SFR-SMR requirements to fit into a future European electricity network

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Outline

- EU Energy and Climate Targets
- European Power System Characteristics
- Potential Power Mix:
  - To get the net-zero target
  - To provide stability of the grid
- Requirements for SFR-SMR based on:
  - EUR and EPRI Requirements for Power Plants
  - Operational performance of current and projected PP
- Conclusions

EU Energy and Climate Targets

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Energy And Climate Targets Established by the European Commission

	By 2030	By 2050
Greenhouse Gases	Net reduction* of emissions >55%	No net emissions of GHG
Energy Sector	32 % RE share (2018) 40 % RE share (2019)	
Heating Sector	Integration heating/cooling systems	
Transport Sector	Support e-fuels in cars	Rev. combustion cars phase-out
Energy efficiency	Consumption reduction** > 9%	

* compared to 1990 level
** compared to 2020 level

Renewable Energy Directive (2018): NECP: National Energy and Climate Plans

European Green Deal (12.2019): Target: decarbonizing the energy system (~ 75% of GHG emissions)

Energy and Climate Targets for 2030 as Presented in National Energy and Climate Plans

	GHG emissions comp. 2005	Share RE in gross final energy cons.	Share RE in elect. consumption	Electricity interconnect.	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 %	74 %	15 %	2030

European Power System Characteristics

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- Transformation of the European electric power system:
  - increasing share of RE wind and solar
  - decentralized electricity sources such as PV and wind
  - smart loads, such as electric vehicles (EV) and smart appliances.
- Hydropower:
  - Significant capacity, although it differs between the countries
  - Natural resources (e.g., rivers channeled between hills) limits development (small scale, modernization existing plants)
- Solar panels and wind farms are the two major actors in VRE.

Characteristics of Power Plants Related to the Power Grid

	AC/DC	Power Generator	Grid Connection	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	AC	SG, RA	HVL	dispatchable

VRE: Variable Renewable Energy; MVL: Medium Voltage Lines; HVL: High Voltage Lines; SG: Synchronous Generator; RA: Rotating Alternator

Energy System Architecture

- VRE vs. Conventional Power Plants (CPP):
  - Fuel: VRE fuel cannot be stored; CPP fuel is a large/long-term storage supporting resilience of system
  - Grid: VRE to distribution/transmission lines via power electronics; CPP to HV via synchronous, alternator.
  - VRE load factor: for European grid, ratio 1:7 (i.e., 100 MW of CPP capacity replaced by 700 MW of VRE).
- Decentralized consumers, electrification of transport and heating: additional uncertainty (demand, grid stability)
- Systems/technologies modulating power generation and power demand:
  - power loads (hydrogen production, storage or charging EV), or power suppliers (batteries discharging mode)
  - embedded in Power Plants as in-built services or setup as stand-alone systems (single facility)

CHARACTERISTICS OF ENERGY STORAGE SYSTEMS

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

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Power mix to get the net-zero target

- What energy mix is compatible with the GHG emissions based on the CO2 intensity of electricity generation

CO2 Intensity of Electricity Generation

Fuel	Coal	Natural Gas	Biomass	Solar	Nuclear	Wind	Hydro
CO_2 production (gCO2eq/kWh)	820	490	230	48	12	12	24

- Considering EU climate targets, possible energy mixes able to achieve net-zero rather limited.

- Two pillars for decarbonizing the electrical power system: renewables along with low-carbon, dispatchable energy sources.

- If low-carbon dispatchable energy sources as Nuclear Power Plants (NPP) are not considered in the energy mix (as German Energy Transition Plan) 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.

Providing Stability to the Grid

- The electrical power system relies on a constant balance of supply and demand, which in turn implies: frequency stability and voltage stability.
- The frequency and voltage stability of the power grid are maintained by active power and reactive power control, respectively.

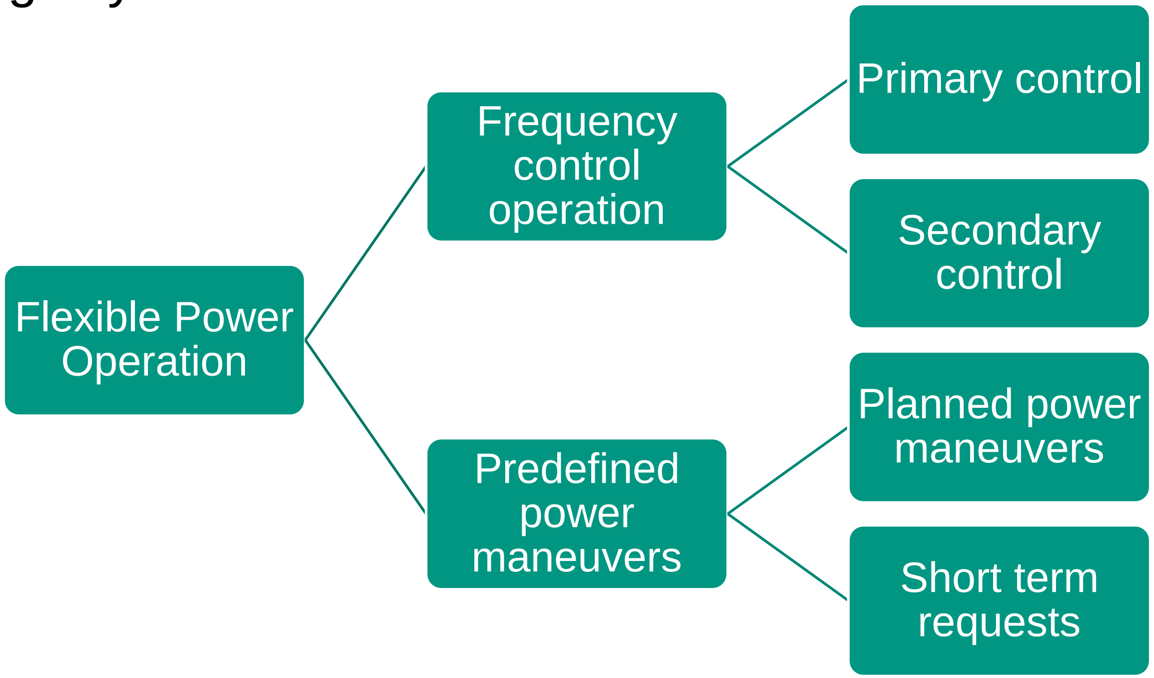
Types and Characteristics of Frequency Control Operations

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.

Grid Stability methods

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

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



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Requirements for Power Plants

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- Power generation systems increasingly being required to have ramping and load following capabilities.
- Utilities in EU and USA have issued requirements for Gen-III and future LWRs to ensure flexibility services.
- Most of new reactors (Gen-III+) are compliant with current utilities’ requirements for the new nuclear plants.

Load Following Requirements Based on EUR and EPRI

	EUR Req.	EPRI Req. (Rev. 13 SMRs)*
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)	

Operational performance

- Power plants currently in operation are able to provide the necessary flexible backups in the short term:
  - primary loop control method of the reactor power (reactor following turbine)
  - controlling the amount of main steam supplied to the turbine (turbine following reactor)

Flexibility of Conventional Power Generation Technologies

	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

Load-following Capabilities of French and German NPP

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

* during its lifetime

Characteristics of SMRs

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Main Characteristics And Load-following Manoeuvring Performance of SMR Designs*

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

* For those where load-followinf data is available in open literature

var.: variation; fl.: floating

Requirements for SFR-SMR

- SFR-SMR can benefit from energy storage integration enhancing the load-following capabilities.
- The use of thermal storage might mitigate the requirements of flexibility to the nuclear reactor.
- The inherent operational flexibility of SFR-SMR, e. g. no Xenon transients, can be further improved by adopting different energy storage options:
  - i) avoiding sodium-water interaction
  - ii) decoupling power generation from power demand.

Advantages and Drawbacks 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

Conclusions

- Considering EU climate targets, possible energy mixes able to achieve net-zero rather limited, being the two pillars renewables along with low-carbon, dispatchable energy sources.
- Without NPP the remaining alternative is large-scale storage systems, which currently do not reach the highest TRL as low-carbon, dispatchable energy sources.
- NPP connected to the grid via synchronous, rotating alternator provide frequency and voltage stability of the power grid by active power and reactive power control, respectively.
- SFR-SMR are required to have ramping and load following capabilities as established by EUR Association and EPRI.
- 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.

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