# SFR-SMR REQUIREMENTS TO FIT INTO A FUTURE EUROPEAN ELECTRICITY NETWORK

S. PEREZ-MARTIN
Karlsruhe Institute of Technology (KIT)
Institute of Neutron Physics and Reactor Technology (INR)
Eggenstein-Leopoldshafen, Germany
Email:sara.perez@kit.edu

E. BUBELIS
Karlsruhe Institute of Technology (KIT)
Institute of Neutron Physics and Reactor Technology (INR)
Eggenstein-Leopoldshafen, Germany

S. RUCK
Karlsruhe Institute of Technology (KIT)
Institute of Neutron Physics and Reactor Technology (INR)
Eggenstein-Leopoldshafen, Germany

**Abstract**

The present paper reports on various factors modulating the characteristics of the future European Union (EU) electricity grid and therefore establishing a basis for the European Sodium Fast Reactor (ESFR) - Small Modular Reactor (SMR) requirements. It provides an overview of the European power system, where the European Green Deal and national climate targets are described together with the potential features of the future European power system and the low-carbon technologies available to get the net-zero target. It also presents methods for providing stability to the grid, where the grid stability and power balance are described, followed by the methods usually used for stabilizing the grid, such as Flexible Power Operation (FPO) and other grid stabilizers, e. g. fast frequency response technologies, kinetic energy supply systems and energy storage systems. The requirements established for Nuclear Power Plants (NPP), both from the European Utilities Requirements (EUR) association are presented together with the operation performance of conventional power plants, NPPs and advanced nuclear reactor systems. Potential requirements for Sodium Fast Reactor (SFR)-Small Modular Reactor (SMR) - SFR-SMR are presented.

## 1. INTRODUCTION

The European Green Deal aims at transforming the EU into a modern, resource-efficient and competitive economy, ensuring no net emissions of GreenHouse Gases (GHG) by 2050. The backbone of this transformation will be the low-carbon technologies as well as the large-scale European electrical network, since system resilience, service quality and cost optimization are easier achieved in well-interconnected electrical power[1] networks.

Conventional power plants directly connected to high-voltage transmission lines via synchronous rotating alternator contribute to the stability of the system. This option is absent for Variable Renewable Energy (VRE), although they have the ability to supply or absorb reactive power. The large VRE integration will stress the problem of maintaining voltage stability and new solutions have to be implemented in the upcoming years to enhance the response of the power electronics inverters. Methods for providing grid stability and supporting the power balance, such as flexible power operation and other grid stabilizers, e.g., fast frequency response technologies, kinetic energy supply systems and energy storage systems are therefore required for low-carbon technologies including ESFR-SMRs.

The existing requirements established for NNP, both from the European Utilities Requirements (EUR) association and from Electric Power Research Institute (EPRI) as well as the proposed operational performance of currently designed advanced nuclear reactor systems are considered as reference for the ESFR-SMR operational requirements. In order to be competitive, ESFR-SMRs have to offer load-following capabilities at least equivalent to the conventional SMRs. The integration of a Thermal Energy Storage (TES) system enables

[1] *Electrical Power* and *Power* are used in the paper indistinctly.

ESFR-SMR to provide wider load-following capabilities, while maintaining safe reactor operation. Conclusions from the present study addresses considerations for ESFR-SMR design.

## 2. EUROPEAN POWER SYSTEM

The European Green Deal [8], presented in December 2019, aims at transforming the EU into a modern, resource-efficient and competitive economy, ensuring no net emissions of GHG by 2050. The set of proposals adopted by the European Commission (EC) wants to make the EU's climate, energy, transport and taxation policies fit for reducing net GHG emissions by at least 55% by 2030, compared to 1990 level. Knowing that the energy consumption accounts for more than 75% of the EU's GHS emissions, decarbonising the energy system is the target to reach 2030 climate objectives and the EU's long-term strategy of achieving carbon neutrality by 2050 [9]. TABLE 1 shows the summary of EU energy policies addressing years 2030 and 2050. The 2018 Renewable Energy Directive set a 2030 target of at least 32% of renewables (RE) in the EU energy mix, based on national contributions. However, the submitted National Energy and Climate Plans (NECP) in 2020 foresaw a projected RE share of 33-34% [10]. With the increase in climate ambition, i.e., to achieve a 55% net GHG emissions reduction by 2030, compared to 1990 levels, the EC established a more ambitious proposal raising the binding EU-level target for renewables to 40% [10]. EU countries were then requested to provide a 10-year integrated NECP for the period 2021-2030 to meet the EU's energy and climate targets for 2030 [9]. TABLE 2 shows the binding target for GHG emissions compared to 2005, the share of energy from renewable sources in gross final consumption of energy, the share of the electricity consumption from renewable energy sources, as well as the level of electricity interconnectivity for some EU countries [20]-[25].

TABLE 1. SUMMARY OF EU ENERGY POLICIES ADDRESSING YEARS 2030 AND 2050 [9]

| | By 2030 | By 2050 |
|---|---|---|
| Greenhouse Gases | Net reduction GHG emissions >55% comp. to 1990 | No net emissions of GHG |
| Energy Sector | 32 % RE in energy mix (2018)[2]<br>40 % RE in energy mix (2019)[3] | |
| Heating Sector | Integration of heating/cooling systems | |
| Transport Sector | Support to e-fuels in cars | Rev. combustion cars phase-out[4] |
| Energy efficiency | Energy cons. reduction > 9% comp. to 2020[5] | |

cons.: consumption

TABLE 2. ENERGY AND CLIMATE TARGETS FOR 2030 AS PRESENTED IN NECP [20]-[25]

| | GHG emissions comp. to 2005 | Share RE in gross final energy cons. | Share RE in electricity cons. | Level of electricity interconnectivity | Coal Phase-out |
|---|---|---|---|---|---|
| Belgium | -35 % | 17.5 % | 37.4% | 33 % | 2020 |
| France | -37 % | 33% | 40 % | 16.5 % | 2022 |
| Germany | -38 % | 30 % | 65 % | - | 2038 |
| Italy | -33 % | 30 % | 55% | 10 % | 2025 |
| Poland | -7 % | 21-23 % | 32 % | 8.7 % | - |
| Spain | -26 % | 42 %[6] | 74 % | 15 % | 2030 |

[2] Set in the 2018 Renewable Energy Directive

[3] Set in the European Green Deal

[4] Proposed law for combustion cars phase-out by 2035 rejected assuming green fuel engines to be allowed (Ref. [28])

[5] Equivalent to 39% and 36% energy efficiency for primary and final energy consumption in Climate Target Plan.

[6] Although the specified target is 42%, 35% is set in the draft law on climate change and energy transition.

### 2.1. Power system characteristics: European Features

The electricity system across Europe is rapidly changing with an increasing share of renewable variable wind and solar energies, decentralised electricity sources such as solar photovoltaic (PV) and wind power plants as well as smart loads, such as electric vehicles (EV) and smart appliances [2]. All these factors are driving the transformation of the European electric power system. As a result of public policies and a sharp drop in the cost of solar panels and wind farms, a massive development of low-carbon electricity generation from variable renewable energy (VRE) sources is currently underway in Europe and world-wide. Europe already has a significant hydropower capacity, although it differs between the countries. Hydropower will continuously contribute to the future energy mix, however, the limitations on natural resources (e.g., rivers channelled between hills) limits future development probably to small scale projects and/or the modernization of existing installations. Thus, solar panels and wind farms are the two major actors in VRE. The characteristics of power plants related to the power grid connection are provided in TABLE 3 (MVL: Medium Voltage Lines; HVL: High Voltage Lines; SG: Synchronous Generator; RA: Rotating Alternator).

TABLE 3. CHARACTERISTICS OF POWER PLANTS RELATED TO THE POWER GRID

| | AC/DC | Power Generator | Connection to the grid | Power Generation |
|---|---|---|---|---|
| Solar Farms | DC | power electronics | MVL | non dispatchable |
| Wind Farms | AC | power electronics | MVL | non dispatchable |
| Biomass | AC | SG, RA | MVL/HVL | dispatchable |
| Hydroelectric | AC | SG, RA | HVL | dispatchable |
| Nuclear | AC | SG, RA | HVL | dispatchable |
| Coal | AC | SG, RA | HVL | dispatchable |
| Combined Cycle Gas PP | AC | SG, RA | HVL | dispatchable |

Considering the energy system architecture, solar panels and wind farms technologies differ from conventional power plants due to:

- **Fuel:** Wind and solar radiation cannot be directly stored, whereas in centralised, dispatchable power plants, fuel provides a large and long-term storage supporting the resilience of the system.
- **Grid connection:** VRE are connected either to the distribution or to the transmission networks through power electronics, and, thus, are not able to provide the same inertia response as synchronous generators in the case of system disturbances. Conventional power plants are directly connected to high-voltage transmission lines via synchronous, rotating alternator supporting the stability of the system.
- **VRE load factor:** VRE capacity does not replace conventional plants with 1:1 ratio due to the low-capacity factor and dependency on atmospheric conditions. For the European grid [2], this ratio is ~ 1:7 (i.e., 100 MW of conventional capacity are replaced by 700 MW of VRE sources).

Electric power demand is not only increasing due to population growth, but it is also evolving quickly due to decentralized consumers, as well as by the electrification of the transport, such as EVs, and heating sectors (air-conditioning, heat pumps). All these factors add an additional uncertainty in the prediction of power demand and therefore on the stability of the grid. The transport sector is currently experiencing significant changes as a result of the rapid deployment of EVs, including both fully electric and hybrid electric vehicles. On the other side, space cooling and heating is also contributing to increase the electricity consumption. Air-conditioning systems, household fans and dedicated dehumidifiers represent the larger part of space cooling devices and are being largely installed in households, industrial companies, commercial enterprises, offices, etc.

There are systems and technologies that modulate the power generation and power demand. Depending on the grid needs, they behave as power loads, e.g., hydrogen production, storage systems or charging EV, while sometimes they behave as power suppliers, e.g., batteries in discharging mode, fuels, etc. Some of these technologies might be embedded in power plants as in-built services (co-operatively controlled systems) or can be setup as stand-alone systems (single facility). They consist of batteries, TES systems, hydro pumping stations, compressed air systems, hydrogen production, flywheels, etc. (see TABLE 4, [2]).

TABLE 4. CHARACTERISTICS OF ENERGY STORAGE SYSTEMS [2]

| Storage System | Efficiency | Storage capacity | Power cost ($/kW) | Energy cost ($/kW) | Maturity |
|---|---|---|---|---|---|
| Hydrogen | 30-40% | Hours - weeks | Med-high | Low | Medium |
| Pumped storage | 75-80% | Hours - days | Medium | Low | High |
| Lithium battery | ~85 % | 1-4 hours | Medium | Med | Med-high |
| Redox battery | ~70 % | ~10 hours | Med-high | Low-med | Medium |
| Flywheel | 90 % | ~1 minute | Low | Med-high | High |

Power generation is linked to end-consumers through a network consisting of several levels. Normally, a transmission high-voltage network meshes a country with interconnections to neighbouring zones. The distribution network then lowers the voltage and delivers power to the consumer in a tree-like network. Large-scale networks have larger system resilience and service quality compared to small networks. Moreover, large-scale networks ensure cost optimisation, making room for baseload plants and thereby reducing the overall price paid by consumers [2]. As already addressed by the EU Green Deal, the grid stability needs the support of the interconnections between European national grids. The appropriate development of interconnections will make it easier to find a balance between supply and demand, mainly by: i) allowing more power to be transported from one area to another and ii) transforming the issue of managing intermittency at the local distribution network level to handling variability at the level of the interconnected system [2].

### 2.2. Power mix to get the net-zero target

In order to achieve the European energy targets presented above, the national governments have to consider what energy mix is compatible with the GHG emissions based on the $CO_2$ intensity of electricity generation. During the entire life cycle, the $CO_2$ intensity of electricity generation (see TABLE 5) varies very much among the various types of electricity generation. Therefore, considering the EU climate targets, the possible energy mixes able to achieve net-zero are rather limited where the two pillars for decarbonising the electrical power system are renewables along with low-carbon, dispatchable energy sources. If low-carbon dispatchable energy sources as NPP or further innovative power generation technologies are not considered in the energy mix, as in the German Energy Transition Plan, the remaining alternative is large-scale storage systems, including long-term seasonal storage, power-to-X, and Carbon Capture, Use and Storage which currently do not reach the highest Technology Readiness Level as low-carbon, dispatchable energy sources. Depending on the VRE integration, the power system needs different timescale flexibility. In systems with low share of VRE, conventional plants are needed to compensate supply and demand in case VREs are not available, and to adjust an increasing net demand variability. For systems with larger share of VREs, flexibility for increasingly longer timescales and shorter timescales are needed in case wind and solar are not available. For even higher VRE integration levels, seasonal generation and low-carbon generation are needed, which includes nuclear, hydro, and storage, e.g., synthetic fuels.

TABLE 5. $CO_2$ INTENSITY OF ELECTRICITY GENERATION [1]

| Fuel | Coal | Natural Gas | Biomass | Solar | Nuclear | Wind | Hydro |
|---|---|---|---|---|---|---|---|
| $CO_2$ production ($gCO_2eq/kWh$) | 820 | 490 | 230 | 48 | 12 | 12 | 24 |

## 3. PROVIDING STABILITY OF THE GRID

Over the years, large-capacity steam turbine power plants, such as NPP and thermal power plants, have operated at base load and demand control has been performed by power plants that start and stop quickly, such as liquefied natural gas (LNG) power plants and hydroelectric power plants. However, as the share of VRE increases, it becomes more difficult to demand control as the gap between the maximum and minimum of the power generation output becomes very large. The electrical power system relies on a constant balance of supply and demand, which in turn implies: frequency stability and voltage stability.

Demand for electricity can never be determined with exact precision in advance and, thus, there is a certain random variation in demand resulting in frequency fluctuations. Abundant energy in the grid will speed up generators and lead to an increase of the power grid frequency. Similarly, a shortage of power generation slows down the same generators and reduces the systems frequency as kinetic energy stored in the generator is transformed into electrical energy [12]. Control systems, from primary to tertiary control, are foreseen in the grid system to ensure the balance of supply and demand by closely monitoring the frequency and maintaining it close to the desired reference value, i.e., $f = 50\ Hz$ in Europe [12][13]. Large deviations of the frequency away from the reference are to be avoided as they require decisive control actions and cause high costs. TABLE 6 shows the types and characteristics of frequency control operations. The frequency and voltage stability of the power grid are maintained by active power and reactive power control, respectively. Voltage stability is the ability to maintain the voltage within a predetermined range on all buses after a fault or failure to prevent power outages [11].

TABLE 6. TYPES AND CHARACTERISTICS OF FREQUENCY CONTROL OPERATIONS [13]

| Frequency control | Time-frame |
|---|---|
| Primary frequency control | Short-term adjustments of electricity production according to demand every 2 to 30 seconds |
| Secondary frequency control | Longer time frames (from sec. to min.); restores the exact frequency by calculating an average frequency deviation over a period of time. |
| Tertiary frequency control | Slower control than prim. and sec. frequency control. It sets reference power values to individual power units for a network optimal dispatch. |

Various methods are normally used to provide stability and support the power grid. These include: i) flexible power operation of power plants, ii) fast frequency response technologies, iii) kinetic energy supply systems and iv) energy storage systems. The gap between the maximum and minimum of the VRE power generation output becomes very large and needs to be filled with flexible power generation. This is the case of load-following operations adjusting the output of the existing large-capacity thermal power plant or NPP according to the increase or decrease in the load. Due to the different kind of need requested by the power grid [4][14], the following operational modes are foreseen for FPOs (see FIG. 1): Frequency control operation and load following. In order to keep the plant frequency stable at the rated frequency, the frequency of the grid must be monitored and the generation level must be adjusted immediately, this is the so-called primary control [7].

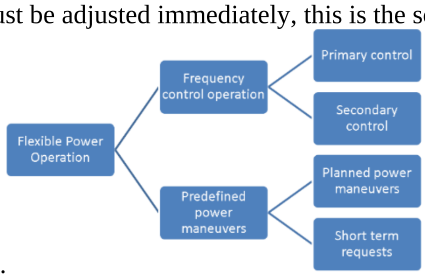


*FIG. 1 Operational modes foreseen for FPOs*

## 4. REQUIREMENTS FOR POWER PLANTS

Electrical power generation systems connected to the grid are increasingly being required to have ramping and load following capabilities in order to adjust output so that grid utilities ensure a balance between electricity supply and demand throughout the day [2]. Utilities in Europe [16] and the United States [4] have issued requirements for generation III reactors [5][3] and future light water reactors (LWRs) to ensure that new NPPs provide flexibility services to the system. The EPRI User Requirements Document also includes requirements for SMRs. Most of the new reactors (Gen-III+) are compliant with the current utilities' requirements for the new nuclear plants. These utility requirements are mainly focused on the operational flexibility of nuclear plants. The main requirements for NPP have been collected from [2]-[5][7][11][16][18][26].

The EUR cover a wide range of conditions for NPP to operate efficiently and safely [7]. It states that modern nuclear reactors must implement significant manoeuvrability and, in particular, be able to operate in load-following mode. The European flexibility requirements for new LWRs are summarized in TABLE 7,

[26][11][2][14]. New NPP designs developed in accordance with the EPRI Advanced LWR Utility Requirements Document (URD) support FPO. The EPRI maintains the URD as a major compendium of guidelines and specifications for standardized plant designs, including specifications for desired load-following characteristics. EPRI recently updated the URD to Rev.13 specifically to envelope SMRs. The new version contains more aggressive load-following specifications to reflect the more flexible features anticipated for SMRs [18]. For existing NPPs transitioning from baseload operations to FPO URD requires modifications to support FPO [4]. The EPRI requirements for LWRs and for SMRs are presented in TABLE 7 showing the load-following characteristics included in EPRI URD specifications [18]. In addition, it is presented the ramping and load following capabilities as requested by utilities in Europe [16][11] and the United States [4][18].

TABLE 7. LOAD FOLLOWING REQUIREMENTS BASED ON EUR AND EPRI [16][11][4][18]

| | EUR Req. | EPRI Req. (Rev. 13)* |
|---|---|---|
| Normal operation (mandatory) | 50%-100% at 3-5%/min. | Daily 100% → 20% → 100 % |
| Minimum power level (optional) | 20% | |
| Primary control (mandatory) | ±2%/min | automatic frequency response |
| Primary control (recommended) | ± 5%/min | |
| Secondary control (optional) ~sec-min. | ±10% | |
| Grid restoration with load steps up to | 10% | |
| Secondary control (optional) | ±10%, at 1%/min. | 40 %/hour; 20 % var. in 10 min. |
| In full cycle, load-following up to | 90% | |
| Full-minimum-full power operation | 2/day; 5/ week; 200/year | |
| Emergency load variation | 20%/ min. (down); 1-5%/min. (up) | |

* For EPRI Req., not all data are available in open literature.

### 4.1. Operational performance

Power plants currently in operation are able to provide the necessary flexible backups in the short term (see TABLE 8 [11][27]). There are two ways to regulate the thermal output of NPPs. The first is a primary loop control method of the reactor power (reactor following turbine), and the second is a method for controlling the amount of main steam supplied to the turbine (turbine following reactor) [11]. For the primary frequency control, power modulations are performed within ±2% nominal power ($P_r$) in French NPPs. While for secondary frequency control, the NPP modifies the power level within a range of ±5% $P_r$ [14]. TABLE 9 shows the load-following capabilities of French and German NPPs.

TABLE 8. FLEXIBILITY OF CONVENTIONAL POWER GENERATION TECHNOLOGIES [11][27]

| | NPPs | Coal-fired PP | Ignited-fire PP | CCGPP | PPP |
|---|---|---|---|---|---|
| Start-up Time CC | ~40 h | ~6 h | ~10 h | <2 h | ~0.1 h |
| Start-up Time WC | ~40 h | ~3 h | ~6 h | <1.5 h | ~0.1 h |
| Ramp-up Gradient | ~5%/min. | ~2%/min. | ~2%/min. | ~4%/min. | >40%/min. |
| Ramp-down Gradient | ~5%/min. | ~2%/min. | ~2%/min. | ~4%/min. | >40%/min. |
| Min. Shutdown Time | No | No | No | No | ~10 h |
| Min. Load | 50% | 40% | 40% | <50% | ~15% |

NPP: Nuclear Power Plants; PP: Power Plants; CCGPP: Combined-cycle Gas-fired Power Plants; PPP: Pumped-storage Power Plants; CC: Cold Conditions; WC: Warm Conditions

TABLE 9. LOAD-FOLLOWING CAPABILITIES OF FRENCH AND GERMAN NPP [14]

| French NPP | German KONVOI NPP |
|---|---|
| daily variations by several tens of % of $P_r$ | 15,000 cycles* with daily variations 100% - 60%<br>100,000 cycles* with variations 100% - 80% |

* during its lifetime

The minimum requirements for the manoeuvrability capabilities of modern Generation III/III+ reactors are defined by the utility requirements, for EUR and EPRI requirements based grid operator requirements. Most of the modern Gen III+ designs implement even higher manoeuvrability capabilities, with the possibility of planned and unplanned load-following in a wide power range and with ramps of 5%/min. Some designs are capable of extremely fast power modulations in primary or secondary frequency regulation modes with ramps of several percentage points of the rated power per second, but within a narrow band around the rated power level [14]. Collecting information openly available for SMRs, TABLE 10 shows the main characteristics and load-following manoeuvring performance of those SMR designs, where the manoeuvring capabilities are numerically described in the literature.

TABLE 10. CHARACTERISTICS OF SMRs

| Name | Power (MWe) | Reactor System | Manoeuvring |
|---|---|---|---|
| Xe-100 [17] | 82.5 | HTGR | 100%-40%-100% |
| SMR-LWR [17] | 225 | LWR | daily 100%-20% at 5%/min.; ±10% var. at 2%/min. |
| Nuscale [18] | 50 | LWR | able to meet all of new EPRI Rev.13 URD |
| Fast Modular Reactor [17] | 50 | Helium FR | load-following of about 20%/min. ramping |
| Natrium [17] | 345-500 | SFR | 30% - 150% of reactor power variations |
| KARAT-100 [19] | 100 | BWR | daily variation 20% - 100% of nominal capacity |
| BWRX-300 [19] | 270-290 | BWR | load following 50 - 100% at 0.5%/min. |
| GTHTR300 [19] | 100-300 | HTGR | able to provide max. required load follow 5%/min |
| PBMR-400 [19] | 165 | HTGR | load follow 40% - 100% |
| SVBR [19] | 100 | LMFR | load follow 100–50–100% |
| Westinghouse LFR [19] | 450 | LMFR | Host a TES capable of providing load-levelling |
| Integral MSR [19] | 195 | MSR | substantial load following capability |
| ThorCon [19] | 250 | MSR | load following capability |
| KLT-40S [19] | 2×35 | PWR fl. | 10% - 100% operation 26,000 h up to 0.1 %/s. |
| ABV-6E [19] | 6-9 | PWR fl. | 20–100% operation of 26,000 h up to 0.1%/s |

var.: variation; fl.: floating;

### 4.2. Requirements for SFR-SMR

In order to be competitive, SFR-SMRs have to offer load-following capabilities at least as the SMRs presented above. Moreover, and based on EPRI recommendation [2], SFR-SMR has to tackle not only operational flexibility, but also additional features. As a normal trend in new SMR designs, SFR-SMR can benefit from energy storage integration enhancing the load-following capabilities. Additionally combined heat and power systems can provide further capabilities and therefore attractiveness by simultaneously producing electricity and useful heat for industrial processes or district heating. Grid services and ancillary markets are the added value of SFR-SMR so that not only dispatchable power is generated, but also frequency grid regulation, voltage control, and reactive power support are provided.

The use of thermal storage might mitigate the requirements of flexibility to the nuclear reactor and provides the standard mode of use of TES for stable and baseload production [15][6]. The inherent operational flexibility of SFR-SMR, e. g. no Xenon transients, can be further improved by adopting different energy storage options. By coupling the primary loop with a TES system, as in the case of the NATRIUM reactor [15], SFR-SMR would benefit from i) avoiding sodium-water interaction and ii) decoupling power generation from power demand. Alternatively, the sodium secondary loop could be used as a small TES. TABLE 11 presents the advantages and drawbacks of different load following options for SFR-SMRs.

TABLE 11. PROS AND CONS OF DIFFERENT LOAD FOLLOWING OPTIONS FOR SFR-SMRs

| Load Following Option | Advantages | Drawbacks |
|---|---|---|
| Reactor load following | Flexible as current NPP fleet | Thermal fatigue |
| TES load following | Flexible without affecting the reactor | Cost and complex operation |
| Reactor + TES load following | Much more flexible | Cost and complex operation |

## 5. CONCLUSIONS

The paper presents an overview of the European electrical power system, where the EU Green Deal and national climate targets are presented together with the potential features of the future European power system and the low-carbon technologies available to reach the net-zero target. The methods for providing stability to the grid are presented, where the grid stability and power balance are supported by usual methods, such as flexible power operation, fast frequency response technologies, kinetic energy supply systems and energy storage systems.

Conventional power plants are directly connected to high-voltage transmission lines via synchronous rotating alternator contributing to the stability of the system. VREs do not provide such support, however, they can supply or absorb reactive power. Large VRE integration stresses the problem of maintaining voltage stability and new solutions have to be implemented in coming years to enhance the response of power electronics inverters.

The Requirements established for NPPs, both from the EUR Association and EPRI, are presented together with the operation performance of conventional PP, NPP and ANRS systems. Finally, potential requirements for SFR-SMR are discussed taking as basis the operational performance of currently designed ANRS. The main conclusion obtained is that in order to be competitive, SFR-SMRs have to offer load-following capabilities at least equivalent to the conventional SMRs while being cost-effective. When integrating a TES System, SFR-SMR can provide load-following capabilities, while not compromising safe reactor operation and life-cycle of the reactor components.

## ACKNOWLEDGEMENTS

The publication is part of the ESFR-SIMPLE project addressing the design and features of an SFR-SMR. This project has received funding from the Euratom Research and Innovation Programme 2021-2025 under Grant Agreement No 101059543 from the HORIZON-EURATOM-2021-NRT-01.

## REFERENCES

[1] Pathways to net zero using nuclear innovation. International perspectives on the role of nuclear energy and innovation in reaching our climate targets. Booklet Published for the Clean Energy Ministerial 12, 31st May – 6th June 2021, Chile

[2] NEA 2021 Advanced Nuclear Reactor Systems and Future Energy Market Needs. OECD 2021 NEA No. 7566 Nuclear Technology Development and Economics

[3] EPRI (2014), "Advanced Light Water Reactors Utility Requirements Document" Revision 13, Technical Report No. 3002003129.

[4] EPRI 2014 Program on Technology Innovation: Approach to Transition Nuclear Power Plants to Flexible Power Operations. 3002002612. Final Report, January 2014 2014 TECHNICAL REPORT

[5] EUR (2012), "European Utility Requirements for LWR Nuclear Power Plants", available at: www.europeanutilityrequirements.org

[6] IAEA (2018) Non-baseload operation in nuclear power plants: load following and frequency control modes of flexible operation. IAEA NUCLEAR ENERGY SERIES No. NP-T-3.23

[7] NEA (2011) Technical and Economic Aspects of Load Following with Nuclear Power Plants OECD/NEA, Paris (2011)

[8] EUROPEAN COMMISSION commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en (visited 30.05.2023)

[9] EUROPEAN COMMISSION commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/energy-and-green-deal_en (visited 30.05.2023)

[10] EUROPEAN COMMISSION ec.europa.eu/commission/presscorner/detail/en/qanda_21_3544 (visited 30.05.2023)

[11] CHANG, C., OYANDO, H. C. (2022). Review of the Requirements for Load Following of Small Modular Reactors. *Energies*, *15*(17), 6327. MDPI AG. Retrieved from http://dx.doi.org/10.3390/en15176327

[12] J. KRUSE, B. SCHÄFER D. WITTHAUT, "Predictability of Power Grid Frequency," in *IEEE Access*, vol. 8, pp. 149435-149446, 2020, doi: 10.1109/ACCESS.2020.3016477

[13] J. MACHOWSKI, J. BIALEK, J. BUMBY, Power System Dynamics: Stability and Control. Hoboken, NJ, USA: Wiley, 2011.

[14] A. LOKHOV. Load-following with nuclear power plants. NEA updates, NEA News 2011 – No. 29.2 18-20

[15] TANDEM EU Project D4.1 "Status on Safety Analysis in Europe from the Operational Flexibility and Cogeneration Viewpoint" available on-line

[16] EUR Association eur.preprod.rollingbox.com

[17] WNN www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx (visited 30.05.2023)

[18] D. T. INGERSOLL, C. COLBERT, ET AL. Can Nuclear Power and Renewables be Friends? Proceedings of ICAPP 2015 May 03-06, 2015 – Nice (France) Paper 15555

[19] IAEA. Advances in Small Modular Reactor Technology Developments; A Booklet Supplement to the IAEA Advanced Reactors Information System (ARIS); IAEA: Vienna, Austria, 2020; p. 354

[20] Assessment of the final national energy and climate plan of Belgium SWD/2020/900 French or English

[21] Assessment of the final national energy and climate plan of France SWD/2020/909 French or English

[22] Assessment of the final national energy and climate plan of Germany SWD/2020/904 German or English

[23] Assessment of the final national energy and climate plan of Italy SWD/2020/911 Italian or English

[24] Assessment of the final national energy and climate plan of Poland SWD/2020/920 Polish or English

[25] Assessment of the final national energy and climate plan of Spain SWD/2020/908 Spanish or English

[26] BRUYNOOGHE, C.; ERIKSSON, A.; FULLI, G. Load-Following Operating Mode at Nuclear Power Plants (NPPs) and Incidence on Operation and Maintenance (O&M) Costs. Compatibility with Wind Power Variability; European Commission: Luxembourg, 2010

[27] PIERRE, I.; LORUBIO, G. Flexible Generation: Backing Up Renewables; Union of the Electricity Industry-EURELECTRIC Depot legal: D/2011/12.105/47; RESAP: Paris, France, 2011

[28] CNN 2023 edition.cnn.com/2023/03/24/cars/eu-combustion-engine-debate-climate-intl/index.html (visited 31.05.2023)