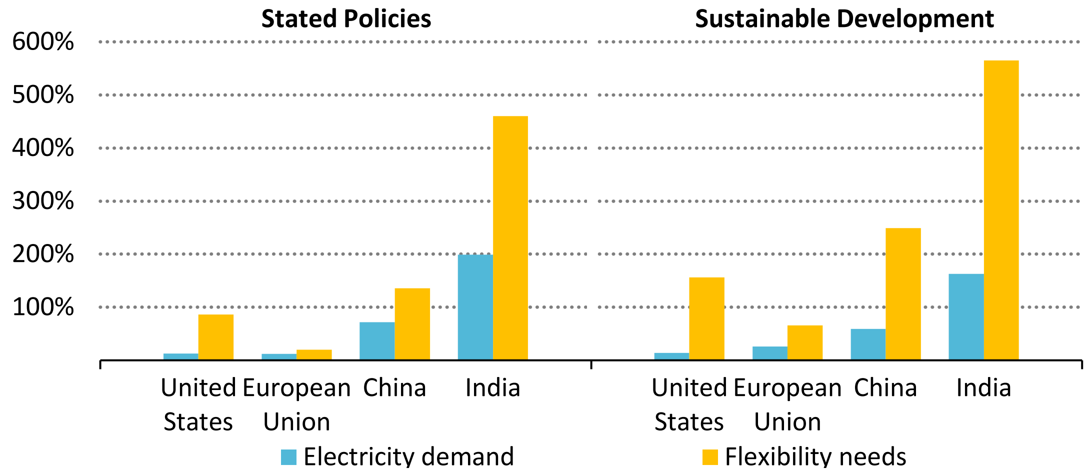

Figure 41. Growth in electricity demand and flexibility needs by selected region and scenario, 2018–2040

Source: IEA.

Key point: Flexibility needs[15] *increase much faster than electricity demand, driven by rising shares of variable renewables, more electric vehicles, and higher demand for cooling.*

The speed of increase in flexibility needs depends mainly on how fast the share of VRE expands. The share of variable renewables in the power generation mix is set to more than triple in China and the United States in the Stated Policies Scenario, as well as at the global level. In India, it increases fivefold, and in Southeast Asia, sevenfold.

Flexibility needs are also affected by the changing demand profile, how well the rising variable renewables supply matches the demand profile of a particular power system, and the power system size. Increasing use of air conditioners is adding to loads during the summer, particularly during peak periods. Electric vehicles potentially may strongly affect peak demand, especially if smart charging is not fully developed.

In the Sustainable Development Scenario, as the power sector moves toward decarbonisation and as electric mobility spreads, flexibility needs increase even more strongly. In this scenario, flexibility requirements in India's power system are six times today's level. In China they more than triple, and in the United States they are 150% higher.

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[15] Flexibility is a multifaceted concept that refers to the ability of power systems to balance demand and supply and can be provided by different services (e.g., frequency regulation, operational reserves, load balancing). The change in the net load from one hour to the next (hourly ramping requirements) provides a useful indicator of flexibility and is used in this analysis. For more information on the drivers of increasing demand for flexibility and flexibility sources, see the *WEO-2018 Special Focus on Electricity* (IEA 2018b).

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16.2 A Diverse Portfolio of Flexibility Options Will Be Required

Flexibility needs in the scenarios are based on analysis in which hourly demand profiles for projected years in different regions are assessed and fluctuations in net load are calculated in our World Energy Model. Based on the capacity mix of the specific region, the capability of the power system assets to change their output by the hour is simulated to identify which technologies can provide the flexibility required.

Conventional sources of flexibility in the form of power plants and interconnections have long maintained the reliability of power systems around the world. Today, thermal power plants (both fossil and nuclear) provide the bulk of the flexibility required by many electricity systems, and this remains the case to 2040 in the Stated Policies Scenario (Figure 42). This is made possible by the retrofitting of existing thermal power plants, which helps increase ramp rates (IEA 2018a), and by the construction of more flexible power plants such as gas turbines. Hydropower also remains an important source of flexibility in many regions. Interconnections between power systems and regions continue to alleviate network congestion by taking advantage of varying supply and demand patterns and pooling available flexibility resources.

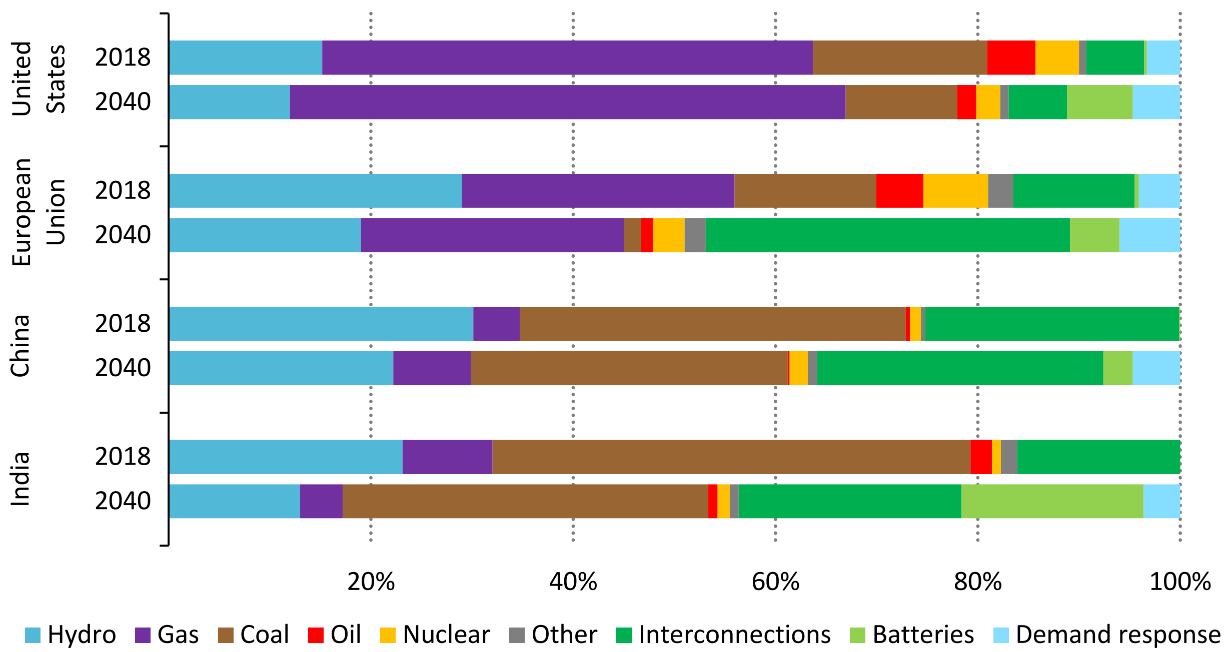

Figure 42. Sources of flexibility by region in the Stated Policies Scenario

Source: IEA.

Key point: Thermal power plants continue to provide the bulk of flexibility needs, along with interconnections, but batteries and demand-side response are rising fast.

Nonetheless, new flexibility sources will be needed. Batteries, demand response, and sector coupling are poised to play pivotal roles in making sure future power systems are secure and reliable. Demand-side response also has a large part to play in meeting rising flexibility needs, for example by shaving peak demand and redistributing electricity to time periods when the load is smaller, and electricity is cheaper. Distributed resources, including variable renewables, storage, and demand response, can also become key flexibility sources with appropriate market designs, as is happening in several countries (IEA 2019a).

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Digitalisation is likely to have a major role in capitalising on the flexibility options. Regional trends to 2040 show there are no one-size-fits-all approach to flexibility. The European Union is expected to source a significant portion of its flexibility needs from the large-scale deployment of interconnections. China is set to rely on more flexible coal-fired power plants and large-scale interconnections. In the United States gas-fired power plants are set to remain a cheap source of power system flexibility through 2040. Most of India's additional flexibility needs are to be met by flexible coal-fired power plants, batteries, and interconnections.

Changes in policy and regulatory frameworks, as well as economic incentives, are essential to ensure timely investment in flexibility assets and to make the most of the flexibility potential of existing power plants. Competitive electricity markets were originally designed with dispatchable power plants in mind. The rise of variable renewables is now challenging the suitability of those market designs to deliver efficient and timely investment. For example, there is a widening gap between electricity supply costs and revenues from energy sales, particularly in the European Union and the United States (IEA 2019a). These markets may require reforms to spur investment and to establish a cost-effective set of flexibility measures.

The transformation of the power generation fleet is even more pronounced in the Sustainable Development Scenario, with variable renewables making up 40% of electricity generation by 2040. The increased reliance on variable renewables often translates into higher hourly ramp rates, which requires more flexibility, including what can be provided by batteries and demand response measures.

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17 Organization for Economic Co-operation and Development Nuclear Energy Agency: The Role of Nuclear Toward the Flexibility Requirements of Future Energy Systems

Prepared by Michel Berthélemy and Sama Bilbao-Y-Leon, Nuclear Energy Agency, a specialized agency within the Organization for Economic Co-operation and Development.

Traditionally, nuclear reactors have been viewed solely as a source of electricity and operated as a base load technology. Considering their high fixed costs and low variable costs, continuously operating a nuclear reactor at the rated power level is usually more efficient, simpler, and more economic (NEA 2011). In other words, it is in the economic interest of a nuclear operator to maximize the energy produced (i.e., the load factor) to recover these high fixed costs. In addition, nuclear power represents a relatively small share in the electricity mix in most countries[16]; thus, the maneuvering requirements for the plants are typically limited to meeting safety requirements (e.g., safe shutdowns in case of load rejection) and, when required by the system operator and permitted by the nuclear regulator, providing frequency regulation.

However, this situation is different in a number of Organization for Economic Co-operation and Development countries (i.e., France, Germany, Belgium, Slovak Republic, and Sweden). In these countries, either the share of nuclear power in the national electricity mix is so important that the utilities have to implement or improve the maneuverability of nuclear units, or flexible operation from nuclear units has been implemented to accommodate the seasonal and inter-annual variability of hydroelectric production or to ease the integration of VRE into the system. More recently, some North American nuclear power plants have been operated in a flexible mode to manage profitability in deregulated energy markets with priority dispatch for VRE.

New nuclear power plants are already designed for flexible operations, and existing plants can be retrofitted to improve their maneuvering capabilities (Patel 2019). Many of the existing LWRs in the above countries have been upgraded to improve their operational performances and maneuvering capabilities. The required retrofits involve the instrumentation and control system, the in-core measurement and monitoring equipment, the adoption of less absorbing control rods (i.e., grey rods, as discussed in Section 4) and the optimization of fuel rods and pellets.

Table 14 summarizes the load-following capabilities of existing nuclear reactors, compared to other dispatchable technologies.

[16] As of 2018, nuclear power represents less than one-third of the electricity generation mix in 20 out of the 30 countries with nuclear reactors in operation.

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Table 14. Load Following Capabilities of Existing Nuclear Reactors Compared to Other Dispatchable Technologies (Source: NEA, 2012)

	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

Yet, while the flexibility capabilities of nuclear power plants are well known from a technical perspective, they raise a number of economic and policy questions considering the expected transformation of energy markets with the advance of variable renewables, and also the development of new flexibility solutions with varying degrees of technological and industrial maturity.

The understanding of the role of nuclear in future energy systems, and the potential of further development and implementation of flexible nuclear production, is a core focus of recent and ongoing work at the NEA. These analyses cover both technical and economic aspects and—as importantly—are conducted both at the plant and at the system levels.

17.1 Flexibility Attributes of Advanced Reactor Systems in Future Energy Markets

The NEA Expert Group on Advanced Reactors and Future Energy Market Needs is finalizing an in-depth analysis of the flexibility attributes that advanced reactors (i.e., Gen III/III+, SMR and Gen-IV) could provide to address future energy market needs, considering at the same time potential new environmental and regulatory constraints (NEA ARFEM Expert Group 2017).

Since the early 1990s, utilities in Europe and the United States have issued requirements for the Gen-III LWRs (EPRI, 2014; EUR, 2012) to ensure that the new reactors are capable of providing flexibility services to the system. These utility requirements are mainly focused on operational flexibility of the nuclear plants.

It is increasingly recognized that advanced reactors (i.e., Gen-III, SMR, and Gen-IV) can also be suitable for applications beyond electricity production. For instance, different fuels and coolants and operation at higher temperatures broaden the scope of nonelectric applications that could be met by nuclear energy. Building on flexibility criteria first put forward by EPRI (2017), it is possible to expand the traditional approach of flexible nuclear production around three attributes: operational flexibility, deployment flexibility, and product flexibility, as were described in Section 13.2.

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These flexibility attributes are summarized in Table 15. A key finding from this analysis is that advanced reactors should be well-suited to extended flexible nuclear production beyond operational aspects and to offer deployment and product flexibility attributes.

Table 15. Beyond Base Load Power: New Flexibility Attributes for Tomorrow's Nuclear Energy Systems (Source: NEA based on EPRI framework)

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	Economics and security of fuel supply
	Island Operation	System resiliency, remote power, microgrid, emergency power applications
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

Regarding product flexibility, a renewed interest for nuclear cogeneration can be observed in a number of NEA and non-NEA member countries. This includes active research and development programs, but also the construction of demonstration units such as the HTR-PM in China. This interest is driven in part by the suitability of nuclear energy to decarbonize hard-to-abate energy sectors, such as industrial heat applications. At the same time, from a system perspective, nonelectric applications could also be viewed as a source of flexibility for integration with an increasing share of VRE resources on the grid while improving the overall economics of nuclear operations.

The type of potential applications depends on the temperature of the thermal energy delivered by the nuclear reactor. Seventy-four nuclear reactors around the world (about 17% of the world's fleet) have provided either district heating, desalination or some other form of process heat for industrial applications. Nuclear cogeneration is therefore a proven low-carbon solution to meeting variable net electricity demand from a technical and industrial perspective. The higher temperature advanced reactors will enable additional industrial applications, including chemical industries, hydrogen production and petroleum refineries. Figure 43 summarizes how different advanced nuclear systems will fit the needs of different industrial heat applications.

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These issues are currently being investigated in a dedicated NEA Expert Group (NEA COGEN Expert Group 2017) on the role and economics of nuclear cogeneration in low carbon energy systems. This group is reviewing lessons learned from past experience with nuclear cogeneration and developing a standardized methodology for assessing the economic case for nuclear cogeneration. An important focus of this ongoing study also relates to the different business models that can foster nuclear cogeneration.

17.2 Insights From NEA System Analysis Studies on the Role and Value of Nuclear Flexible Operation in Future Energy Systems

In addition to plant level analysis of various flexibility attributes, it is necessary to develop a system approach to understand the interplays and tradeoffs between the different parts of the power and energy systems. To this end, the Nuclear Energy Agency has developed over the last few years specific modeling capabilities, in collaboration with MIT, to assess the economic and technical features of alternative low-carbon electricity systems capable of achieving strict carbon emission reductions consistent with the Paris Agreement.

The 2019 Nuclear Energy Agency Cost of Decarbonization study assesses the total costs of six different scenarios of the electric power sector of a representative Organization for Economic Co-operation and Development country, all of which are consistent with a low-carbon constraint of only 50 gCO2 per kWh, but which contain different shares of nuclear energy and renewable energy, in particular wind and PV. These shares vary between 0% and 75% of total electricity consumption. A low VRE investment cost scenario completes this analysis by assuming significant future cost reductions for VRE. Two sensitivity analyses built around different levels of available flexibility resources (availability of interconnection or flexible hydroelectric resources) complete a suite of altogether eight scenarios, allowing a good understanding of the principal drivers for the costs of decarbonization (see Figure 44). In particular, the study highlights the impacts that the variability of wind and solar PV production have on electricity system costs, which appears as costly adjustments to the residual system.

The model builds on state-of-the-art capacity-expansion modeling of the electricity sector with hourly resolution over the course of one year, also taking into account the interconnection of a reference region with its neighboring countries.

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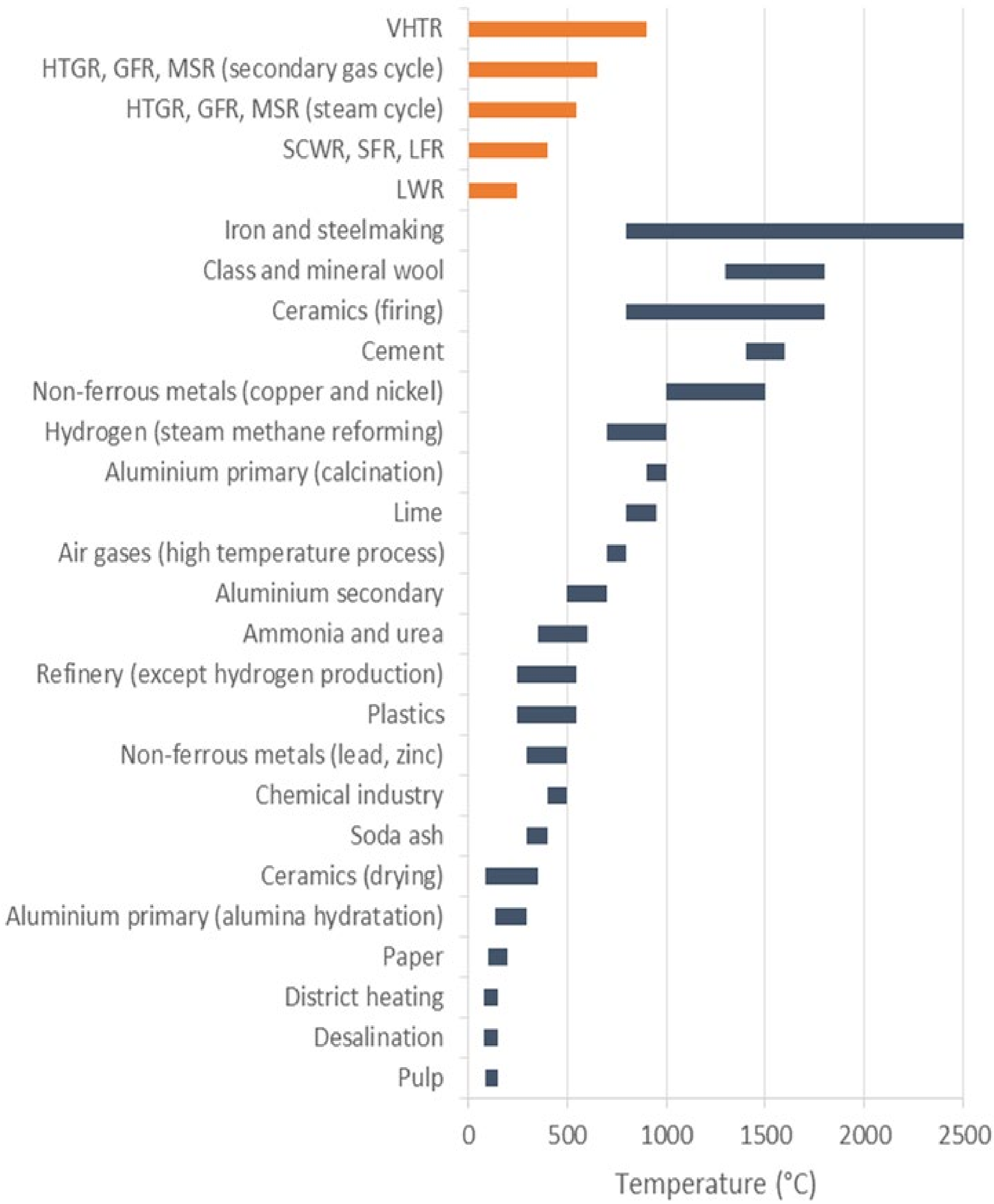

Figure 43. Process temperature ranges by industrial application and nuclear reactor capabilities

Source: NEA COGEN Expert Group.

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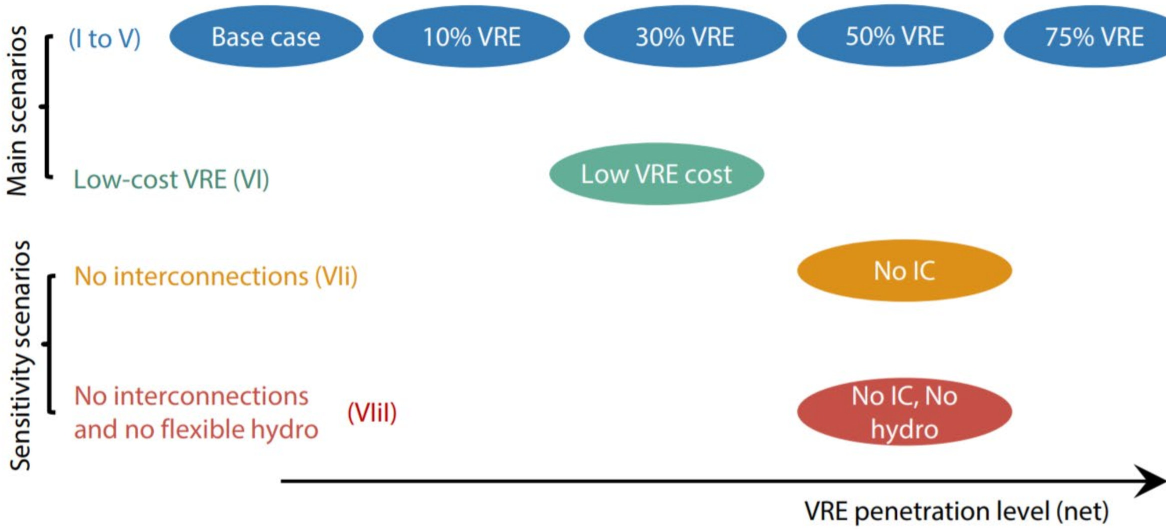

Figure 44. Eight scenarios to study the cost of low-carbon electricity systems with 50 gCO2 per kWh

Source: NEA.

This Nuclear Energy Agency study shows that combining explicit targets for VRE technologies and a stringent limit on carbon emissions has important impacts on the composition of the generation mix and its cost. In particular, the required generation capacity increases significantly with the deployment of VRE resources. Since the load factor and the capacity credit of VRE is significantly lower than that of conventional thermal power plants, a significantly higher capacity is needed to produce the same amount of electricity. While about 98 GW are installed in the base case scenario without VRE, the deployment of VRE up to penetration levels of 10% and 30% increases the total capacity of the system to 118 and 167 GW, respectively. The total installed capacity would more than double to 220 GW if a VRE penetration level of 50% must be reached. More than 325 GW (i.e., more than three times the peak demand) are needed if VRE generate 75% of the total electricity demand. In other words, as the VRE penetration increases vast excess capacity, thus investment, is needed to meet the same demand.

Figure 46 shows the projected hourly generation pattern of the nuclear fleet for four of the five main scenarios considered (there is no nuclear generation under the 75% VRE). This allows a visualization of the increased flexibility requirements from nuclear plants, as well as the reduction in nuclear capacity associated with VRE deployment.

Nuclear capacity progressively decreases with the share of renewables. In the base case scenario with the lowest cost and no VRE, nuclear power is the major source of low-carbon electricity and produces about 75% of the total electricity demand with minimal demand for flexibility. At higher rates of VRE, the demand for nuclear flexibility increases progressively. In the 50% VRE case, nuclear units must ramp up and down by a maximal 30-35% of their installed capacity in 1 hour. Conversely, under the 10% VRE share, most of the flexibility needs of the electricity system can be met by the open and combined cycle gas turbines, meaning that nuclear power plants can be fully utilized as base load. In addition, the base case without a VRE target shows that—under the 50 g/kWh carbon constraint—it can be optimal to operate a mix where nuclear does not only operate as base load but also load-follows according to variation in demand.

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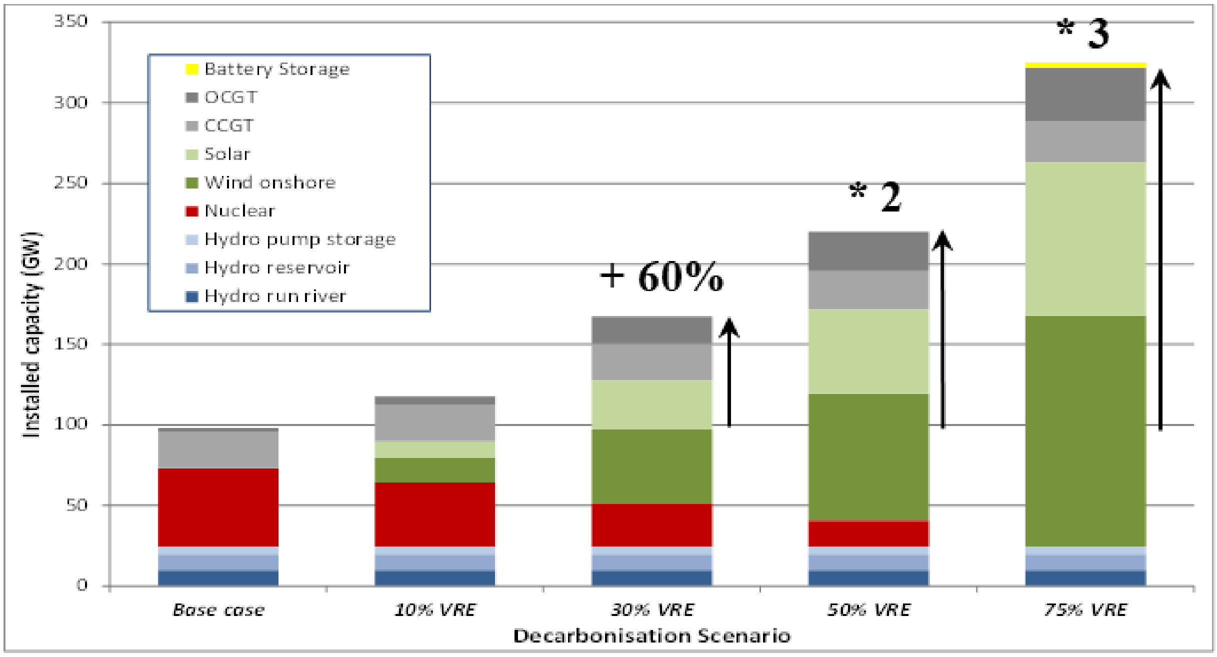

Figure 45. The capacity mix with different shares of VRE

Source: NEA.

In addition, as with all modeling work, a range of assumptions underpins these results. For instance, costs assumptions are based on projected costs for 2020 by the IEA/Nuclear Energy Agency (Wittenstein et al. 2015). A more forward-looking view on the expected costs reductions for VRE and storage technologies would support market-entry of VRE in the base-case scenario, up to about one-third of the overall generation mix.

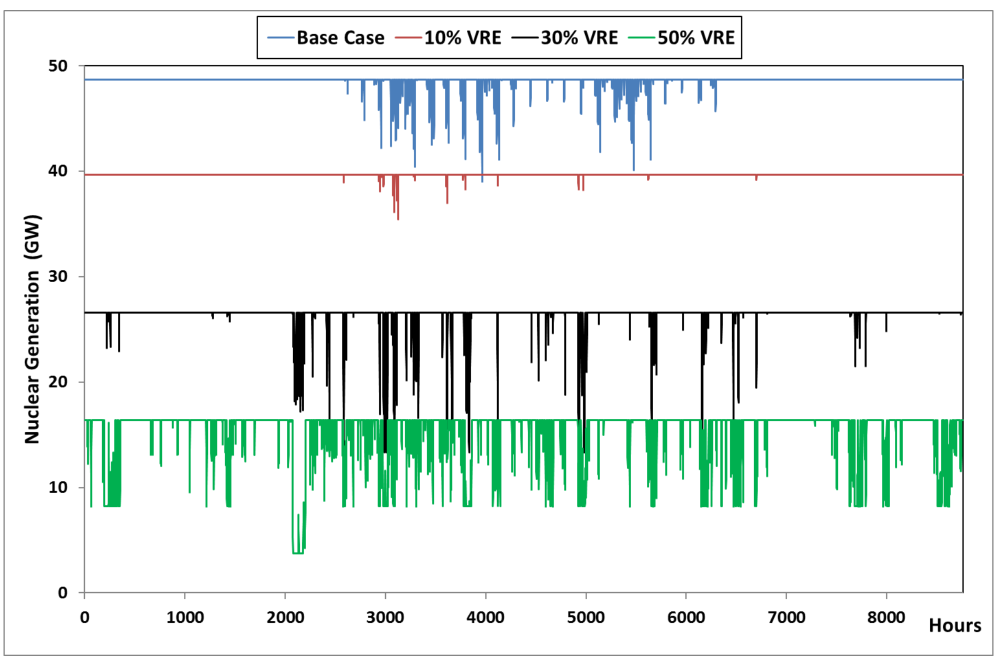

Figure 46. Projected generation pattern from nuclear power plants

Source: NEA.

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18 Conclusions

A central purpose of the NICE Future initiative and its Flexible Nuclear Campaign is to pool international experience on nuclear energy flexibility and share this experience with the broader CEM community. Through collaboration, we can help realize the enormous potential of a wide range of low-emission energy sources. The Campaign also represents a call for ambitious action to overcome barriers to the widespread use of flexible nuclear technologies. Throughout this report, prominent research laboratories, industry, and international organizations have shared their experiences and research results associated with flexible nuclear energy. Several conclusions can be drawn from this body of technical work.

Nuclear energy can work in harmony with renewables to expand the use of clean energy sources. As the percentage of VRE in electricity systems increases, nuclear flexibility is often cited as a way to provide a backstop for weather-related impacts on VRE generation, with wind and solar energy commonly referenced. Indeed, chapters in this report showed that flexible nuclear energy can allow for increased penetration of wind and solar in the electricity system. Nuclear energy can also provide a reliable source of clean energy in regions of the world where other clean energy sources might not be available or are seasonal (as is sometimes the case for hydroelectricity). Additionally, other energy sectors, such as transportation and industry, can reduce emissions through use of hydrogen produced by nuclear energy. As demonstrated in this report, countries that choose to implement nuclear energy can increase the feasibility of other clean energy sources as well.

Nuclear energy is operating flexibly today in some forms, and innovation can lead to more pathways for nuclear flexibility. As demonstrated by operating experience, some nuclear power plants can and do operate flexibly to support variations in daily and seasonal demand. Many established research programs indicate even greater opportunities for nuclear energy to provide both operational and product flexibility to enable more clean energy use. Building on this experience, both current fleet and future advanced reactors have a large role to play in the future of nuclear flexibility.

Integrated energy systems that connect nuclear energy to multiple energy products present novel opportunities for nuclear flexibility and enhanced system value. Nuclear energy has always been a capital-intensive investment compared to many other energy sources. At the same time, nuclear systems provide more value to both the plant owners and society by producing reliable, affordable, low-emissions energy (equivalent to renewables) at very high capacity factors throughout their operational life. Commercial nuclear reactors have primarily been used for electricity production, but there are many proven and innovative applications that could utilize both thermal and electrical energy from nuclear reactors. Nuclear-generated thermal and electrical energy can be used to produce primary or secondary products that are valuable to society. Integrated energy systems seek to couple the production of nonelectric products to the reactor to increase overall operational efficiency and the opportunity for nuclear energy to serve multiple energy demands beyond just electricity. These technologies have the potential to use nuclear energy more fully and efficiently, and thus maximize revenue streams and associated capital investments.

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Nuclear energy can safely operate flexibly based on an established body of international knowledge. To facilitate broader application of flexible nuclear operation, the nuclear community could amplify the body of operational experience that demonstrates that flexible operations are safe based upon research and industry experiences. That experience and additional research on flexible nuclear energy can be translated into national-level licensing frameworks that support nuclear plants to operate flexibly. International organizations and national governments could demonstrate and communicate the safety of flexible nuclear energy to their regulatory authorities through collaboration with countries which already operate nuclear systems in this manner.

While this study fills some technical data gaps, more work needs to be done to incorporate nuclear flexibility into existing nuclear research, development, demonstration programs, and energy planning processes. The contributing organizations have engaged in extensive and world-renowned research on the topics of nuclear safety, efficiency, reliability, sustainability, economics, and proliferation resistance. However, flexibility is becoming an increasingly valuable asset for nuclear generators, and more could be done to ensure flexibility of these systems in meeting a wide range of energy needs and providing benefits to society. Traditional fields of material science, reactor physics, and thermal hydraulics would benefit from incorporating nuclear flexibility concepts into their research. The same is true of energy planners in their modeling, analytical, and planning processes.

Cost-effective energy storage would benefit all generation technologies, especially nuclear energy. There are multiple ways to curtail or reduce the output of all generation sources. Geothermal plants can ramp down, solar PV can be curtailed through electronic control systems, and nuclear energy can reduce its core thermal output. However, for technologies with higher capital costs and low operating costs, like nuclear energy, energy storage allows generation assets to run at full output and use the coupled storage component as the source of flexibility. Utilizing power generation technologies at full capacity lowers the overall levelized cost of energy and increases the efficiency of energy systems. Different timescales for energy services require different storage technologies. Electrochemical batteries are economical on the order of seconds to hours, thermal energy storage is economical on the order of hours to days, and chemical storage (such as hydrogen) can be economical on the order of days to months. Although all energy storage systems have the opportunity to help energy generation technologies provide greater flexibility and efficiency. The NICE Future initiative looks forward to partnering with other CEM work streams on the subject of energy storage, recognizing that energy storage benefits all generating technologies.

No two energy systems, countries, or economies are the same, and analysis for flexible nuclear energy should be tailored to each jurisdiction. The work summarized in this report includes perspectives and experiences from many countries and international organizations. Each energy system will require tailored analysis as it relates to flexible nuclear energy. From technology, economic, and public acceptance perspectives, each country has unique values and variables. Hence, there is no universal methodology that can calculate the value of flexible nuclear energy throughout the world. There are, however, lessons from each analysis that can be transferred or adapted to other energy systems. This report shares some of the analyses, methodologies, and lessons learned from previous work to provide countries with a background on steps they can take to understand the value of flexible nuclear energy in their own economies. Through its collection of authors and contributors, this report provides a broad range of technical

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and economic expertise that other CEM members can use as they consider their own clean energy transitions.

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19 Perspectives for the Future of Flexible Nuclear Energy

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Looking to the future, whether we are government leaders, business leaders, research institutions, technology developers, investors, analysts, policy advisors, climate and energy modelers, or other clean energy stakeholders, we all have a role to play and unique insights to provide given our own national circumstances in driving new clean energy options and innovations.

This chapter provides valued insights from NICE Future initiative participant countries who are either considering or actively pursuing nuclear energy as a part of their future diverse energy mix. While these sections do not provide technical analysis of flexibility, they offer insight as to how flexible nuclear is being considered for their energy futures in the context of evolving energy systems that seek both energy diversification and acceleration of emissions reductions. Additionally, these sections provide information on participant countries' energy systems and clean energy goals that are motivating their consideration of nuclear energy.

A key approach of the CEM is to actively engage the views of industry, who are at the forefront of investing in and implementing advanced technology and innovations. We close with perspectives about the future from global nuclear industry leaders, key partners in developing options for accelerating clean energy transitions.

19.1 Jordan

Prepared by Kamal Araj of the Jordan Atomic Energy Agency.

Jordan, as of 2007, has set its course on energy diversification. The dependence on more than 95% on a single and mostly imported energy has proven catastrophic at instances to the economy. After the Arab Spring and the repeated interruptions of gas supply, renewable energy (primarily PV) power plants were constructed at an accelerated pace. Today, Jordan is one of the regional leaders in the share of renewables as part of total electricity generation. Nuclear energy has been considered as part of its future energy mix since 2007, and it is envisioned that a plant (primarily SMR) will be operational by 2030. Energy source diversification draws the issue of flexibility to the forefront.

Flexible operation of a nuclear power plant on the Jordanian power grid is subject to technical and economic hurdles. In our review of different technologies, we see that most of the nuclear technologies safely operate when ramping power up and down upon demand, within defined technical specifications. Economics of operational flexibility, however, is a different issue to be considered, particularly for a small grid as is the case for Jordan. Nuclear energy is capital-intensive, so it may prove overly expensive if the plant is operated below its nominal power level, particularly in the first years (debt repayment years), rendering it infeasible.

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Table 16. Key Energy Metrics for Jordan

National Clean Energy goal (All numbers in 2018 values)	31% of electricity generation from renewables by 2030
Total Primary Energy Consumption	9.712 Mtoe
Electricity Consumption	17.5 TWh
Total CO2 Emissions	26 million tons
Renewables Generation	2188 GWh
Renewables Energy Percent of Electricity Generation	11%
Nuclear Energy Policy	Deployment of SMR nuclear power plant by 2030

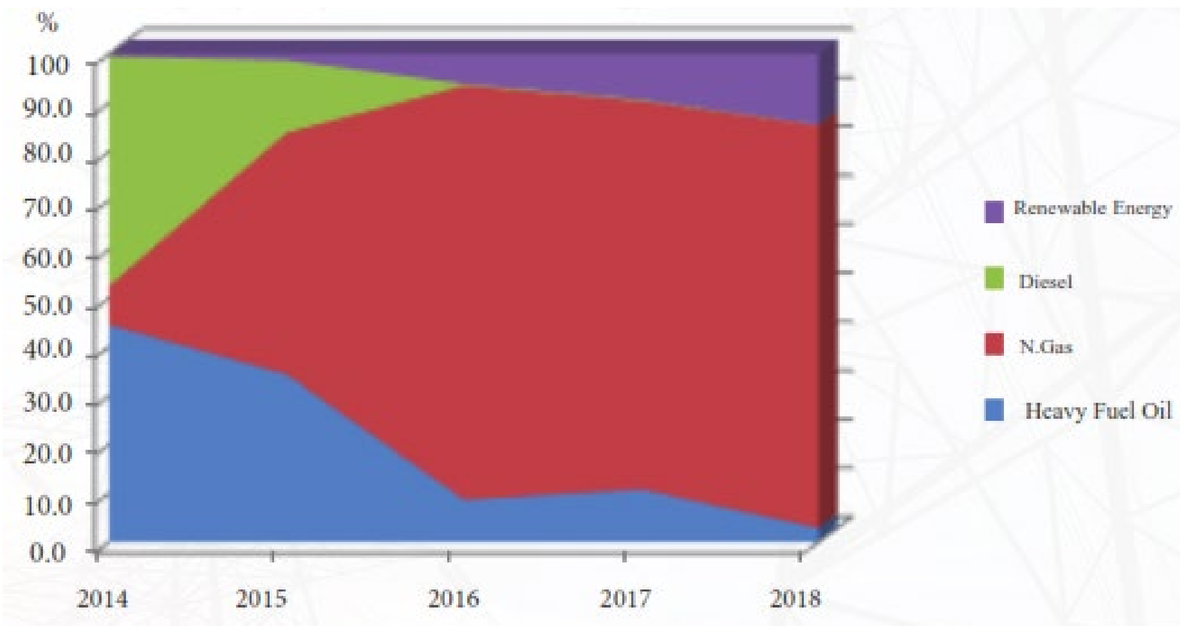

Figure 47. Contribution of primary and renewable energy sources in electricity generation

For Jordan's small grid, emerging SMR options excel over large nuclear power plants. Most SMRs are modular in nature and are included in plants with modular expansion in mind. With this said, the plant can initially operate as a base load generator and, as it becomes economically viable, move into the second phase (debt has been paid off for the first units), these first units can go into load following operation. At this point in time, more SMR modules would have been added and can be presumed to be operating at nominal power levels. SMRs offer the opportunity to meet the objective of achieving true energy diversification, while doing so with an amount of flexibility offered by balancing how demand is met via operation of the deployed units. Gradual SMR plant expansion and flexibility in operation of each unit will offer significant ability to work with other clean energy systems on the grid.

The economic challenges of nuclear energy are not specific to nuclear alone. The introduction of renewable generators into the Jordanian energy mix, coupled with a slowdown in demand, has caused grid imbalances in which conventional power plants had to be operated with low loading

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factors which increases the price of electricity and reduces the efficiency. This periodic overproduction and grid imbalance occurred during times of expedited planning and PV expansion. Lack of proper planning coupled with unforeseen circumstances, will usher in unwanted surprises. Introduction of flexible nuclear technologies, such as an SMR plant that can support both base load and flexible demand, can support Jordan's goals relative to energy diversification.

19.2 Kenya

Prepared by Edwin Chesire, technical advisor to Kenya Nuclear Power and Energy Agency.

Kenya has been conducting long-term planning to consider our clean energy mix for the future. The country currently generates over 70% of its electricity from renewables and looks forward to 100% non-emitting electricity generation This will enable the country to meet economic growth potential and non-emitting energy needs.

Table 17. Key Energy Metrics for Kenya

National Clean Energy goal (All numbers in 2018 values)	100% of electricity generation from non-emitting electricity by 2030
Total Primary Energy Consumption	10.012 Mtoe
Electricity Consumption	11.5 TWh
Total CO2 Emissions	96 million tons
Renewables Generation	10.196 GWh
Renewables Energy Percent of Electricity Generation	73.48%
Nuclear Energy Policy	Deployment of first nuclear power plant by 2036 as NOAK. SMR is also being considered

As of December 2019, the interconnected system in Kenya had a total installed generation capacity of 2,789 MW, comprising 826.2 MW of hydroelectric power, 720.3 MW of thermal, 828.4 MW of geothermal, 335.5 MW of wind, 50.3 MW of solar, and 28 MW from cogeneration. There is also 30.17MW in isolated mini grids bringing the total installed capacity to 2,819 MW. The percentage of the installed capacity is shown in Figure 48.

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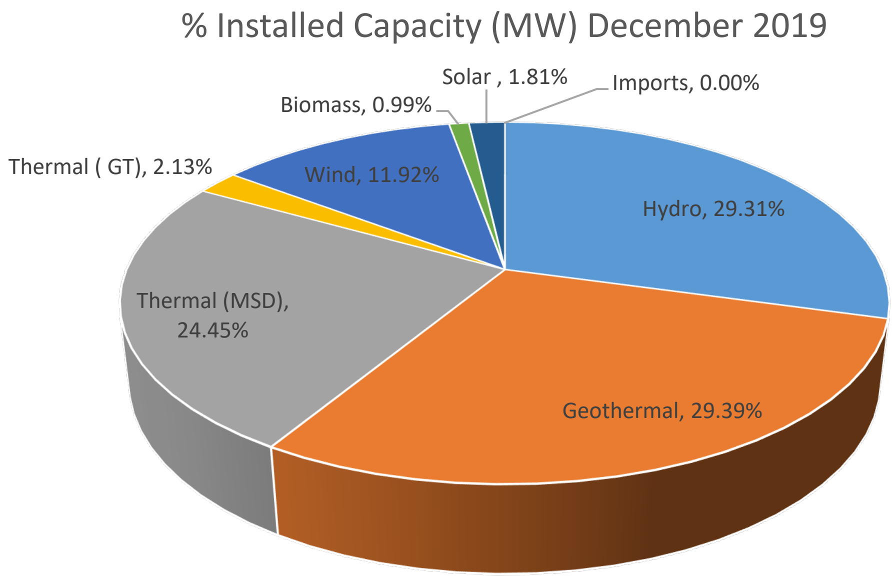

Figure 48. Installed capacity by technology share 2019

Source: Kenya Power annual accounts. Used with permission.

Energy purchased increased to 11,493 GWh in Fiscal Year 2018/19 from 10,702 GWh in the previous financial year. Actual sales increased by 4% from 8,459 GWh in FY 2017/18 to 8,769GWh in Fiscal Year 2018/19, as can be seen in Figure 49.

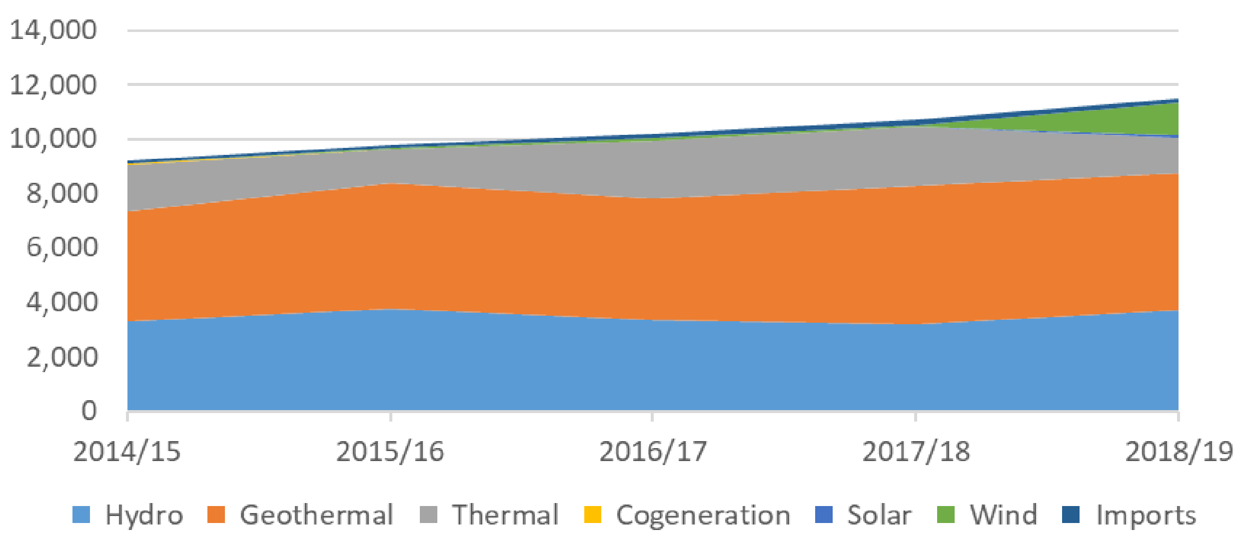

Figure 49. Energy purchased in GWh from 2014 to 2019

Source: Kenya Power annual accounts. Used with permissions.

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Kenya is also considering the potential role of nuclear power in the future energy mix. The country is following the IAEA guidelines laid out in the milestones in the development of a national infrastructure for nuclear power, NG-G-3.1, rev. 1. As Kenya embarks on the nuclear power program, extensive national stakeholder engagements were undertaken in the establishment of a robust regulatory framework, which will regulate the application of nuclear science and technology in the country. Furthermore, Kenya has undertaken various technical studies, including siting, reactor technology assessment, and grid evaluation. In ensuring a competent and skilled workforce, Kenya has endeavored to establish local and international capacity building initiatives.

Following the Enactment of the Energy Act 2019, the Nuclear Power and Energy Agency, which is a parastatal under the Ministry of Energy, is mandated to be the implementing organization for the nuclear energy program. The Nuclear Power and Energy Agency will also promote the development of nuclear electricity generation in Kenya and will carry out research, development, and dissemination activities in the energy and nuclear power sector.

To holistically integrate the various energy sources, The Nuclear Power and Energy Agency and the Ministry of Energy are considering long-term economic and other modeling projections and scenarios. Current analysis shows that Kenya has abundant sources of renewable energy, including geothermal, solar, and wind.

Kenya welcomes this opportunity to share information with this global expert working group to more fully understand opportunities and roles for flexible nuclear systems to work in tandem with renewables, leveraging electric and nonelectric applications, to bring various benefits to society, such as desalination and process heat for industrial processes.

19.3 Nuclear Industry Leaders

Prepared by Maria Korsnick, President and CEO, Nuclear Energy Institute; Agneta Rising, Director General, World Nuclear Association; Tim Stone, Chairman, UK Nuclear Industry Association; John Gorman, President and CEO, Canadian Nuclear Association; Shiro Arai, President, Japan Atomic Industrial Forum.

Humanity faces two urgent, contradictory needs:

The first is more energy. Energy to provide refrigeration and food processing, clean water, heating and cooling, lighting, communications and transportation, for hundreds of millions of people rising out of poverty. The U.S. Energy Information Administration predicts that by 2050 worldwide demand for electricity will rise by nearly 50%. Other estimates are for an even greater increase.

We also need to reduce emissions. Over the same time period, by 2050, the Intergovernmental Panel on Climate Change has said that carbon dioxide emissions from electricity must fall to nearly zero. This will prevent the worst effects of a changing climate: making air more breathable, preventing a rise in global sea levels that could displace more than 150 million people, and maintain levels of rainfall, heat, and cold in the approximate patterns we have relied on as we have built our homes, factories, and farms, and that all the other creatures with which we share the planet are relying on.

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How do we reconcile these needs? We must find ways to reduce emissions of our energy systems. Because we depend on electricity for so many critical uses that affect our health, safety and communications, it also means ensuring system reliability by complementing increasing amounts of carbon-free variable energy resources like wind and solar with carbon-free dispatchable power from nuclear—the only scalable, minimal-carbon power source that can fill this need.

Many of us recognize nuclear's indispensable role in solving this equation. But we need to act now, because the challenges are no longer in the distant future. Hunger, thirst, and disease are not abstract issues for those facing them, and droughts, heat waves, cold spells, and more intense storms are not trends we can ignore. In fact, one-fifth of the new century is already behind us, and the scientific consensus is that we need to take urgent action to meet the mid-century goals to avoid yet worse effects of climate change.

These challenges require a fundamental rethinking of energy. Since the inception of commercial energy systems, they have been organized around a least-cost solution. But as the world has become more complex and the health and prosperity of its 7.6 billion people more interrelated, more considerations have come into play. This means that we need to address not only how we integrate zero-carbon technologies into our system, but also how the market compensates these zero-carbon generators.

We will have to integrate vast amounts of new zero-emitting energy generation. Burning fossil fuels was surely simpler, but clean air and a stable climate require something new.

And part of that something will be increased use of nuclear energy. According to the IEA, that requires retaining much of our existing generation and building new nuclear generators, in a plethora of forms, some familiar, some more innovative.

Human ingenuity can solve our problems, through harnessing the power of the sun, the wind, falling water and another elemental force, the atom. We are going to need all of them.

Shiro Arai
President
Japan Atomic Industrial Forum

John Gorman
President and CEO
Canadian Nuclear Association

Maria Korsnick
President and CEO
Nuclear Energy Institute

Agneta Rising
Director General
World Nuclear Association

Tim Stone
Chairman
UK Nuclear Industry Association

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