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Summary

List of requirements for the flexible SMR-SFR in view of EU2050 and possible critical scenarios (taking into account different factors: energy policies of EU countries, share of renewable energies, fleet of electrical cars, status of energy storage systems, fusion power plants)

Approval

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Summary

This deliverable presented an overview of the European Power System, where the EU 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, Nuclear Power Plants and Advanced Nuclear Reactor Systems.

Potential requirements for Small Modular Reactor (SMR) - Sodium Fast Reactor (SFR) are presented as well taking as basis the best operational performance of currently designed Advanced Nuclear Reactor Systems.

Keywords

SMR-SFR, European Power System, Load-following operation, grid stability, frequency control

Abbreviations and acronyms

Acronym	Description
AAC	Alternative AC
AC	Alternating Current
AGC	Automatic Generation Control
AGR	Advanced Gas-cooled Reactor
ARS	Advanced nuclear Reactor Systems
AVR	Automatic Voltage Regulator
BEV	Battery Electric Vehicle
BWR	Boiling Water Reactor
CAES	Compressed Air Energy Storage
CCG	Combined Cycle Gas-fired Power Plants
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Use and Storage
CHP	Combined Heat and Power
CSP	Concentrated Solar Power
DC	Direct Current

EC	European Commission
ENTSO-E	European Network of Transmission System Operators for Electricity
EPRI	Electric Power Research Institute
ESR	Effort Sharing Regulation
EUR	European Utilities Requirements
EV	Electric Vehicle
FOAK	First of A Kind
FP	Full Power
FPO	Flexible Power Operation
GCR	Gas-Cooled Reactor
GDC	General Design Criteria
GDP	Gross Domestic Product
GF	Governor-Free
GFL	Grid-Following
GFM	Grid-Forming
GHG	Green House Gas
HTGR	High-Temperature Gas-Cooled Reactor
HV	High voltage:
HVDC	High Voltage Direct Current
HWR	Heavy Water Reactor
IEA	International Energy Agency
ISO	Independent System Operator
LFR	Lead-Cooled Fast Reactor
LMFR	Liquid Metal cooled Fast Reactor
LNG	Liquefied Natural Gas
LV	Low voltage
LWR	Light Water Reactor
MSR	Molten Salt Reactor
MV	Medium voltage
NECP	National Energy and Climate Plan
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission

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PCT	Power Conversion Technology
PHS	Pumped hydro storage
PPS	Preferred Power Supply
Pr	Rated Power
PV	PhotoVoltaic
PWR	Pressurized Water Reactor
RED	Renewable Energy Directive
REO	Rated Electrical Output
RES	Renewable Energy System
RTP	Rated Thermal Power
SFR	Sodium Fast Reactor
SMR	Small Modular Reactor
TANDEM (EU Project)	Small Modular ReacTor for a European sAfe aNd Decarbonized Energy Mix
TES	Thermal Energy Storage
TRL	Technology Readiness Level
TSO	Transmission System Operator
URD	User Requirements Document
VRE	Variable Renewable Energy
WP	Work Package

1 Introduction

It is highly impossible to predict how the future EU electricity network will look like coming years. This report however tries to collect the policy plans and programs that the EU Commission is approving for the future, so that the main characteristics of the electricity grid can be settled and be used as reference for establishing the grid requirements that the ESFR-SMR will have to address.

In section 2 the European power system is presented. It includes the EU Green Deal and national climate targets (section 2.1), the potential features of the future European power system (section 2.2) and the low-carbon technologies available to get the net-zero target (section 2.3).

Methods for providing stability to the grid are presented in Section 3. First, grid stability and power balance are presented in section 3.1, then methods for stabilizing the grid are presented in section 3.2, such as Flexible Power Operation (FPO) (section 3.2.1) and other grid stabilizers (section 3.2.2).

Section 4 describes the requirements established for Nuclear Power Plants (NNP), both from the European Utilities Requirements (EUR) Association in section 4.1 and from Electric Power Research Institute (EPRI) in section 4.2. The operation performance of power plants are then described in Section 4.3, including conventional plants (section 4.3.1), NPP (section 4.3.2), and Advanced Nuclear Reactor Systems (ARS) (sections 4.3.3, 4.3.4, 4.3.5 and 4.3.3).

The potential requirements for SMR-SFR are presented in section 4.4 taking as basis the best operational performance of currently designed ARS and the features of SFRs.

Section 5 finally presents the conclusions from this study and addresses considerations for ESFR-SMR design.

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2 European Power System

2.1 On the way to the Net-zero target

2.1.1 EU Green Deal

The European Green Deal (Ref. [17]), presented in December 2019, aims at transforming the EU into a modern, resource-efficient and competitive economy, ensuring no net emissions of greenhouse gases by 2050. The set of proposals adopted by the European Commission want to make the EU's climate, energy, transport and taxation policies fit for reducing net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels. Knowing that the energy consumption accounts for more than 75% of the EU's greenhouse gas (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 (Ref. [18]). Table 1 shows the summary of EU energy policies addressing 2030 and 2050.

	By 2030	**By 2050**
Greenhouse Gases	Net reduction of GHG emissions by >55% comp. to 1990 levels	No net emissions of GHG
Energy Sector	32 % RE in energy mix (2018)[1] 40 % RE in energy mix (2019)[2]	
Heating Sector	Integration of the heating/cooling systems in the power	
Transport Sector	Support to e-fuels in cars	Revision of internal combustion engine cars phase-out[3]
Energy efficiency	Energy consumption reduced by > 9% comp. to 2020 ref. scenario[4]	

Table 1: Summary of EU energy policies addressing 2030 and 2050

In order to reach the targets, the European Green Deal focuses on 3 key principles for the clean energy transition (Ref. [18]):

1. To ensure a secure and affordable EU energy supply
2. To develop a fully integrated, interconnected and digitalised EU energy market
3. To prioritise energy efficiency, improving the energy performance of our buildings and developing a power sector based largely on renewable sources

The 2018 Renewable Energy Directive set a 2030 target of at least 32% of renewables in the EU energy mix, based on national contributions. When member states submitted their National Energy and Climate Plans (NECP) in 2020, the cumulative impact of the 27 plans already went beyond this figure, adding up to a projected renewables share of 33.1-33.7%, based on the announced measures (Ref. [20]). With the increase in climate ambition – to achieve a 55% net greenhouse gas emissions reduction by 2030, compared to 1990 levels – the European Commission (EC) established a more ambitious proposal raising the binding EU-level target for renewables to 40% (Ref. [20]).

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[1] Set in the 2018 Renewable Energy Directive

[2] Set in the European Green Deal

[3] The proposed law envisioning a total ban of new diesel and gasoline cars by 2035 was rejected based on the idea that engines powered by "green" fuels have to be allowed (Ref. [31])

[4] This is equivalent to the 39% and 36% energy efficiency targets for primary and final energy consumption included in the Climate Target Plan.

The EC is aware of the need to build interconnected energy systems and better integrated grids to support renewable energy sources, especially considering the strong support to develop the full potential of Europe's offshore wind energy.

EU countries were then requested to provide a 10-year integrated national energy and climate plan (NECP) for the period from 2021 to 2030 so to meet the EU's energy and climate targets for 2030 Ref. [18]). These NECPs were introduced by the regulation on the governance of the energy union and climate action (EU) 2018/1999, agreed as part of the Clean energy for all Europeans package which was adopted in 2019. Table 2 shows the binding target for greenhouse gas (GHG) emissions compared to 2005 under the Effort Sharing Regulation (ESR), 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 (Refs.[54]-[59]) for some EU countries.

	GHG emissions comp. to 2005 by 2030	Share RE in gross final energy consumption by 2030	Share RE in electricity consumption by 2030	Level of electricity interconnectivity by 2030	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 %[5]	74 %	15 %	2030

Table 2: Energy and Climate targets for 2030 as presented in NECPs Refs.[54]-[59]

Compliance with reduction targets is binding and if a member state does not meet the targets, it must purchase emissions allowances from other member states to cover the excess (Ref. [28])

Energy system integration means linking the various energy carriers - electricity, heat, cold, gas, solid and liquid fuels - with each other and with the end-use sectors, such as buildings, transport or industry. (Ref. [19]). The electrification of transport is an example of the potential for integration.

As for the combustion car, it is currently proposed that vehicles with combustion engines can still be newly registered after 2035 if they use only CO_2-neutral fuels. For that, EC will work now on drafting specific rules to implement the agreement (Ref. [31]).

The plans of three European countries are presented hereafter as emblematic examples due to their ambitious net-zero program without NPP (DE), their high share of nuclear power (FR) and their ambitious plans of new nuclear building (UK).

2.1.2 DE Policies

As of 14 December 2020, Germany modified its energy law to create the legal basis for continuing the expansion of renewable energy in the long term. The law came into force as of 1 January 2021. However, as for 26 November 2021 (Ref. [22]) and in order to meet its renewable energy targets, the federation and the states established a new federation/states Cooperation Committee under the Renewable Energy Sources Act. According to a new report published by the Federation and the states, the targets are not to be fulfilled if new wind-power projects are not approved since the land dedicated to on-shore wind farms is not sufficient to

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[5] Although the specified target is set at 42%, in the Spanish draft law on climate change and energy transition the level is set to 35%.

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meet the 2030 target, which amounts to 71 GW of installed capacity and for annual auction volumes (Ref. [22]).

According to the Federal Climate Protection Act, GHG neutrality must be achieved in Germany by 2045 at the latest, where technical negative emissions, i.e. carbon removal technologies such as "Carbon Capture and Storage", are considered for the first time as a necessary supplement to the natural sinks. The summary of the German energy transition targets is presented in Table 3 (Ref. [23],[24],[25],[26] and [27]).

German energy transition targets	
2025	• 40 – 45 % Share of renewables to be reached in the power consumption
2030	• 65% of its electricity from clean sources • Cut of GHG emissions by 55 % from 1990 levels • 80 % more wind and solar energy • At least 80 % of electricity consumption covered by renewable energies
2038	• Phasing out the use of coal in electricity generation
2050	• Both electricity supply and electricity consumption carbon-neutral before 2050 • Renewable energy use to rise to 60 % of gross energy consumption • Reduction of 50 % in the primary energy consumption compared to 2008

Table 3 German energy transition targets

2.1.3 FR Policies

The 2019 Energy and Climate Law legislated carbon neutrality by 2050 and a tighter emissions reduction pathway. In 2020, the government updated the National Low-Carbon Strategy (Stratégie nationale bas-carbone, SNBC) and the Multiannual Energy Program (Programmation pluriannuelle de l'énergie, PPE) towards the goal of carbon neutrality by 2050 (Ref. [29]). In addition, France adopted an energy and climate planning law in 2019 to increase the share of renewables to 33% by 2030 (Ref. [30]).

In 2018, the Renewable Energy Directive (RED) set a target of 32.5% of the gross final energy consumption for 2030. However, because of the disruption caused by the COVID crisis, climate change, and the geopolitical situation, EU lawmakers have agreed on an increased overall target of 42.5% (Ref. [30]). Several EU member states were in favour of a 45% target. So did France, but on condition that low-carbon energies could participate in achieving this objective (Ref. [30]). The summary of the French energy targets is presented in Table 4 (Ref. [1]).

French energy targets	
2030	• Increase the share of renewables to 33% • 42.5% gross final energy consumption
2040	• 33% of produced electricity and heat from renewable energy sources • +50% of electricity generated by emission-free units
2050	• Carbon neutrality • 85% emissions reduction compared to 1990 levels

Table 4 French energy targets

2.1.4 UK Policies

In 2019, the UK became the first major economy to adopt a legally binding obligation to reach net zero greenhouse gas emissions by 2050 (Ref. [1]). Between 1990 and 2018, economy-wide emissions fell by 43 % while Gross Domestic Product (GDP) rose by 75 %, with the UK decarbonising faster than any other G20 country since 2000. Nowadays more than 50% of the UK's power comes from low-carbon technologies (Ref. [32]). Beyond Nuclear Power Plants, UK aims to build a commercially viable fusion power plant by 2040. The summary of the UK energy targets is presented in Table 5 (Ref. [1],[32]).

UK energy targets	
2030	• 40 GW of offshore wind • 1 GW floating offshore wind
2040	• Commercially viable fusion power plant
2050	• Net zero greenhouse gas emissions

Table 5 UK energy targets

2.2 Power system characteristics: European Features

A power system is a complex system interconnecting power generators, networks (transmission and distribution) and consumers, where the primary goal is delivering electricity to consumers in real time. The electricity system Europe-wide 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 and smart appliances (Ref. [2]). All these factors are driving the transformation of the European power system.

The power generation is described in section 2.2.1, the power demand in section 2.2.2 and the power grid characteristics are presented in section 2.2.4.

2.2.1 Power Generation

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 is very different from one country to the other. Hydropower will continue contributing to the energy mix in the future, however, given the limitations on natural resources (e.g. rivers channelled between hills), future development may go towards small scale projects and the modernization of existing installations. Thus, solar panels and wind farms will be the two major actors in VRE.

Three main facts make solar panels and wind farms technologies to differ from conventional power plants Ref. [2]:

- Fuel (i.e. wind and solar radiation) cannot be directly stored, which in centralised, dispatchable Power Plants acts as a large, long-term storage contributing to the resilience of the system.
- They are connected either to the distribution or to the transmission networks through power electronics not able to provide the same inertia response as synchronous generators in the case of system disturbances. In contrast to conventional power plants which are directly connected to high-voltage transmission lines via synchronous, rotating alternator that contributes to the stability of the system.
- VRE integration reduces baseload generation and increases the peaking plants used as backup. New VRE capacity does not replace conventional plants with 1:1 ratio due to both a low-capacity factor and of the high dependence on atmospheric conditions. The ratio is closer to 1:7 (i.e. 100 MW of conventional capacity replaced by 700 MW of newly connected VRE sources, according to Ref. [2], for the European grid, with 60% of VRE sources and an additive of 100 MW of wind turbines).

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The characteristics of power plants related to the power grid connection are provided in Table 6.

	AC/DC	Power Generator	Connection to the grid	Power Generation
Solar Farms	DC	power electronics	Connection to Medium Voltage Lines	Non distpachable
Wind Farms	AC	power electronics	Connection to Medium Voltage Lines	Non distpachable
Biomass	AC	synchronous generator, rotating alternator	Connection to Medium/High Voltage Lines	Distpachable
Hydroelectric	AC	synchronous generator, rotating alternator	Connection to High Voltage Lines	Distpachable
Nuclear	AC	synchronous generator, rotating alternator	Connection to High Voltage Lines	Distpachable
Coal	AC	synchronous generator, rotating alternator	Connection to High Voltage Lines	Distpachable
Combined Cycle Gas (CCG) PP	AC	synchronous generator, rotating alternator	Connection to High Voltage Lines	Distpachable

Table 6 Characteristics of Power Plants related to the power grid

2.2.2 Power Demand

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 (electric vehicles) 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. Although the impact of Battery Electric Vehicle (BEVs) on the electricity grid stays still unclear, the flexibility in BEV charging timing and the potential of BEVs for energy storage may contribute to improving grid stability issues (Ref. [2]).

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.

2.2.3 Power Modulators

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, thermal energy storage systems, hydro pumping stations, compressed air systems, hydrogen production, flywheels, etc. Figure 1 shows the comparison of energy storage systems by duration characteristics (taken from Ref. [2]).

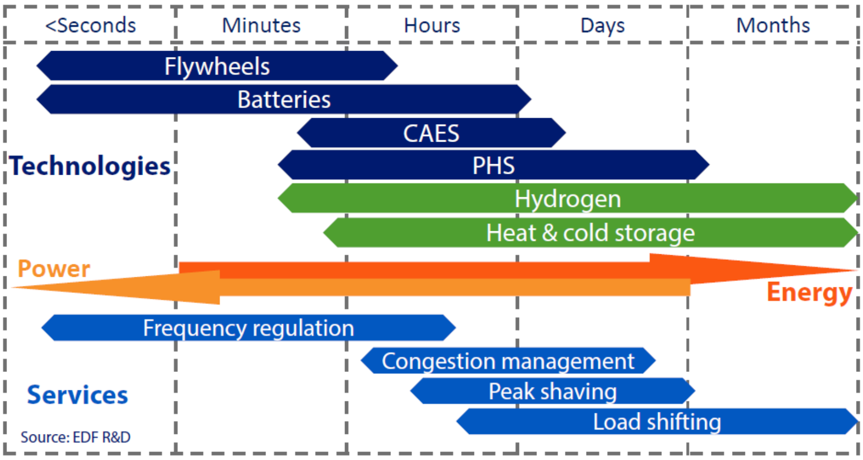

Figure 1 Comparison of energy storage systems by duration characteristics (taken from Ref. [2])

Type of storage	Round-trip efficiency	Timescale of storage	Power capital cost (USD/kW)	Energy capital cost (USD/kWh)	Maturity
Hydrogen	30%-40% power to power	Hours to weeks	Med-high	Low	Medium
Pumped storage	75-80%	Hours to days	Medium	Low	High
Lithium-ion battery	~85%	1 hour to 4 hours	Med	Med	Med-high
Redox flow battery	~70%	~10 hours	Med-high	Low-med	Medium
Flywheel	90%	~1 minute	Low	Med-high	High

Table 7 Characteristics of energy storage systems (Ref. [2])

There are several technologies well-suited to electricity storage (see Table 7), namely (Ref. [2]):

- Pumped hydro storage (PHS) provides daily and weekly load following capability in order to maintain balance between supply and demand, as well as to provide reserves for the power system. Pumped storage is already widely deployed in many countries, but it is likely to prove difficult to develop new sites since most of the suitable geological sites have already been exploited.
- Hydrogen storage is currently the only storage option to cover changes in energy demand over relatively long periods of time (i.e. weeks). It is considered relatively mature given the current commercial demands and some deployment in early trials of refuelling stations.
- Lithium-ion batteries provide short timescales storage therefore are being deployed to provide frequency response, guaranteeing system stability. Their price also has significantly decreased in recent years.
- Flywheels store energy in the form of rotational kinetic energy and offer very limited storage capacity but are a mature and well-established technology successfully used to minimise fluctuations associated with PV farms, as a small buffer during cloud cover.

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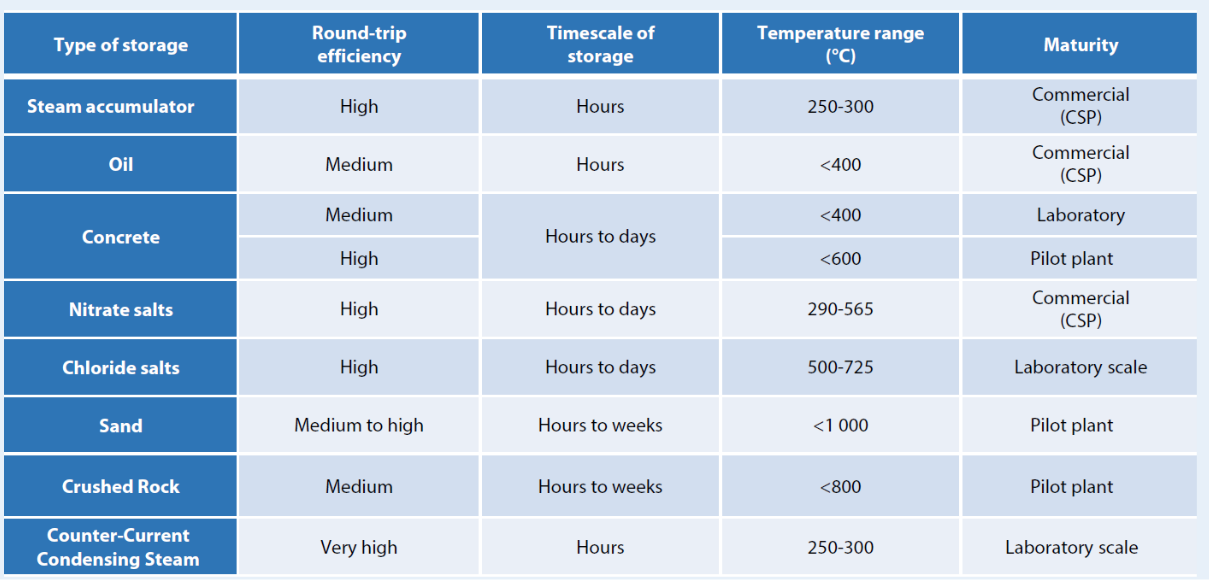
- Compressed Air Energy Storage (CAES) offers relatively short timescales storage and has few secondary service benefits. Its relatively low efficiency and high operation and maintenance costs are the major drawbacks.

Beyond electricity storage, other systems can store the excess of thermal energy and can be used hours, days or even months later. Given the high level of heat demand, and the need to decarbonise this demand, heat storage is likely to play an increasingly important role in the future. Actually thermal energy storage systems coupled with power plants (Ref. [2]) is under consideration in many new design, since it enables to control electricity generation according to the price fluctuation by storing heat from the heat source (reactor, boiler, etc.) and sending stored heat to the generator. Heat storage technologies can be applicable to all heat generating technologies, such as concentrated solar power (CSP), nuclear power and geothermal energy. Multi-gigawatt-hour-scale storage using nitrate salt as a storage material have already been equipped in utility-scale CSP systems in order to avoid selling electricity at times of low prices and enable the sale of electricity at higher prices. In the same way, if applicable, heat storage technology has a potential to enhance the flexibility and profitability of nuclear power plants. Table 8 shows the characteristics of various heat storage systems.



Type of storage	Round-trip efficiency	Timescale of storage	Temperature range (°C)	Maturity
Steam accumulator	High	Hours	250-300	Commercial (CSP)
Oil	Medium	Hours	<400	Commercial (CSP)
Concrete	Medium	Hours to days	<400	Laboratory
	High		<600	Pilot plant
Nitrate salts	High	Hours to days	290-565	Commercial (CSP)
Chloride salts	High	Hours to days	500-725	Laboratory scale
Sand	Medium to high	Hours to weeks	<1 000	Pilot plant
Crushed Rock	Medium	Hours to weeks	<800	Pilot plant
Counter-Current Condensing Steam	Very high	Hours	250-300	Laboratory scale

Table 8 Characteristics of heat storage systems (taken from Ref. [2])

Other systems, worth to mention, modulating the power generation and demand interface are the synthetic fuel production or the so-called power-to-X systems, where conversion technologies decouple power from the electricity sector for use in other sectors, for example the production of hydrogen through water-splitting using electricity from VRE sources, or the production of other kinds of liquid fuels and chemical materials via the processing of the hydrogen produced.(Ref. [2]).

2.2.4 Power Grid

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 ensures cost optimisation, making room for baseload plants and thereby reducing the overall price paid by consumers (Ref. [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 (Ref. [2]).

Currently the Electricity in EU looks like shown in Figure 2 (Ref. [5]).The different synchronous zones of the European power system are indicated with different colours. Whereas the Continental European grid is the largest subnetwork, Ireland, the United Kingdom, Scandinavia (with only parts of Denmark), and the Baltic region have their own synchronous zones. These areas are interconnected via DC lines (dark green).

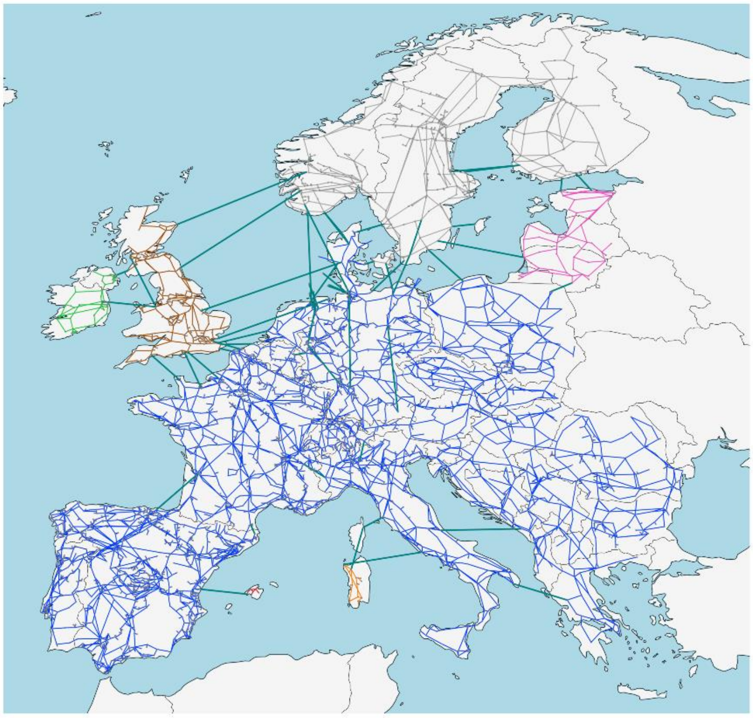


Figure 2 The different synchronous zones of the European power system (Ref. [5])

Figure 3 shows also the different synchronous zones of the European power system (Ref. [6]) as provided by ENTSO-E, the European Network of Transmission System Operators for Electricity, which is the association for the cooperation of the European transmission system operators (TSOs).

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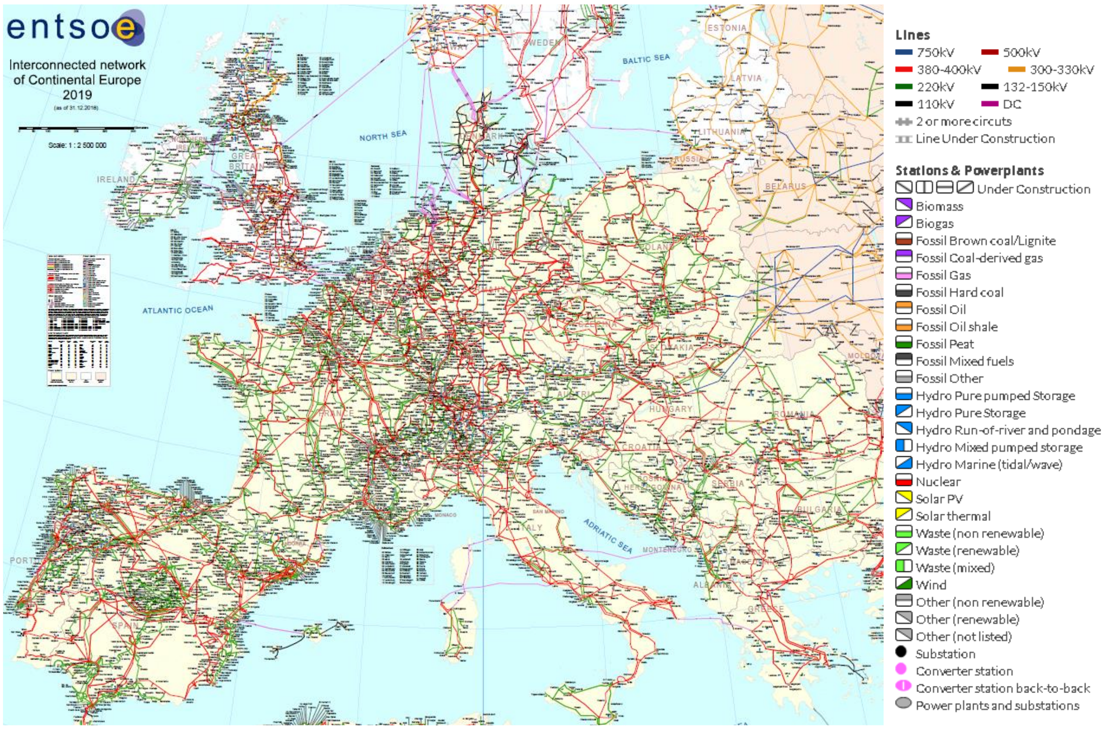

Figure 3 The different synchronous zones of the European power system (Ref. [6])

Looking into the future, other aspects of the power grid will play a significant role, such as the Smart grids and the high voltage direct current (HVDC) grids. Starting from the latter, although power grids were first developed in the early 20th century with alternating current (due to high-voltage operation requirements), today it is possible to operate high-voltage grids using direct current. This helps to avoid loss of energy coming from flow direction changes in the case of alternating current. Therefore, the HVDC transmission is an alternative to AC-technology. Up to now, HVDC is mainly applied to transmit electricity via sea cable in West Europe (Ref. [11]), but the European Commission is supporting new developments in this area thanks to research projects such as HVDC-WISE project, supported by the Horizon Europe program, to develop a toolkit for grid developers to evaluate the grid's performance under extreme conditions and to plan systems in a way that realizes the full range of potential benefits from deep integration of HVDC technology into the European transmission system (Ref. [13]). The project runs from 2022 to 2026.

Regarding future smart grids, the electricity network system could be better managed, have a more efficient consumption while maintaining the stability by optimising the electricity flow from both supply and demand sides thanks to digital technologies (Ref. [2][21]). Smart grids are energy networks that can automatically monitor energy flows and adjust to changes in energy supply and demand accordingly. When coupled with smart metering systems, smart grids reach consumers and suppliers by providing information on real-time consumption. Additionally, smart grids enhance the possibility for consumers producing their own energy to respond to prices and sell excess amounts back to the grid (Ref. [21]). All this will be possible thanks to the smart metering system which is an electronic system capable of measuring electricity fed into the grid, or electricity consumed from the grid, providing more information than conventional meters and being able of transmitting and receiving data for information, monitoring and control purpose, using a form of electronic communication. Smart meters can provide close to real time feedback on energy consumption.

Smart meters need a secure smart data network to automatically and wirelessly send meter readings to energy suppliers, enable remote filling of balances for pre-payment customers and near real time energy consumption and expenditure to be visible to domestic energy consumers (Ref. [32]).

2.3 Power mix to get the net-zero target

In order to achieve the energy targets as presented in section 2.1, 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 9) varies very much among the various types of electricity generation. Figure 4 shows the GHG emissions from electricity generation (taken from Ref. [2]).

Fuel	CO_2 intensity of electricity generation (gCO_2eq/kWh)
Coal	820
Natural Gas	490
Biomass	230
Solar	48
Nuclear	12
Wind	12
Hydro	24

Table 9: CO_2 intensity of electricity generation (gCO_2eq/kWh) (REF. [1])

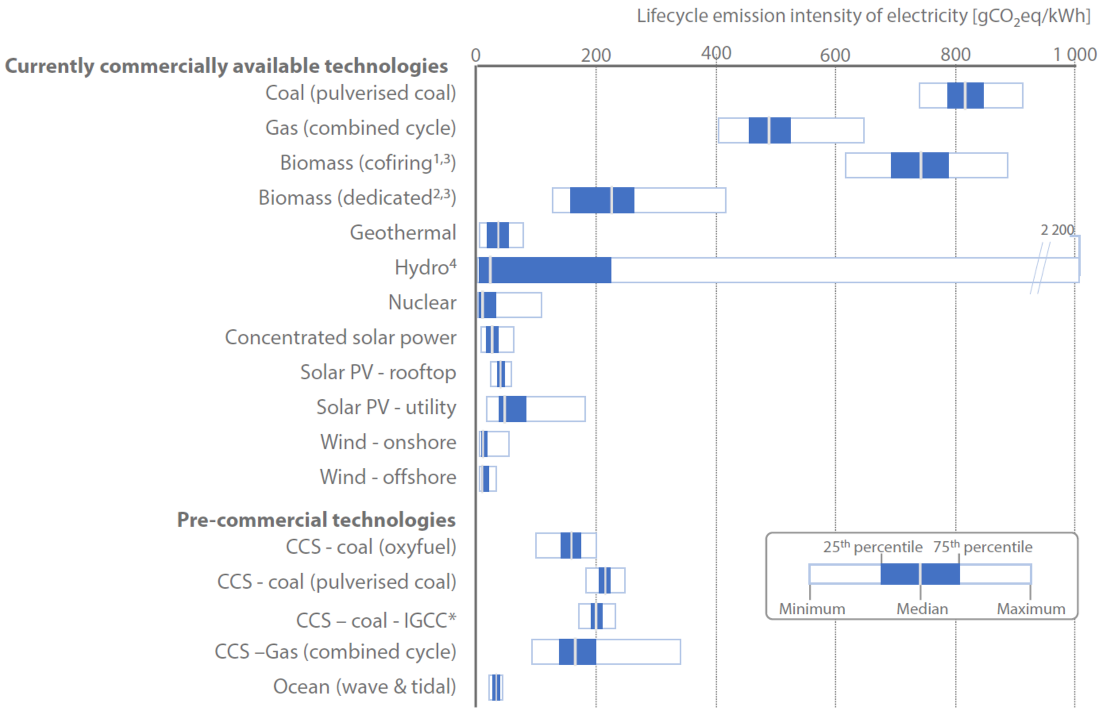

Figure 4 GHG emissions from electricity generation (taken from Ref. [2])

Therefore, considering the conclusions of the previous sections, the possible energy mixes able to achieve net-zero are rather limited where the two pillars for decarbonising the power system are renewables along with low-carbon, dispatchable energy sources. If low-carbon dispatchable energy sources as NPP 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 (CCUS) (Ref. [2]) which currently do not reach the highest Technology Readiness Level (TRL) as low-carbon, dispatchable energy sources.

Depending on the VRE integration, the power system needs different timescales flexibility. Table 10 shows the power system flexibility needs depending on VRE integration. For low VRE integration, conventional plants are necessary to balance supply and demand when VRE sources are not available, and to adjust an increasing net demand (total demand minus VRE production) variability. On the contrary, for larger VRE penetration, both increasingly longer timescales and shorter timescales are needed for periods when wind and solar are not available, as well as for frequency response and ramping, respectively (Ref. [2]). For the targeted VRE integration levels, seasonal displacements of generation are needed, and low-carbon generation, such as nuclear and hydro, as well as seasonal storage, e.g. synthetic fuels such as hydrogen, allows a shift in the generation to times when VRE sources are not available.

VRE integration	Timescale Flexibility Needed	Cause / Impact
Low	Short timescales (min. to hours)	VRE sources not available Impact on net load
Medium	Short timescales (min. to hours)	Frequency response and ramping
	Medium timescales (hours to days)	VRE sources not available
Larger	Ultra-short timescales (second)	Short-term stability problems
	Medium timescales (hours to days)	VRE sources not available
	Long timescales (days to months)	VRE sources not available
Final stage	Seasonal	VRE sources not available

Table 10: Grid flexibility depending on VRE integration

3 Methods for providing stability of the grid

3.1 Grid stability and power balance

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
- Voltage Stability

3.1.1 Frequency 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 (Ref. [37]). 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 (Ref. [37][38]). Large deviations of the frequency away from the reference are to be avoided as they require decisive control actions and cause high costs (Ref. [37][39]). Table 11 shows the types and characteristics of frequency control operations (Ref. [38]).

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 several seconds to several minutes); restores the exact frequency by calculating an average frequency deviation over a period of time.
Tertiary frequency control	Slower control than primary and secondary frequency control. It sets reference power values to individual power units for a network optimal dispatch.

Table 11 Types and characteristics of Frequency Control operations

3.1.2 Voltage stability

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 (Ref. [36]). Once a generator is synchronized to the power grid, the active power of the generator can be controlled through the shaft torque, while the reactive power can be controlled by the field current. VRE do not have, however, the ability to supply or absorb reactive power, Therefore the large VRE integration stresses the problem of maintaining voltage stability.

Currently, most commercial photovoltaic (PV) inverters operate as grid-following (GFL) sources regulating the power output by measuring the grid voltage angle using a phase-locked loop. Hence, they merely follow the grid angle/frequency but do not actively control their frequency output. In contrast, a grid-forming (GFM) source actively controls its frequency and

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voltage output and has been extensively used in microgrid configurations. However, power electronics inverters have typically much smaller power ratings compared to synchronous machines, thus the system load of inverter-based infrastructure must be satisfied with a much larger number of inverters. For large power grids, this translates into the need to install millions of inverter interface variable renewable energy (VRE) units over a large geographical area (Ref. [36]).

3.2 Grid Stability methods

Various methods are normally used to provide stability and support the power grid. These include:

- Flexible power operation of power plants
- Fast frequency response technologies
- Kinetic energy supply systems
- Energy storage systems

3.2.1 Flexible Power Operation (FPO)

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 not implying a large increase in power generation costs. This is the case of load-following operations adjusting the output of the existing large-capacity thermal power plant or nuclear power plant according to the increase or decrease in the load is required.

FPO is the term used to describe any plant operation mode in which the electric power output is modified, either manually or remotely, in response to electrical grid demands. Due to the different kind of need requested by the power grid (Ref. [9][40]), the following operational modes are foreseen for FPOs (see Figure 5):

1. **Frequency control operation:** to control the frequency of the grid within a set of predefined conditions as directed by the Independent System Operator (ISO). It can include:

a. **Primary control** (frequency response): to stabilize grid frequency transients.

b. **Secondary control:** to restore grid frequency to the scheduled value following grid frequency transients.

2. **Load:** predefined power programmes to adjust grid power production to match expected demand, i.e. reductions or increases in power output agreed in advance with the TSO) to counterbalance electricity supply and demand. These power manoeuvres can occur as:

a. **Planned power manoeuvres** based on expected grid generation and demand variations due to the time of day, day of the week, and season.

b. **Short term requests** from the grid operator to manually adjust the plant power levels based on grid congestion or other grid events in accordance with the established protocols.

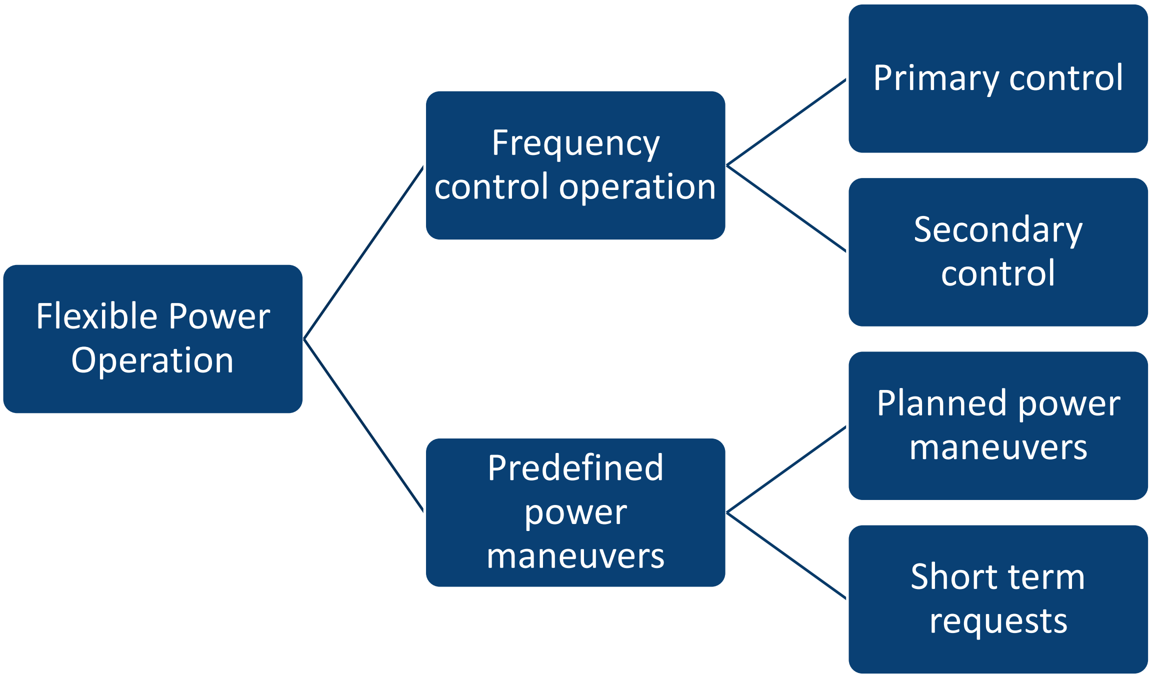

Figure 5 Operational modes foreseen for FPOs

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 (see Figure 6, Ref. [15]). The variation in the frequency, Δf requires a change in the power of:

$$\frac{\Delta P}{P_0} = \frac{1}{s}\frac{\Delta f}{f_0} \rightarrow \Delta P = k\Delta f,\ with\ k = \frac{1}{s}\frac{P_0}{f_0}$$

where f_0 is the target frequency, e.g., 50 Hz in Europe, P_0 is the power level of the plant (as a % of the rated power, P_r), Δp is the power change, and s is the droop measured in % (Ref. [36]).

The primary frequency control is also called governor-free (GF) control and provide short-term adjustment in the 2-30 s timeframe after deviations in power generation and demand are observed. Conventional power plants monitor the frequency on the grid and immediately adapt their production in order to keep the frequency stable at the desired value.

The secondary frequency control method operates in longer time units (e.g., seconds to minutes) and calculates the average frequency deviation over a period of time to restore the rated frequency. The secondary frequency control is also called Automatic Generation Control (AGC), In AGC mode, the transmission system operator (TSO) gives control commands to the generator. Generally, this secondary control is important when the international grids are interconnected (Ref. [15][36]

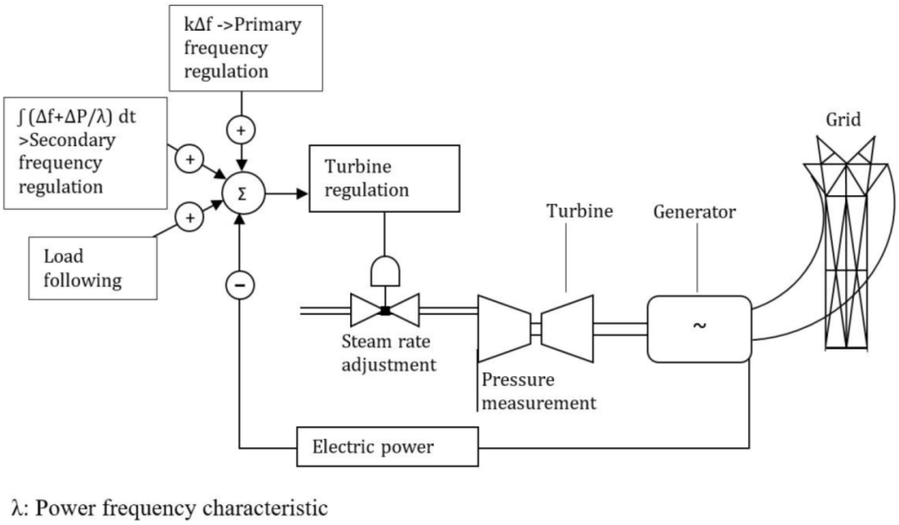

Figure 6: Frequency control in a power plant (taken from Ref. [36])

3.2.2 Other grid stabilizers

Fast frequency response technologies prevent frequency interference in the power grid by injecting power, or reducing the load in less than a minute in response to a system frequency disturbance. They often consist of large-scale batteries (Ref. [2]).

Kinetic energy supply systems provide inertia to the power grid in order to absorb fluctuations in power supply and demand and stabilise the frequency. They often consist of systems such as flywheels (Ref. [2]).

Energy storage systems are also important to balance the system in the face of fluctuations in generation from VRE sources and fluctuations in demand (Ref. [2]). They were explained in section 2.2.3.

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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 (Ref. [2]).

Utilities in Europe (Ref. [48]) and the United States (Ref. [9]) have issued requirements for generation III reactors (Ref. [10] [8]) and future light water reactors (LWRs) to ensure that new nuclear power plants 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 (Ref. [2]).

For defining the FPO Operational Performance, it is needed to establish the plant's ability to vary power output in response to grid demand using the following four parameters (Ref. [9]):

- Rate: The rate at which a plant can change power levels over time.
- Depth: The extent (% of full power) of a power reduction a plant can make while still having the capability to return to the initial power level.
- Duration: The length of time that a plant will maintain a given power level.
- Frequency: The frequency of significant changes to a plant's power levels.

Since both EUR and EPRI requirements are not openly available, the main requirements have been collected from secondary references such as Refs. [2][8][9][10][15][36][48][50][60].

4.1 European Requirements

The EUR Association aims at contributing to safe, competitive, and licensable nuclear new build projects in Europe through harmonised requirements and assessments of future Nuclear Power Plant designs, and strong interactions with vendors and regulatory bodies (Ref.[48]). They aim at ensuring the compliance with the safety and technical requirements established by national nuclear authorities, and to facilitate NPP vendors and designs to enter the European market by making the design requirements harmonised and more transparent (Ref.[48]). The strategic objectives of the EUR Association are:

1. To develop and regularly update the "EUR Document" for the design of new Light Water Reactor of NPPs, including SMRs.
2. On request of designers or vendors of nuclear power plants, to perform the detailed assessment of their designs against the EUR Document.
3. To be a recognised actor in discussions with other important external stakeholders in Europe and worldwide, about the design of new NPPs and harmonisation of utility requirements.

The EUR document is a NPP specification written by a group of the potential investors in electricity generation in Europe. The primary objective was to give a common frame to the development of next generation LWR NPPs, so as to allow the emergence of several standardised LWR designs that would be well fitted to the European utility future needs and that could be proposed throughout Europe without any major design change.

The EUR cover a wide range of conditions for NPP to operate efficiently and safely [15]. 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 as follows (see also Table 12, Refs. [60][36][2][40]):

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- Continuous operation between 50% and 100% of rated power (P_r), with a rate of change of electric output of 3-5% of P_r per minute.
- The standard plant design shall allow the implementation of scheduled and unscheduled load-following operation during 90% of the entire fuel cycle.
- The unit may be required to participate in emergency load variations, with a rate of change of 20% of P_r per minute (decreasing) and of 1-5% of P_r per minute (increasing).
- The unit shall be capable of taking part in the primary control of the grid, with a minimum range of ±2% of the rated power P_r, but values up to ±5% of P_r are recommended.
- The unit shall be able to contribute to grid restoration; and the unit should be capable of withstanding sudden load steps of up to 10% of P_r.
- The standard plant design shall allow the implementation of a secondary control (optional).
- The minimum control range for secondary control operation shall be ±10% of P_r, with a variation rate of 1% of P_r per minute. Higher values could be achieved, though not higher than 5% of P_r per minute (IEA, 2018).

EUR Requirements	Parameter
Continuous operation (mandatory)	50%-100% P_r with 3-5%/min. variation rate
Down to minimum (option)	20%
Primary control (mandatory)	±2% P_r/min
Primary control (recommended)	± 5% P_r/min
Activating total primary range of control requested	within 30 s
Secondary control (option) ~seconds to ~minutes	±10%
Support grid restoration with sudden load steps of up to	10% of P_r.
Secondary control (optional)	±10% of P_r, with a variation rate of 1% of P_r /min.
Load-following capability until ( ) % of whole fuel cycle	90%
Full power to minimum load variations and back to full power operation	2 per day 5 per week Cumulatively 200 per year
Emergency load variation (agreement grid operator and unit operator)	20% P_r / min. (decreasing) 1-5% P_r / minute (increasing)

Table 12: Power Margins of European Light Water Reactor NPPs (Ref. [36])

4.2 US Requirements

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 Ref. [50].

For existing NPPs transitioning from base-load operations to FPO URD requires modifications to support FPO (Ref. [9]). The EPRI Requirements for LWRs and for SMRs are presented in Table 13 showing the load-following characteristics included in EPRI URD specifications (Ref. [50]).

	As in Rev. 12	As in Rev. 13 (SMR)
Daily load cycles	100% → 50% → 100 %	100% → 20% → 100 %
Ramp rate	25 % per hour	40 % per hour
Automatic frequency response	compulsory	compulsory
Step change in 10 min.	20 %	20 %
Frequency variation tolerance	compulsory	compulsory

Table 13 Load-following characteristics included in EPRI URD specifications (Ref. [50])

The EPRI's flexibility criteria consists of not only the operational flexibility (see Figure 7), but also on (Ref. [2]):

- Deployment flexibility: licensing, financing, building, etc.
- Product flexibility: non-electrical applications e.g. district heating, industrial steam, water desalination, etc.)
- Hybrid systems: new outlets to compensate for low load factors integrating various energy inputs and producing various products while hosting various energy storage systems, and various production facilities using thermal and/or electrical energies.
- Diversified fuel use: ability to operate using a variety of fuel designs, fuel structural materials (e.g. cladding) and fuel compositions
- Island mode operation: ability to operate in isolation from local, regional or national electricity distribution networks, either on a routine or exceptional basis.

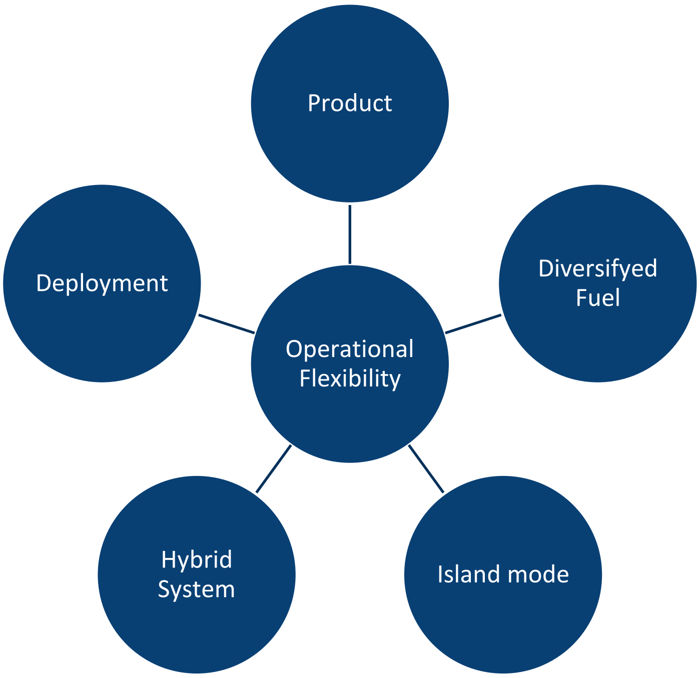

Figure 7 Flexibility features of advance Nuclear Systems according to EPRI

Although the flexibility attributes other than operational are not of much interest for the purpose of this deliverable, which is mainly focused on the interaction between NPP and the power grid, however they are also worth to mention.

4.3 Operational performance

It is of interest to know how the conventional power plants (section 4.3.1), the Nuclear Power Plants (section 4.3.2), as well as the Advanced Nuclear Reactor Systems (sections 4.3.3 and 4.3.4) address the operational flexibility needed to support the grid request and stability.

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4.3.1 Conventional Power Plants

Power plants currently in operation are able to provide the necessary flexible backups in the short term. Table 14 shows the flexibility of conventional power generation technologies (Ref. [36][61]).

Description	Nuclear Power Plants	Hard coal-fired Power Plants	Ignited-fire Power Plants	Combined-cycle Gas-fired Power Plants	Pumped storage Power Plants
Start-up Time “Cold”	~40 h	~6 h	~10 h	<2 h	~0.1 h
Start-up Time “warm”	~40 h	~3 h	~6 h	<1.5 h	~0.1 h
Load Gradient (up) ”nominal output”	~5%/min.	~2%/min.	~2%/min.	~4%/min.	>40%/min.
Load Gradient (down) ”nominal output”	~5%/min.	~2%/min.	~2%/min.	~4%/min.	>40%/min.
Minimal Shutdown Time	No	No	No	No	~10 h
Minimal Possible Load	50%	40%	40%	<50%	~15%

Table 14: Flexibility of Conventional Power Generation Technologies as considered in Ref. [36]

4.3.2 Nuclear Power Plants

So far, large-scale nuclear power plants operated at maximum output (base load) in principle. This is because the capital cost is high and the fuel cost is low. Therefore, the nuclear power plants should be operated at the highest safely achievable power. However, France, which has a high proportion of nuclear power, is known to operate a load-following operation, and in recent years, as the share of renewable energy, which is an intermittent power source, has increased, the load following of nuclear power plants has emerged as an important concern. There are two ways to regulate the thermal output of nuclear power plants. The first is a primary loop control method for controlling the fuel rod (reactor following turbine), and the second is a method for controlling the amount of main steam supplied to the turbine (turbine following reactor) (Ref. [36])

For the primary frequency control, power modulations are performed within ±2% P_r in French nuclear power plants. While for secondary frequency control, the NPP modifies the power level within a range between ±5% P_r (Ref. [40]).

Table 15 shows the load-following capabilities of French and German power plants.

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French NPP	German KONVOI NPP
daily power variations by several tens of per cent of rated power P_r	15,000 cycles with daily power variations from 100% P_r to 60% P_r,
	100,000 cycles with power variations from 100% P_r to 80% P_r

Table 15 Load-following capabilities of French and German power plants (Ref. [40])

From operating experience, the common capabilities that are currently included in design and utilized in some nuclear power plant operations include the following (Ref. [14][15]):

- A power (load) cycle between 100% and 20% rated thermal power (RTP), sometimes on a daily basis;
- A power (load) cycle over a smaller range more frequently, or over a larger range less frequently;
- When power cycling, a ramp rate of 2% RTP per minute;
- Power adjustments of up to ±5% RTP, in the Automatic Generation Control (AGC) mode;
- Power adjustments of up to ±2% RTP within 30 seconds in the Automatic Frequency Control (AFC) mode;
- No flexibility at certain times, such as during fuel conditioning or at the end of a cycle (in PWRs);
- A minimum power for extended low power operations of 20–40% RTP.

Figure 8 shows the flexible operation limits during a fuel cycle in French PWR (Ref. [14]).

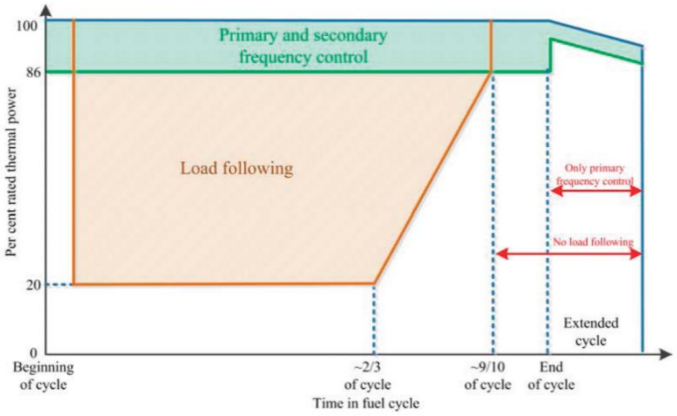

Figure 8 Flexible operation limits during a fuel cycle in French PWR (taken from Ref. [14])

German Konvoi reactors were designed for 15,000 cycles with daily power variations from 100% P_r to 60% P_r, and 100,000 cycles with power variations from 100% P_r to 80% P_r (Ref. [40]). In Germany, nuclear power plants were required to operate in load following mode because of the large share (~31%) of variable renewable resources. KWU/Siemens nuclear power plants have integrated enhanced load-following capabilities at the design stage, which allows them to conduct these operations throughout the fuel cycle and with higher ramp rates (up to 140 MW/min in Konvoi reactors). Before the nuclear phase-out, NPPs in Germany increased their flexible operations in response to the increasing penetration of renewables in the country (Ref. [2]).

Figure 9 shows a German PWR flexibility scheme considered in the design phase of Konvoi technology. The blue lines show the grid requirements at the time (1992) that were considered in the safety analysis and in establishing the design limits (red lines) for flexible operation. The

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operational limits (green lines), which were reviewed and approved by the regulatory body, and the grid requirements (blue lines) were confirmed and qualified during commissioning. The commissioning tests demonstrated that the design was proven to allow for load change performance up to the design criteria (red lines) (i.e. 10% rated thermal power (RTP)/min in a power range of 100–20% RTP, with a 5 minute pause between power down and power up manoeuvres). The test also demonstrated that the flexibility capability according to the licensed operational manual limits (i.e. operational limits and conditions) was met, and at the same time, the existing grid requirements were fulfilled. Finally, the blue shaded area represents the planned range of load following and frequency operation by German PWRs to meet the grid needs at the time (Ref. [14]). The design also provided a substantial margin at each power level over the operational limits approved by the regulatory body.

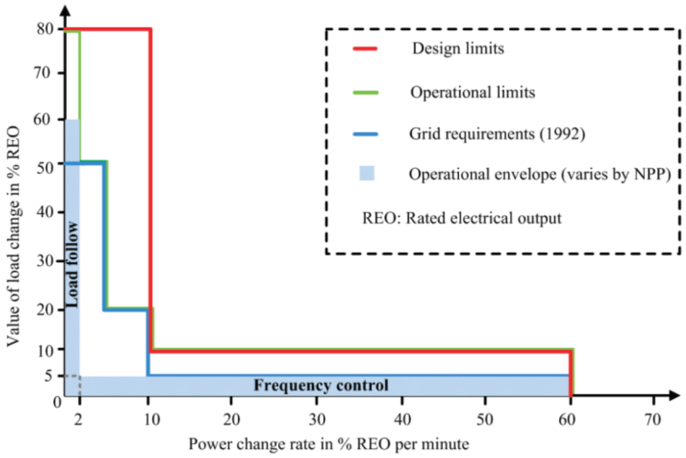

Figure 9 German PWR flexibility requirements and design capabilities (taken from Ref. [14])

Table 16 shows some of the key features of the German nuclear power plant design for flexible operation. These design features have been incorporated into the design since the early years of the operation, when flexible operation was not expected (Ref. [36]).

Response Base	Response Mode	Parameter and Properties
Predicted daily demand variations	Load following	Low-power period (power level and duration) Power change rate (slow, fast) Time in cycle (beginning, end)
Spontaneous limited demand variations	Frequency control	Local frequency control: frequency deviation (ΔF) converted into power change (ΔP) (ΔP amplitude, slope of change) Remote frequency control: signal from the dispatcher (ΔP amplitude, slope of change) Superimposition of local and remote frequency control
Grid disturbances	Spinning reserve	Ramp (amplitude, slope, from minimum power level) Steps (amplitude, from minimum power level) House load capability (loss of off-site power without reactor trip) Fast (e.g., 5% rated thermal power/minute) return to full power without advance notice
Longer-term forecasted demand	Extended low-power operation	Reduced power level during extended period (number of occurrences, duration)

Table 16: Design Philosophy for Flexible Operation in German Light Water Reactor (Ref. [36])

In the United States, Nuclear Regulatory Commission (NRC) regulations prohibit NPP systems from interfacing with the grid control system; however, they do allow for pre-planned changes by a licensed reactor operator within safety limits. Current nuclear fleet experience is, therefore, limited to seasonal pre-planned power level changes (Carl and Fedor, 2017). The EPRI has a programme on flexible operations and is conducting studies to support US utilities, with assessment tools for transition from baseload to flexible power operation (Ziebell, 2017) (Ref. [2])

Not only LWR are able to performe load-following operation. CANDU nuclear power plants may also adjust their power level for seasonality (Ref. [2]) and Russian designed pressurised water reactors (VVER-10001) are capable of achieving ramp up rates of ±3-4% per minute with 70% of the fuel cycle, and ±1-1.5% per minute thereafter (Ref. [2])

As for the Power Output Control (Ref. [9]), the electrical power output of an NPP is varied by changing the mass flow rate of steam that enters the turbine, which may be accomplished in one or both of the following ways:

- Change reactor power and steam production by the Nuclear Steam Supply System (NSSS)
- Divert a portion of steam produced by the NSSS away from the turbines.

Manipulating reactor core thermal power is an effective method to change electrical output, but changing reactor power has significant effects on the core burnup rate, core lifetime, xenon transients, thermal limit concerns, flux distributions, and core response to transients.

Table 17 shows the Power Output Control Methods (Ref. [9])

	Power Output Control Method
Implementation	**In BWR:** • Control Rods • Recirculation Pump Control • Turbine Steam Bypass • Grey/Partial Worth Control Rods **In CANDU:** • Control Rods • Adjuster Rods • Zone Control Tubes • Turbine Steam Bypass **In PWR:** • Control Rods • Boric Acid Reactivity Control • Turbine Steam Bypass • Grey/Partial Worth Control Rods
Effects	• More frequent reactor power changes • Potential need for more precise reactivity control • Potential need for changing the rate of reactivity and power control
Potential Issues	• Systems not typically optimized for less than 100% power • Systems may not be designed for frequent reactivity changes • Systems may not be designed or optimized for fine control at less than 100% power

Table 17 Power Output Control Method Ref. [9]

4.3.3 Gen III+

The minimum requirements for the manoeuvrability capabilities of modern Generation III/III+ reactors are defined by the utility requirements (see sections 4.1 and 4.2, for EUR and EPRI requirements, respectively) which are based on the requirements of the grid operators.

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% P_r/minute. 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 (Ref. [40]).

4.3.4 SMR

SMRs are usually based on proven water-cooled reactors similar to currently operating NPP reactors, but on a smaller scale. Collecting information openly available for SMRs, Table 18 shows the main characteristics and load-following manoeuvring performance of those SMR designs, where the manoeuvring capabilities are numerically described in the literature.

Name	Power (MWe)	Reactor System	Designer	Status	Manoeuvring
Xe-100 Ref. [49]	82.5	HTGR	X-Energy LLC USA	Basic Design	100%-40%-100%
SMR-LWR Ref. [49]	225	LWR	Westinghouse, USA		daily 100%-20% at a rate of 5%/min. load changes ±10% power at a rate of 2%/min.
Nuscale Ref. [50]			USA		able to meet all of new EPRI Rev.13 URD
Fast Modular Reactor Ref. [49]	50	Helium FR	GA-Framatome		load-following of about 20%/min. ramping
Natrium Ref. [49]	345-500	SFR	GE Hitachi and Terrapower		plant output can vary between 30% and 150% of reactor power.
KARAT-100 Ref. [53]	100	BWR	NIKIET Russian Federation	Conceptual Design	daily power variation from 20% to 100% of nominal capacity
BWRX-300 Ref. [53]	270 – 290	BWR	GE-Hitachi Nuclear Energy, USA, Japan	Pre-licensing	load following range of 50 to 100% with a ramp rate of 0.5%/min.
GTHTR300 Ref. [53]	100 – 300	HTGR	JAEA Japan	Pre-licensing	electric demand increase of 5%/min with corresponding reduction in heat rate, which is the maximum required for ramp load follow.
PBMR-400 Ref. [53]	165	HTGR	PBMR SOC Ltd South Africa	Preliminary Design	reactivity control system facilitates load following between 40% and 100%
SVBR Ref. [53]	100	LMFR	JSC AKME Engineering Russian Federation	Detailed Design	load-follow operation in the range 100–50–100%
Westinghouse LFR Ref. [53]	450	LMFR	Westinghouse, USA	Conceptual Design	including a TES capable of providing load-levelling
Integral MSR Ref. [53]	195	MSR	Terrestrial Energy Inc. Canada	Conceptual Design	substantial load-following capability
ThorCon Ref. [53]	250	MSR	ThorCon International Consortium	Basic Design	load following capability
KLT-40S Ref. [53]	2 × 35	PWR (floating)	JSC Afrikantov OKBM Russian Federation	In Operation	10% - 100% continuous operation of 26,000 hours manoeuvring; speed of up to 0.1 %/s.
ABV-6E Ref. [53]	6-9	PWR (floating)	JSC Afrikantov OKBM Russian Federation	Final design	20–100% continuous operation of 26,000 hours. manoeuvring rate of up to 0.1%/s

Table 18 Characteristics of SMRs

The Natrium Reactor presents similar characteristics to ESFR-SMR concept. Therefore, it is described here in more details. The Natrium concept is the outcome of a collaboration between GE Hitachi and Terrapower. It is based on a PRISM reactor of 345 MWe and uses molten salt to store heat so that the output could be increased to about 500 MWe for up to five hours for load-following. The primary coolant is sodium, the secondary coolant is molten salt, which can store heat or use it to make steam in a heat exchanger, switching between the two as required so that plant output can vary between 30% and 150% of reactor power. It would “help customers capitalize on peaking opportunities driven by renewable energy fluctuations.” Natrium is part of the DOE Advanced Reactor Demonstration Program (ARDP) offering funds on a cost-share basis and in October 2020 was awarded an initial grant of $80 million. In October 2020 Bechtel joined the consortium to provide design, licensing, procurement and construction services to the project (Ref. [49]).

In June 2021 TerraPower announced plans to build a demonstration Natrium unit in Wyoming at a retired coal plant site. It plans to submit a construction permit application in 2023 and an operating licence application in 2026. The plant is expected to cost under $1 billion apart from financing (Ref. [49]). Figure 10 shows the layout of NATRIUM single unit site.

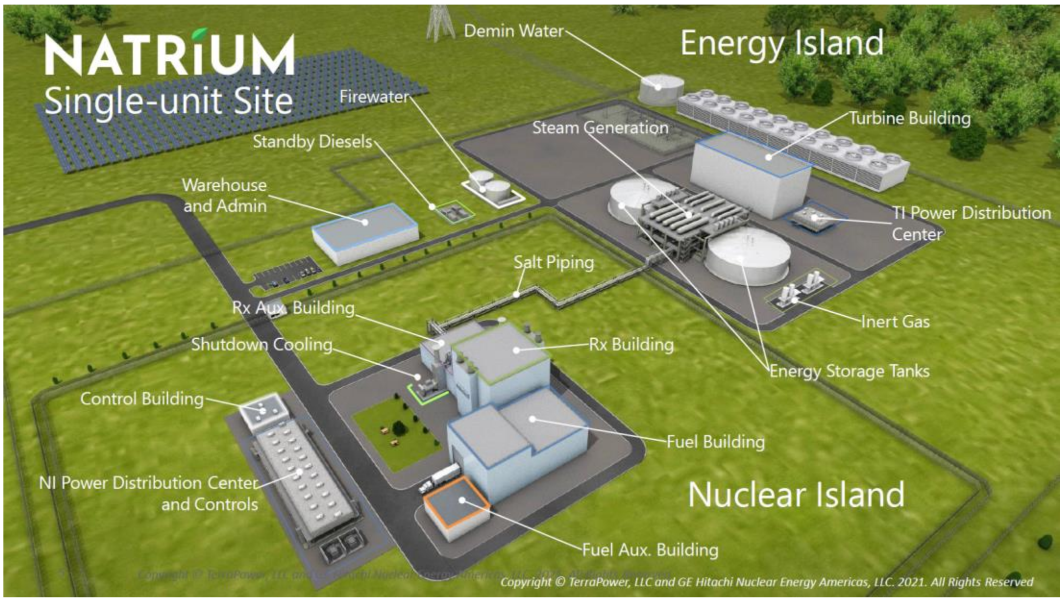

Figure 10 Layout of Natrium single unit site

4.3.5 Gen IV

4.3.5.1 SFRs

The Gen-IV reactor concepts that are dedicated to electricity production and have higher TRL, in particular SFRs, have already taken into account some operational flexibility aspects in their design. Nonetheless, none of the SFRs seem to be operated with a full grid frequency control and/or load following. In France, for instance, only the Phenix reactor has been operated with primary frequency control operation, as a passive control (i.e. no dedicated regulation) resulting from the natural coupling between the turbo-machinery rotating velocity and the grid frequency. There were challenges for the flexible operation of the early demonstration of SFRs, as well for the Superphenix SFR, as frequency control was unauthorised because of insufficient demonstration of the fuel behaviour under frequent power fluctuations associated with fuel cladding interaction concerns. Within the framework of the ASTRID project, predictive

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simulations have indicated that neutron power variations of a few percent would not induce any consequence for the fuel cladding interaction (Ref. [2]).

Load following is definitely the main challenge for pool-type SFRs since power variations induce thermal cycling on the non-replaceable emerged inner vessel as a result of changes in the level of the sodium free surface (i.e. the sodium/gas ceiling interface). This leads to its progressive deformation. For addressing this issue, designers are investigating the redesign of the inner vessel to avoid thermal gradients and the insertion of a backpressure to avoid changes in the level of the free surface. An alternative option under consideration is to maintain the reactor at full power, whatever the grid demand is, by storing excess energy or using it as a by-product (steam or electricity) for industrial processes (Ref. [2]).

4.3.5.2 HTGRs

HTGRs also have significant experience. HTGRs employ an all-ceramic fuel form with graphite acting as the neutron moderator and helium as the coolant. The materials and coolant used in HTGRs allow the reactor to operate at high temperatures, with most experience operating such systems at temperatures around 800°C (Ref. [2]).

The given historic operational experience with HTGR technology allows to demonstrate the power manoeuvrability characteristics of such a technology, particularly with respect to startup time after refuelling, operational ramp rates and minimum power levels. As for the minimum power levels, as commonly in many commercial NPPs and conventional (non-nuclear) power stations, HTGR designs nominally have minimum power levels of around 20% of rated power. The minimum power limits, as is also the case for commercial nuclear and non-nuclear plants, are determined by the steam turbine and the power conversion technology (Ref. [2]).

The targeted ramp rate during power operation for HTGR designs is 5% of rated power per minute, which is consistent with the EUR. This design target is tentatively determined by considering the ramp rates of other types of reactors. The Japan Atomic Energy Agency (JAEA) has designed the GTHTR300C, a commercial HTGR cogeneration system, and based on the simulations performed of the load-following operation, they have demonstrated that load-following operation at 5%/min can be achieved (Ref. [2]).

GTHTR300 design has a startup period is around 50 hours. This time is mainly determined by the design limit on the temperature ramp rate of 50°C/hr. This limit comes from the High Temperature engineering Test Reactor (HTTR), a HTGR test reactor. This start-up ramp rate is however not prototypical of the time returning to full power in case of minor faults. In the case of fault in GTHTR300 power operations, the generator is disconnected from the grid and the system is brought to a standby state where the reactor coolant temperatures remain at the rated condition, and the gas turbine speed is kept constant at full speed with turbine flow bypass control. The bypass causes a reduction in the reactor flow, and therefore reactor power will be automatically reduced to about 60%. Since the reactor coolant temperatures remain unchanged, reactor power can be returned to the rated power as quickly as desired, e.g. at 5%/min of the electric output ramp (Ref. [2]).

For many new reactor designs based on Gen-IV technology there is a limited power manoeuvrability experience. Even for systems with some experience operating prototypes, steady-state operation has been the predominant operational regime. In those cases, the simulation of the impact on system components are the normal approach. However, although computer simulations are a powerful tool, when there is limited full-scale experimental or demonstration scale experience, there is a need to ensure the computational models have significant experimental data underpinning the models, and this may not be the case for all advanced reactor systems (Ref. [2]).

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4.4 Requirements for SMR-SFR

In order to be competitive, SMR-SFRs have to offer load-following capabilities at least as the SMRs presented in section 4.3.4. Moreover and based on EPRI recommendation (Ref. [2]), SMR-SFR has to tackle not only operational flexibility, but also additional features (see the previously presented Figure 7).

The specific parameters for meeting the grid system operator requirements and the nuclear power plant capacities may include the following (Ref. [14]):

- Load reduction range in power terms (e.g. 'X'% to 'Y'% of RTP or '±X' MW(e) power) for each flexible operation type (e.g. primary/secondary frequency control or load following).
- Power ramp rates (e.g. 'X'% RTP/min, ascending and descending).
- Maximum/minimum time at reduced power (e.g. maximum 'X' hours at low power or minimum 'Y' hours at a plateau after power increase).
- Number of load cycles (e.g. 'X' numbers per day, month or fuel cycle).
- Periods of no flexibility (e.g. 'X' weeks after refuelling outage or 'Y' months towards the end of the cycle).

As a normal trend in new SMR designs, SMR-SFR can benefit from Energy Storage Integration. Load-following capabilities can be enhanced through the integration of energy storage systems with power plants. Additionally Combined Heat and Power Systems, also known as cogeneration, can provide further capabilities and therefore attractiveness by simultaneously producing electricity and useful heat for industrial processes or district heating.

Generally speaking, grid services and ancillary markets are the added value of SMR-SFR so that not only dispatchable power is generated, but also frequency regulation, voltage control, and reactive power support are provided.

The use of storage, whenever possible in the future at the required level of capacity, might therefore mitigate the requirements of flexibility to be applied to nuclear production, bringing it as far as possible towards the standard mode of utilisation for stable and safe baseload production (Ref. [44][14]).

Inherent operational flexibility of SMR-SFR, e.g. no Xe transients, can be further improved by adopting different energy storage options (see section 2.2.3). By coupling the primary loop with a Thermal Energy Storage (TES) system, as NATRIUM reactor, SMR-SFR would decouple power generation from power demand. Alternatively, the sodium secondary loop can be used as the Thermal Energy Storage. Table 19 presents the advantages and drawbacks of different Load Following Options for SMR-SFRs.

Load Following Option	Pros	Cons
Reactor load following	Flexible as current 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

Table 19 Advantages and drawbacks of different Load Following Options for SMR-SFRs

The final selection of the type of energy storage system to be considered in the ESFR-SMR design will be described in the deliverable D5.2 "Design of a TES in the secondary system" to be issued in month 35 of the project.

5 Conclusions

This deliverable presents an overview of the European Power System, where the EU 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 reach the net-zero target.

The European Green Deal aims at transforming the EU into a modern, resource-efficient and competitive economy, ensuring no net emissions of greenhouse gases by 2050. The corresponding directives approved imply a transformation of the EU Power System, to both power suppliers and the power demanders sectors. Table 20 shows the current and future Power Suppliers and Demanders.

	Power Suppliers	Power Demanders
Now	Fossil Power Plants Nuclear Power Plants Renewable Energies (solar, wind, hydro, …)	Industry Commercial sector Residential
By 2030	Fossil Power Plants Nuclear Power Plants Renewable Energies (solar, wind, hydro, …)	Industry Commercial sector Residential Electrified transportation Electrified heating systems
By 2050	Overproduction from smart-houses Nuclear Power Plants Renewable Energies (solar, wind, hydro, …)	Industry Commercial sector Residential Electrified transportation Electrified heating systems Electric vehicles Storage Systems (to balance supply-demand)

Table 20: Current and future stakeholders in power supply and power demand sectors

As addressed by the European Green Deal, this transformation will be achieved thanks to the large-scale European network, since system resilience, service quality and cost optimisation is feasible in well-interconnected power networks.

This deliverable also presents methods for providing stability to the grid, where the grid stability and power balance are firstly described, followed by the methods usually used for stabilizing the grid, such as Flexible Power Operation and other grid stabilizers, e.g. 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. VRE does not have this option, however, the ability to supply or absorb reactive power exists. Therefore, large VRE integration stresses the problem of maintaining voltage stability and new solutions have to be implemented in the coming years to enhance the response of the power electronics inverters.

The Requirements established for Nuclear Power Plants, both from the European Utility Requirements (EUR) Association are presented together with the operation performance of conventional power plants, NPP and advanced nuclear reactor systems. Table 21 presents

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the ramping and load following capabilities as requested by utilities in Europe (Ref.[48][36])) and the United States (Ref. [9][50]).

	EUR Req.	**EPRI Req. (Rev. 13)**
Continuous operation (mandatory)	50%-100% P_r with 3-5%/min. variation rate	Daily 100% → 20% → 100 %
Down to minimum (option)	20%	
Primary control (mandatory)	±2% P_r/min	Compulsory automatic frequency response
Primary control (recommended)	± 5% P_r/min	
Activating total primary range of control requested	within 30 s	
Secondary control (option) ~seconds to ~minutes	±10%	
Support grid restoration with sudden load steps of up to	10% of P_r.	
Secondary control (optional)	±10% of P_r, with a variation rate of 1% of P_r /min.	40 % per hour 20 % step change in 10 min.
Load-following capability until ( ) % of whole fuel cycle	90%	
Full power to minimum load variations and back to full power operation	2 per day 5 per week Cumulatively 200 per year	
Emergency load variation (agreement grid operator and unit operator)	20% P_r / min. (decreasing) 1-5% P_r / minute (increasing)	

Table 21: Load following requirements based on EUR and EPRI

Finally, this deliverable also presents potential requirements for SMR-SFR taking as basis the best operational performance of currently designed Advanced Nuclear Reactor Systems. In order to be competitive, SMR-SFRs have to offer load-following capabilities at least equivalent to the conventional SMRs, presented in section 4.3.4. When integrating a TES System, SMR-SFR can provide load-following capabilities, while not compromising safe reactor operation.

The selection and design of the TES system to be considered in the ESFR-SMR design will be a target of the project deliverable D5.2 “Design of a TES in the secondary system”.

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