# 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[1]; 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 1 summarizes the load-following capabilities of existing nuclear reactors, compared to other dispatchable technologies.

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[1] 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.

*This document encompasses one section of a larger report, titled Flexible Nuclear Energy for Clean Energy Systems. The full report can be found at https://www.nrel.gov/docs/fy20osti/77088.pdf. The author(s) of each section is/are solely responsible for its content; the publication of these perspectives shall not constitute or be deemed to constitute any representation of the views or policies of any Governments, research institutions, or organizations within or outside the NICE Future initiative.*

**Table 1. 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.

## 1.1 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.

These flexibility attributes are summarized in Table 2. 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 2. 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 1 summarizes how different advanced nuclear systems will fit the needs of different industrial heat applications.

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.

## 1.2 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 2). 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.

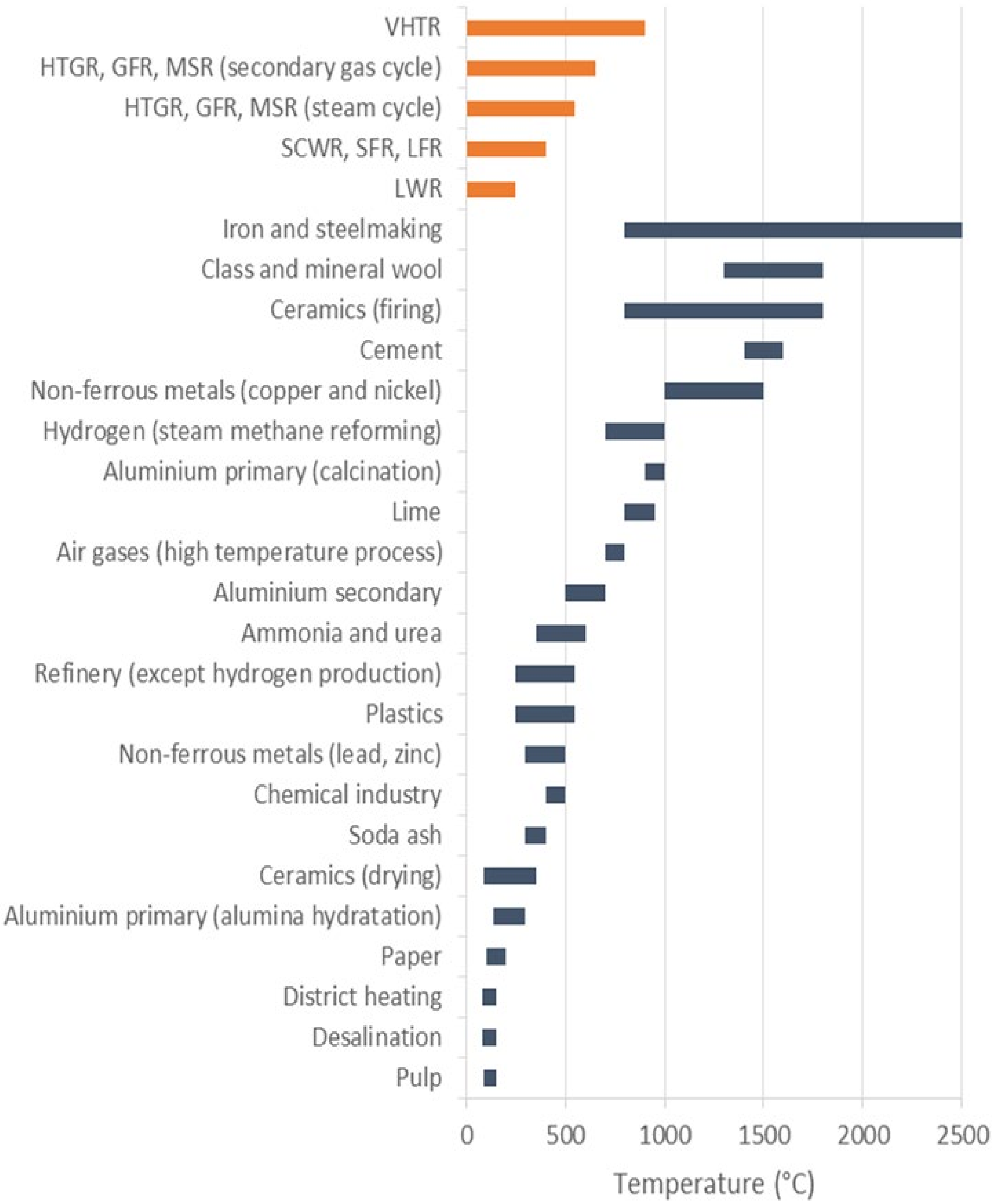

**Figure 1. Process temperature ranges by industrial application and nuclear reactor capabilities**

Source: NEA COGEN Expert Group.

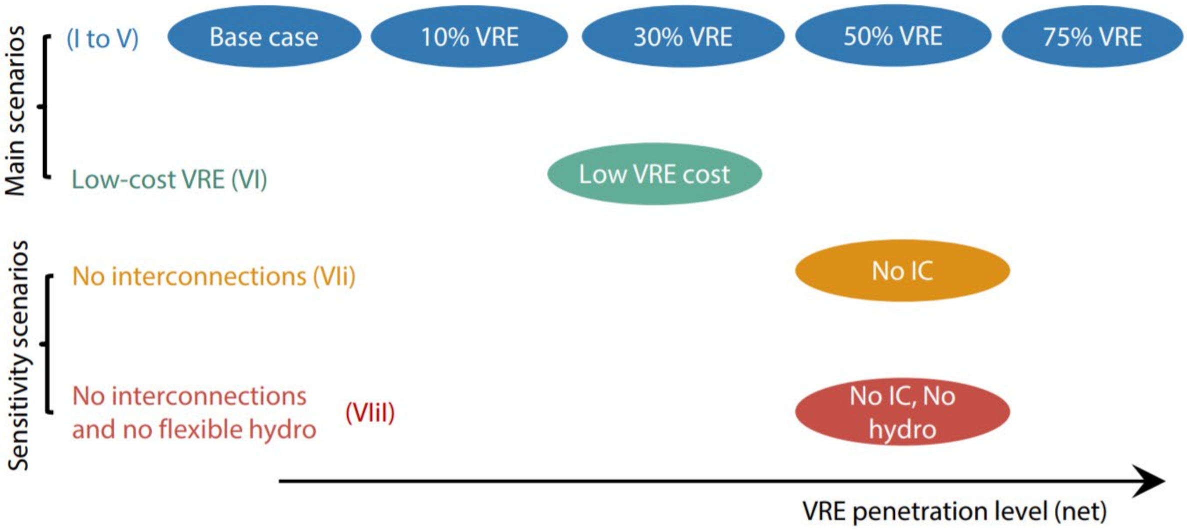

**Figure 2. Eight scenarios to study the cost of low-carbon electricity systems with 50 gCO2 per kWh**

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 4 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.

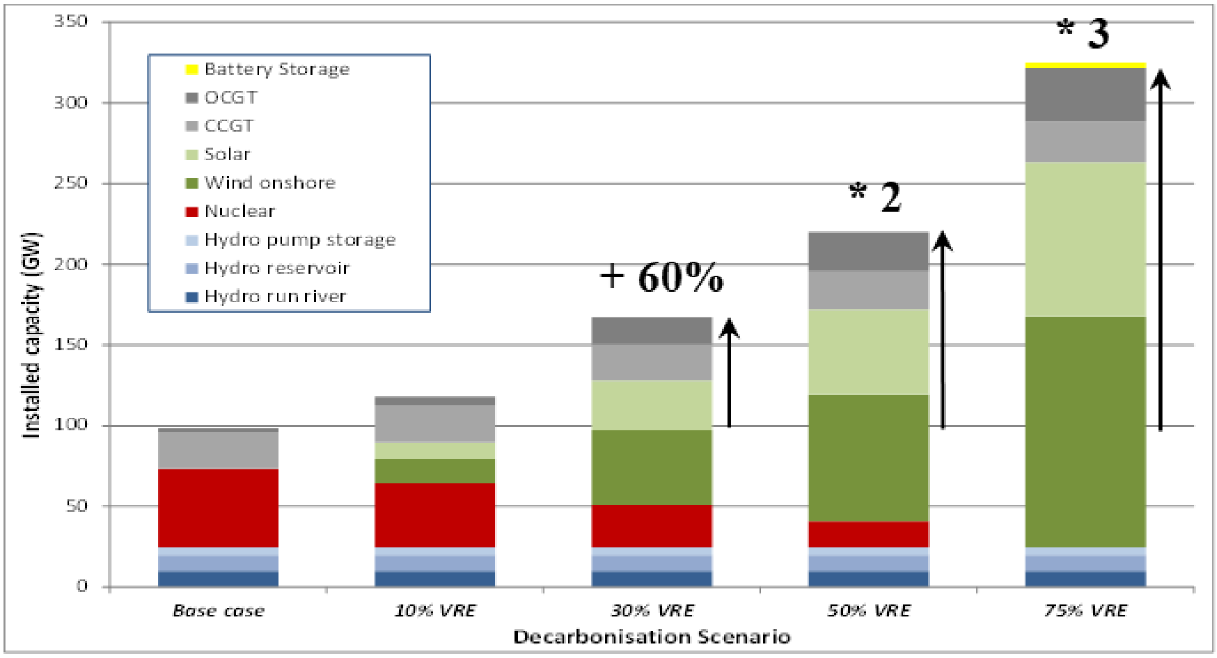

**Figure 3. The capacity mix with different shares of VRE**

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.

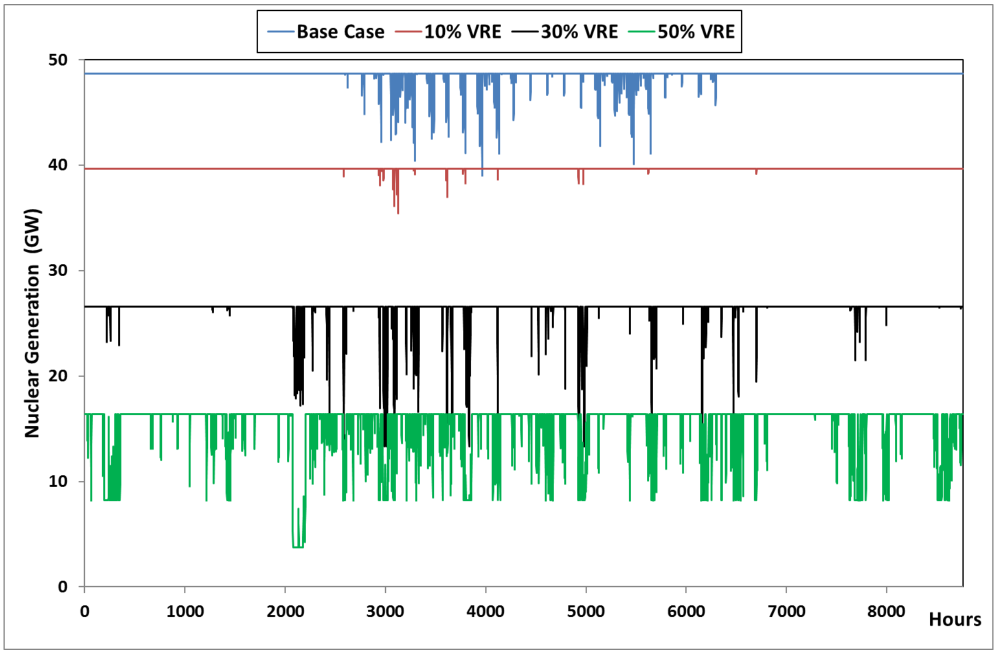

**Figure 4. Projected generation pattern from nuclear power plants**

Source: NEA.

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