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

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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.

1.1 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 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 1). 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 2). The optimal mix will shift from base load to peaking and mid-merit plants.

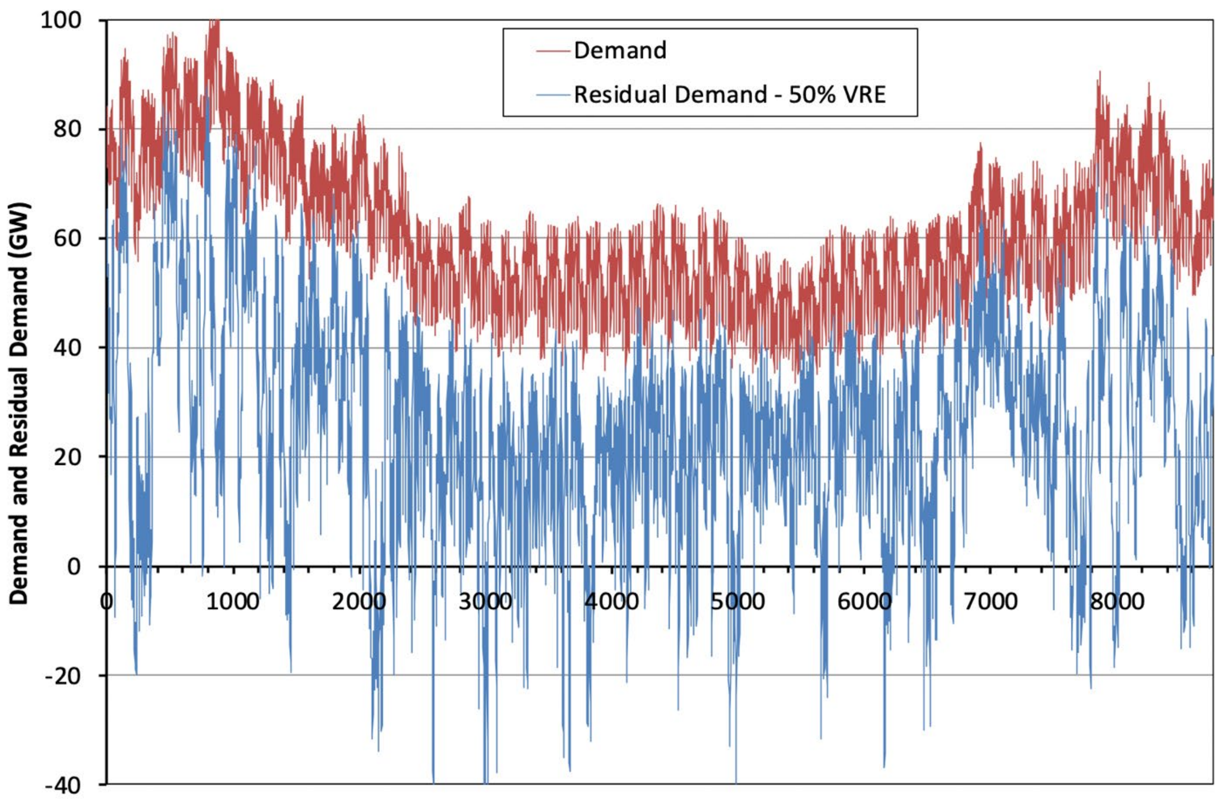

Figure 1. Electricity demand and residual demand at 50% VRE shares

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

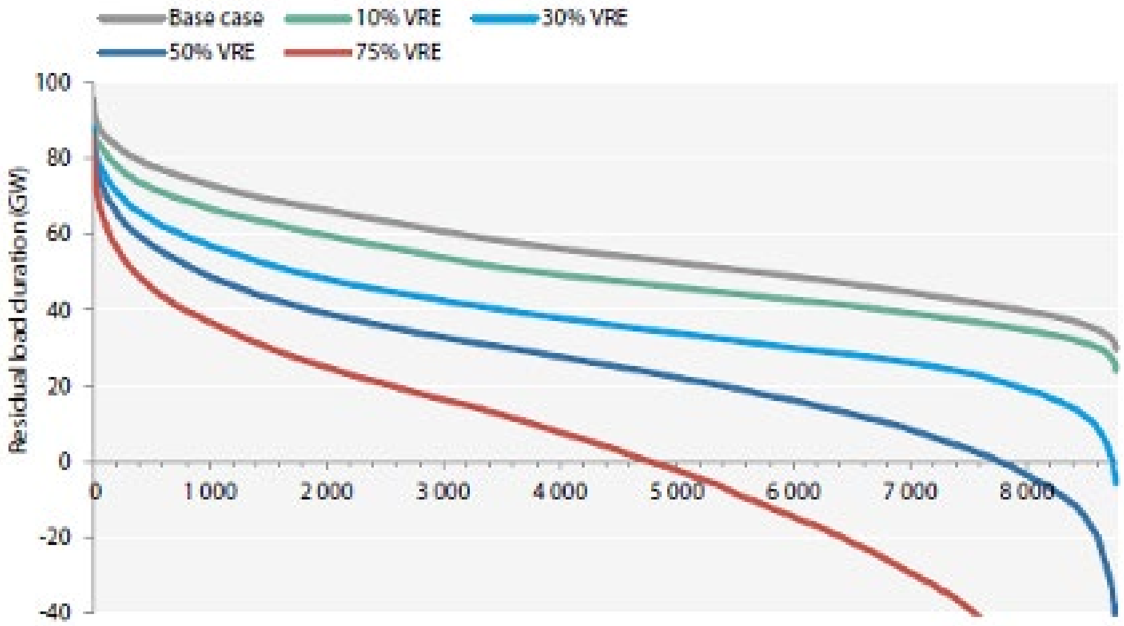

Figure 2. Residual load duration curves at different VRE shares, illustrative cases

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.

1.1.1 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[1] 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 1 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).

[1] 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).

Table 1. 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.

1.1.2 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 1) 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.

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.

1.1.3 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 3).

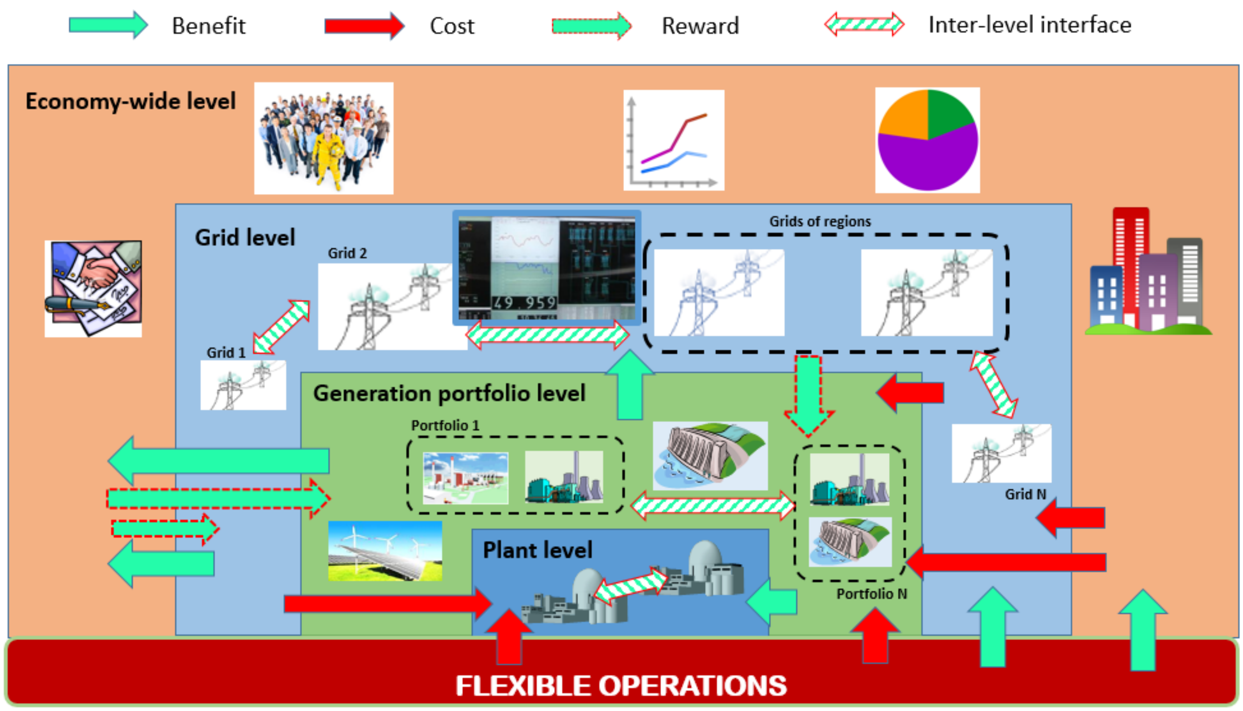

Figure 3. Economic interfaces of flexible operations: impact, value, incentives, regulations at all levels

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 2). It can be concluded that investors and plant operators need to anticipate the load following pattern and its potential effect on life cycle costs.

Table 2. 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.

1.1.4 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 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.

1.1.5 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.

1.2 Advanced Nuclear Energy Systems and Nonelectric Applications

1.2.1 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 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 4 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.

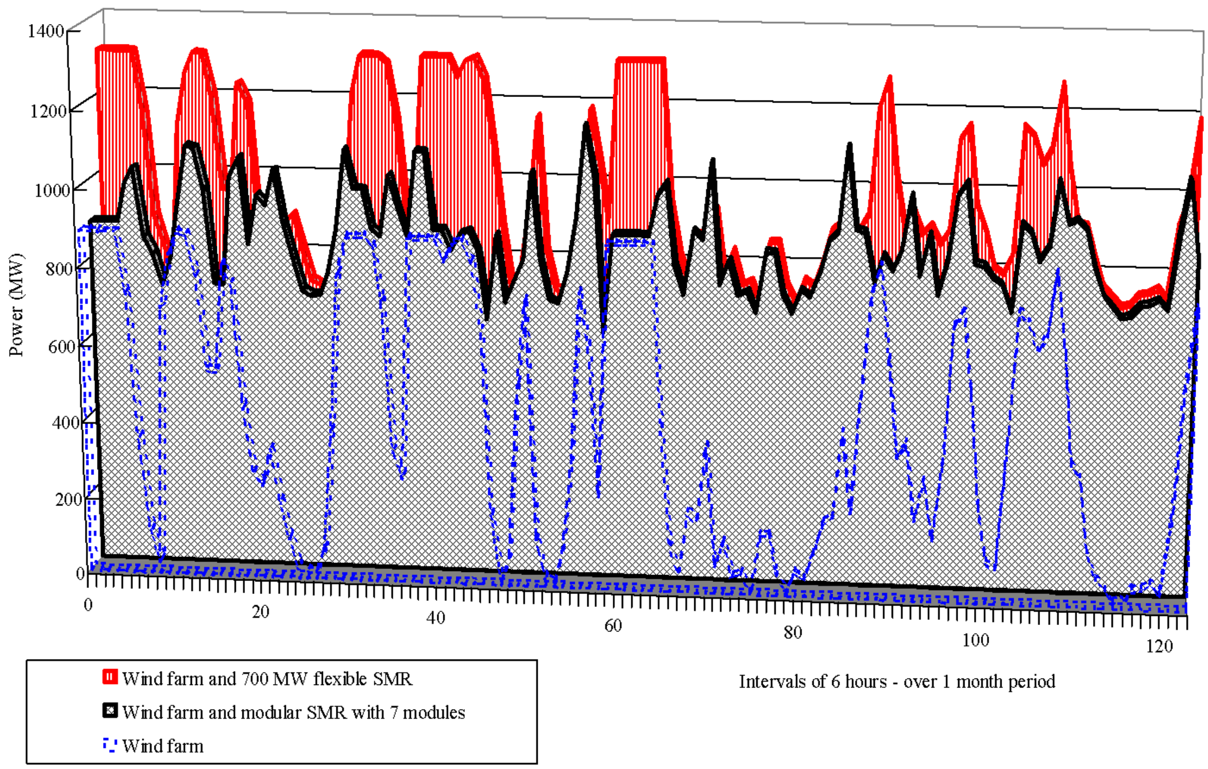

Figure 4. Reduction of electrical variability from the virtual power plant compared to a wind-only system

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.

1.2.2 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 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.

1.3 References

"Climate Change and Nuclear Power." 2020. Vienna: International Atomic Energy Agency.

IAEA. 2016. "Safety of Nuclear Power Plants: Design." No. SSR-2/1 (Rev 1). IAEA Safety Standards Series. Vienna, Austria: International Atomic Energy Agency. https://www.iaea.org/publications/10885/safety-of-nuclear-power-plants-design.

———. 2017. "Industrial Applications of Nuclear Energy." NP-T-4.3. IAEA Nuclear Energy Series. Vienna, Austria: International Atomic Energy Agency. https://www.iaea.org/publications/10979/industrial-applications-of-nuclear-energy.

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

———. 2018b. "Deployment Indicators for Small Modular Reactors: Methodology, Analysis of Key Factors and Case Studies." IAEA TECDOC No. 1854. Vienna, Austria: International Atomic Energy Agency. https://www.iaea.org/publications/13404/deployment-indicators-for-small-modular-reactors.

———. 2018c. "Nuclear–Renewable Hybrid Energy Systems for Decarbonized Energy Production and Cogeneration." IAEA TECDOC No. 1885. Proceedings of a Technical Meeting. Vienna, Austria: International Atomic Energy Agency. https://www.iaea.org/publications/13594/nuclear-renewable-hybrid-energy-systems-for-decarbonized-energy-production-and-cogeneration.

———. 2018d. "Examining the Technoeconomics of Nuclear Hydrogen Production and Benchmark Analysis of the IAEA HEEP Software." IAEA TECDOC No. 1859. Vienna, Austria: International Atomic Energy Agency. https://www.iaea.org/publications/13393/examining-the-technoeconomics-of-nuclear-hydrogen-production-and-benchmark-analysis-of-the-iaea-heep-software.

———. 2019. "Guidance on Nuclear Energy Cogeneration." NP-T-1.17. IAEA Nuclear Energy Series. Vienna, Austria: International Atomic Energy Agency. https://www.iaea.org/publications/13385/guidance-on-nuclear-energy-cogeneration.

IAEA, F. Reitsma, M. H. Subki, and H. Kiuchi. 2018. *Advances in Small Modular Reactor Developments*. 2018 Edition. A Supplement to: IAEA Advanced Reactors Information System (ARIS). Vienna, Austria: International Atomic Energy Agency. https://aris.iaea.org/Publications/SMR-Book_2018.pdf.

"IAEA Overview." 2016. Text. IAEA. June 8, 2016. https://www.iaea.org/about/overview.

International Atomic Energy Agency. 2020. *Status of Molten Salt Reactor Technology, Vienna*.

IPCC. 2018. "Summary for Policymakers." In *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*, edited by V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, et al. https://www.ipcc.ch/sr15/chapter/spm/.

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

Paulin, Philippe. 2016. "Operational Constraints Related to SCC-PCI." In *Pellet-Clad Interaction (PCI) in Water-Cooled Reactors: Workshop Proceedings*. Lucca, Italy. https://www.oecd-nea.org/nsd/docs/2018/csni-r2018-9.pdf.

Persson, Jonas, Karin Andgren, Hans Henriksson, John Loberg, Christian Malm, Lars Pettersson, Johan Sandström, and Timmy Sigrids. 2012. "Additional Costs for Load-Following Nuclear Power Plants: Experiences from Swedish, Finnish, German, and French Nuclear Power Plants." Elforsk. https://energiforskmedia.blob.core.windows.net/media/21094/additional-costs-for-load-following-nuclear-power-plants-elforskrapport-12-71.pdf.