

D2.1 Flexibility, technologies and scenarios for hydro power

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Glossary

ACRONYM	DEFINITION
ACE	Area Control Error
aFRR	Automatic Frequency Restoration Reserve
aFRRIF	Implementation Framework for the exchange of balancing energy from aFRR
AGC	Automatic Generation Controller
ASM	Ancillary Services Matrix
AVR	Automatic Voltage Regulator
BESS	Battery Energy Storage System
BSP	Balancing Service Provider
BUC	Business Use Case
CE	Continental Europe
CH	Switzerland
CRE	Commission de Régulation de l'Énergie
DFIM	Doubly Fed Induction Machine
DSR	Demand Side Response
EBGL	Electricity Balancing Guideline
EFR	Enhanced Frequency Response
ENTSO-E	European Network of Transmission System Operators
EPS	Electric Power System
EU	European Union
FAT	Full Activation Time
FCR	Frequency Containment Reserve
FFR	Fast Frequency Response
FR	France

FRCE	Frequency Restoration Control Error
FRR	Frequency Restoration Reserve
FSFC	Full Size Frequency Converter
HPP	Hydroelectric Power Plant
IEA	International Energy Agency
IGCC	International Grid Control Cooperation
IHA	International Hydropower Association
IN	Imbalance Netting
IRENA	International Renewable Energy Agency
ISGAN	International Smart Grid Action Network
KPI	Key Performance Indicators
LFC	Load-Frequency Control
MARI	Manually Activated Reserves Initiative
mFRR	Manual Frequency Restoration Reserve
mFRRIF	Implementation framework for a European platform for the exchange of balancing energy from mFRR
NC RfG	Network Code Requirements for Generators
PICASSO	Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation
PSP	Pump Storage Plant
PT	Portugal
RES	Renewable Energy Sources
RoCoF	Rate of Change of Frequency
RoR	Run-of-River
RR	Replacement Reserve
RRIF	Implementation Framework for the exchange of balancing energy from RR
SA	Synchronous Area

SIR	Synchronous Inertial Response
SOGL	Network Code System Operations Guideline
SPBC	Standard Product for Balancing Capacity
TRE	Tertiary Regulation Reserve
TERRE	Trans European Replacement Reserves Exchange
TSO	Transmission System Operator
VRE	Variable Renewable Energy
WP	Work Package
XFLEX HYDRO	Hydropower Extending Power System Flexibility project

1 Executive summary

On the path to decarbonization of the world economy, a dramatic increase in variable renewable energy (VRE) production is expected to cause much higher volatility in the EU electricity system. Grid operators must constantly balance demand with supply to keep the system stable, and the growing levels of electric power production from wind and solar sources will increase the complexity of this balancing. In these foreseen scenarios, there will be greater need for flexible and controllable supply from low carbon sources to maintain system security. It is precisely in the dimension of controllability that hydroelectric power plants (HPPs) find a new space of action in view of the growing needs for flexibility in the system in different time scales. Hydropower can provide large quantities of both capacity (short-term power flexibility) and energy (medium-term and long-term power and energy flexibility). Hydropower occupies a unique position from a flexibility supplier perspective as it can store primary energy (GWh) with high efficiency as the potential energy of water. Moreover, it can provide power capacities (GW) at a high degree of predictable availability. This gains even more importance when flexible thermal units are being phased out and when decentralized solutions, such as batteries, electric vehicles and demand response, are expected to provide short-term flexibility, but in a less predictable way.

Envisioning the unique capabilities of hydropower facilities in many aspects of the ancillary services provision, the XFLEX HYDRO project (Hydropower Extending Power System Flexibility) is aiming to demonstrate new technological solutions within the hydropower fleet that will support high levels of VRE penetration in the electricity system. XFLEX HYDRO purpose is to deliver new and effective methods to incorporate state of the art hydroelectric technologies capable of not only providing enhanced flexibility services but also optimize HPP maintenance schedules, increase the availability of HPP and maximize their performance. In this project, these technologies will be evaluated in detail to better understand the technical and economic benefits and/or drawbacks of each solution. Aligned with this, WP2 from XFLEX HYDRO project intends to build up a comprehensive framework around flexibility and system support services provision on future power systems with a strong link to HPPs, system services technical aspects and market mechanisms. Within this scope, the activities that are developed within Task 2.1 "Identification of flexibility services and standardisation" are presented and discussed in this report and are intended to materialize a review of the flexibility products, across Europe, with emphasis on the countries in which demonstrations will take place. In the following paragraphs, the main outcomes drawn-out from this report are synthesized regarding the following main topics:

- Ancillary services and market frameworks – current and future trends;
- Project demonstrators and technological solutions to be assessed and/or implemented;
- Hydropower Flexibility Matrix;
- Future scenarios.

Ancillary services and market frameworks – current and future trends

A key component of Task 2.1 is the identification and characterization of the ancillary services required by the grid, during and after the decarbonization process, and also likely to be more needed in the future. This characterization follows the strategies envisioned by the transmission system operators (TSOs) in Europe for the future operation of the power system and the specification of technical requirements for these ancillary services as identified by these TSOs. For the sake of objectivity, only the requirements that are expected to have a relevant impact for the XFLEX HYDRO project are described, meaning that this is performed for the Continental Europe (CE) synchronous area (SA). This characterization also considers the existing or emerging market frameworks established for the deployment, exchange and remuneration of each ancillary service. Besides, an overview is performed regarding the main services currently being demanded by the local system operator of the countries in

which demonstrations will take place, namely in France, Portugal and Switzerland. All the details concerning these subjects can be found in chapter 4 and chapter 5 of this report. In brief, the basket of ancillary services is composed as follows:

- **Synchronous inertia:** This is the inherent capability of rotating machines directly connected to the power grid to store and inject their kinetic energy, which supports the frequency transient behaviour in the moments subsequent to an active power imbalance. Synchronous inertia may be obtained by increasing the rotating mass connected to the system, which includes the one in synchronous generators, pumps of pump-storage HPPs with fixed speed units, as well as in synchronous condensers. In fact, HPPs with fixed speed technology have an inherent capability to provide synchronous inertia. Regarding inertia future capacity requirements in CE, this is far away from being quantified/specified, being something that starts now to be evaluated. The service is not currently remunerated in CE SA, but is starting to be contracted by TSO of large-scale islands under specific tenders, as it is the case of Ireland and United Kingdom. These tenders are further detailed in section 4.3.4.
- **Synthetic inertia:** Power electronic-interfaced energy sources can provide short-term frequency support through proper control of the coupling interface. While not providing synchronous inertia, they are able to swiftly adapt power output, driven by their control system, to deliver "synthetic inertia", provided some energy buffer is available within the primary energy source as it is the case of the kinetic energy stored in the rotating masses of wind or hydro facilities. Wind turbines may, however, have some energy buffer capabilities limitations to provide synthetic inertia, being the active power response obtained from this service followed by a recovery period where the power can drop below the pre-fault value. This recovery period may, in turn, have dramatic impacts in the global stability/frequency response if not properly accommodated by the response of other sources. The available capacity of synthetic inertia is restricted by the low overload capacity of inverters when compared to synchronous machines. Besides, synthetic inertia requires the frequency to be measured and processed for control purposes, meaning its effect on the grid has a delay that, for very-fast-frequency transients, may not be enough. Therefore, at present, a higher confidence exists on the provision of inertial response from synchronous inertia. Although not foreseen in the short to medium term to be a remunerated service in CE, synthetic inertia will likely start to become mandatory or contracted in CE tendering markets given the expected growth in power electronics-based renewables that will feed the system.
- **Fast Frequency Response (FFR):** FFR is designed to provide an active power response faster than existing operating reserves, typically in less than 2 seconds, in the timeframe following inertial response (i.e., typically after 500 ms) and before activation of FCR (which has a maximum delay of 2 seconds). Although not yet defined or rewarded as a service in CE, FFR is already being explored in other European markets such as in United Kingdom (previously tendered as Enhanced Frequency Response), the Irish and the Nordic markets. As described in section 4.4 of this report, there are many different approaches and variations for the FFR product. They all depend on the specific needs of each SA and, as such, further studies are needed regarding the implementation of such a service in CE SA. However, a common characteristic for all the listed FFR products is that the time that takes to fully activate this product should be less than 2 seconds.
- **Frequency Containment Reserve (FCR),** which, in former terminology, is known as primary frequency control: FCR aims to contain system frequency after the occurrence of an active power imbalance, by maintaining the balance between active power generation and demand within the entire SA and aiming to comply with pre-defined frequency metrics. For FCR providers in CE SA, FCR must be fully activated within 30 seconds and the power-generating module shall be capable of providing full active power-frequency response for a period between 15 to 30 min

(specified by the TSOs of each SA). The minimum technical requirements to be ensured by FCR providers is defined in detail by EU regulation. An overview of these requirements for CE SA is presented in section 4.2.3 of this report. This balancing reserve is already being procured and exchanged in an FCR Cooperation platform in Central Europe (detailed in section 5.1).

- **Automatic Frequency Restoration Reserve (aFRR)** which, in former terminology, is known as secondary frequency control: aFRR is an automatic process aiming to restore the system frequency back to its set point (normal) value and to keep the power interchange program among load-frequency control (LFC) areas. It is a remunerated product being controlled by an automatic and centralized TSO-equipment. In CE, this service already has a standard product, properly defined to be traded in a European platform for the exchange of balancing energy from aFRR. This standard product is developed in close coordination with the PICASSO initiative, a project established by European TSOs for the implementation of an aFRR platform. According to EU regulation, the aFRR activation delay must not exceed 30 s. Besides, a maximum of 5 min is set for the full activation time (FAT) of the aFRR standard product (starting from December 2025). All the characteristics specified for the aFRR standard product are described in section 5.6.2 of this report.
- **Manual Frequency Restoration Reserve (mFRR)** which, in former terminology, is known as direct activated tertiary frequency control: The provision of mFRR is a frequency restoration process, having therefore similar goals to aFRR. It is implemented by TSO instructions for manual FRR activation in the LFC area. This service has a standard product defined to be exchanged in a European platform for the exchange of balancing energy from mFRR, which is specified in close coordination with the MARI project (established by European TSOs for the implementation of an mFRR platform). According to EU regulation, mFRR must be fully activated in 15 min. Within the mFRR standard product, the FAT is set to a maximum of 12.5 min (to consider the delay between an event and the manual transmission of reserve activation orders) and has a minimum delivery period of 5 min. All the characteristics specified for the mFRR standard product are described in section 5.6.3 of this report.
- **Replacement Reserve (RR)**, which, in former terminology, is known as scheduled activated tertiary frequency control: The aim of the RR process is to progressively replace and/or support the frequency restoration control process in the disturbed control area. RR implementation consists in optional TSO instructions for manual activation of reserves in the LFC area, usually performed after the time to restore frequency, in a timeframe between 15 min to 1 h. According to EU regulation, defining the minimum technical requirements of RR providers is a responsibility of the TSOs of each LFC block. This service also has a standard product to be exchanged in a European platform for the exchange of balancing energy from RR, which is specified in close coordination with the TERRE project (established by European TSOs for the implementation of an RR platform). The agreed characteristics for a RR standard product are summarized in section 5.6.4, which include a FAT of 30 min and a minimum delivery period of 15 min.
- **Voltage/reactive power control (Volt/var)**: The Volt/var control process is implemented by manual or automatic control actions, designed to maintain the nominal set values for the voltage levels and/or reactive powers. The requirements for this control are highly dependent of local or regional characteristics of the power system. Nevertheless, EU regulation defines general requirements for this control that are summarized in section 4.2.6 of this report. Nowadays, this is typically a mandatory and not remunerated service. In some countries, there are also bilateral contracts held between service providers and the TSO for the provision of extra Volt/var control, which is remunerated according to each specific contract. Often, upon request by the local TSO, pump storage HPP operate in the synchronous condenser mode to provide Volt/var support to the grid.

- **Black start:** Black start is the process of restarting operation of a power plant during a grid blackout, from a completely non-energized operating state and without any power feed from the network. The service is intended to power up other plants and loads and aims to bring the grid system back to normal operating conditions and to minimize the impact to consumers. Black start is nowadays contracted through bilateral agreements, and it is not expected to have its own market framework in the future. Nevertheless, HPPs are particularly well suited for black start and it is expected that, in future scenarios with a massive increase of renewable power production, the black start capabilities of HPPs will become of crucial importance to guard system security.

Project demonstrators and technological solutions to be assessed and/or implemented

In this report, a preliminary overview is performed about the XFLEX HYDRO demonstrators, addressing in particular the technological solutions tackled within the scope of each demonstrator, in the light of their capability to improve the provision of flexibility/ancillary services and the overall operation of the existing hydroelectric machinery, including its maintenance procedures, availability and efficiency. In particular, the technological solutions to be assessed and/or implemented within the scope of the XFLEX HYDRO project are as follows:

- **Fixed** speed units;
- **Variable speed**, through the installation/conversion to Doubly Fed Induction Machine (DFIM) and Full-Size Frequency Converter (FSFC);
- **Smart Power Plant Supervisor** (SPPS), a methodology to provide an adequate monitoring and extensive knowledge of the machine that will enable the plant owner to manage the risks and costs associated to a temporary off-design operation according to the potential benefits it offers. In this project, SPPS methodology is considered as an umbrella of all the actions, studies and control measures performed to increase the controllability and monitoring of the HPP without the installation of significant hardware.
- **Hydraulic Short Circuit** (HSC), which allows the HPP to generate power at the same time it is pumping water for storage. This enables the simultaneous pumping at rated power and controlling the turbine power generation, varying continuously the consumption of the plant.
- **Hydro-Battery-Hybrid** (HBH), namely the hybridization of the HPP through the installation of a Battery Energy Storage System (BESS).

A general characterization of each demonstrator and its expected evolution regarding hydroelectric machinery and flexibility/ancillary services portfolio evolution is detailed in chapter 6.

Hydropower Flexibility Matrix

The previous described information is the building foundation for the development of the first stage of the hydropower “Flexibility Matrix”, which is described in chapter 0 of this report. This matrix is conceptualized to provide a cross relationship between the expected flexibility services and their market framework with the hydro technologies and the solutions under development within the XFLEX HYDRO project. It is understood that this matrix will be extremely important for the various stakeholders in the hydroelectricity industry, providing a synthetic mapping of new opportunities in the decarbonization plans of the economy, namely to understand more clearly the set of flexibility services expected for the electricity sector, from which new opportunities will emerge for HPP.

The initial concept of a unique “Flexibility Matrix” would leave out significant information about the improvements achieved by XFLEX HYDRO project for HPPs operation that do not fall into the envisaged basket of ancillary services for the future EPS.

Therefore, to properly summarize the overall contributions expected to be draw from the XFLEX HYDRO project, the "Flexibility Matrix" is, in fact, broken down as follows:

- The "Ancillary Services Matrix" that holds the conceptual design of the original one for the wide basket of ancillary services to which HPP are expected to contribute in the short to long term. A first stage of this matrix is presented in section 7.2. In this matrix, the current capabilities of each HPP in providing the identified flexibility services are characterized with the support of the demo owners and equipment manufacturers of each HPP.
- A Key Performance Indicators matrix, named the "KPI Matrix", to display the improvements provided in terms of the HPP overall operation/maintenance/efficiency and in terms of the capabilities to provide flexibility that do not fall back into the envisaged basket of ancillary services for the future EPS. A first stage of this matrix is presented in section 7.3.

These matrixes are expected to be continuously populated alongside the project development, constituting a summary of the main achievements in terms of HPP capabilities towards EPS provision of services and associated efficiency and availability.

Future scenarios

Following the characterization of the framework for the provision of flexibility by HPP (assessment of current services and the respective markets for the provision of such services), scenarios for the future integration of the proposed solutions are also identified in chapter 8, encompassing the knowledge of the players involved in the project as well as the main targets defined at EU level. A literature review is performed regarding the future energy scenarios for Europe, namely regarding the annual energy generation mix (in TWh) and the installed capacity mix (in GW) for 2025, 2030 and 2040. For XFLEX HYDRO project, these future scenarios will help provide a framework for modelling the hydropower technologies at system-scale and wider context, namely in WP2 (Task 2.5), WP10 and WP11.

2 Introduction

2.1. Context and objectives of the report

To achieve a reduction of 80% - 95% in greenhouse gas emissions by 2050, the European Union (EU) expects that Renewable Energy Sources (RES) should hold a 97% share of the European power generation mix considering the high RES scenario envisioned for the decarbonization process [1]. To succeed in such an important endeavour, a substantial and deep transformation of the EU Electric Power System (EPS) is currently being implemented by massively integrating non-dispatchable RES, widely deploying high-energy efficient technologies, a stronger effort for electrifying the economy and eliminating coal as a source of energy. The process of decarbonizing power systems mainly consists of decommissioning traditional generating units sourced by fossil fuels and the installation of clean energy sourced generators to satisfy the growing energy demand, which means a significant transition from classical fossil fuel generators to non-dispatchable RES-based ones. The traditional generators are typically synchronous rotating machines that are controllable and dispatchable in terms of power output and are capable of providing a suite of services to the power grid such as inertia and power balancing (capacity of providing regulating power to the grid to ensure the load/generation balance). Transmission System Operators (TSO) are responsible to assure a secure operation of the grid and, to do so, they heavily rely on balancing services (self-provided or contracted to utilities). With the increasing percentage of non-dispatchable RES in the EPS and the decreasing number of flexible dispatchable power plants, it is crucial to expand and enhance these services to support the proper operation of future EPS.

In 2018, hydropower as dispatchable RES accounted for about 15% of the total electricity generated in the European interconnected transmission system (562.4 TWh out of 3,659.1 TWh) [2]. Dispatchable hydropower most likely will play a key role in supporting the power grid balancing and extending the flexibility of the European EPS for the ambitious future scenario of almost 100% share in the generation mix by RES. It is within this context that the Hydropower Extending Power System Flexibility (XFLEX HYDRO) project is conceived. XFLEX HYDRO aims to realize and improve hydropower potential concerning plant efficiency, availability, and provision of flexibility services to the European EPS. Hydroelectric power plants (HPPs) are already instrumental providers of flexibility to the system regarding regulation capability, frequency and Volt/var control among others. XFLEX HYDRO purpose is to deliver new and effective methods to incorporate state of the art hydroelectric technologies capable of not only enhancing flexibility services but also optimize HPP maintenance schedules, increase the availability of HPP and maximize their performance. These technologies will be evaluated in detail to better understand the technical and economic benefits and/or drawbacks of each solution.

The XFLEX HYDRO project typology is an Innovation Action and, as such, it includes innovation technology development activities (based on the results obtained in other previous R&D projects) followed by a set of key demonstration activities and a set of deployment activities. The project structure consists of 13 Work Packages (WP). Each one has a clear focus on the tasks and contributions to tackle the overall project objectives. Aligned with this philosophy, each WP is grouped into three different kinds of activities: innovation activities, demonstration activities and deployment activities. Aligned with the innovation activities, this technical report refers to the outcomes of Task 2.1 from WP2. Work Package WP2 intends to build up a comprehensive framework around flexibility and system support services provision on future power systems with a strong link to HPPs, system services technical aspects and market mechanisms. Within this scope, the activities that are developed within Task 2.1 are presented and discussed in this report and are intended to materialize a review of different flexibility products, across Europe, with emphasis on the countries in which demonstrations will take place.

Aiming to present the aforementioned findings, this deliverable (D2.1) is divided into 6 main sections, as follows:

- Chapter 3 provides a literature review regarding the definition of flexibility, the future flexibility needs in the EPS and the contribution of hydropower to flexibility.
- In chapter 4, the main goal is to identify and characterize the basket of flexibility products, considering the typology, deployment time, duration of the delivery period and market framework, across Europe, with emphasis on the countries in which demonstrations are taking place (Portugal, France and Switzerland).
- A full characterization of the future trends with respect to flexibility services requirements (and associated market frameworks), with emphasis on HPP, is performed in chapter 5 considering an exhaustive review of recent and ongoing projects, European Network of Transmission System Operators (ENTSO-E) trends, guidelines and outcomes.
- Chapter 6 describes the XFLEX HYDRO project demonstrators and the technological solutions to be implemented in each site.
- Chapters 4, 5 and 6 are the building foundations for the development of the hydropower “Flexibility Matrix” described in chapter 0. This matrix is conceptualized to provide a cross relationship between the expected flexibility services and their market framework with the hydro technologies and the solutions under development within the XFLEX HYDRO project.
- In chapter 8, the future scenarios for RES integration in the EPS as well the expected trends regarding the growth of hydropower in Europe are presented and discussed, encompassing the knowledge and plans of the players in the hydropower sector involved in the project, together with European Commission targets and the inputs from the advisory board members.

2.2. Methodological approach

The following methodological approach is pursued to support the development of the activities foreseen under Task 2.1, which are compiled in this document.

For chapter 3, a detailed literature review is conducted regarding the definition of flexibility, the future needs of the EPS in terms of flexibility and the contribution of hydropower regarding those needs. This review is mainly focused on an analysis of existing documentation and technical papers, namely from the International Smart Grid Action Network (ISGAN) [3] [4], from the International Energy Agency (IEA) [5] [6] and from the International Renewable Energy Agency (IRENA) [7].

With respect to chapter 4 and chapter 5, dealing with flexibility services and associated trends, a preliminary assessment of different flexibility services across the world is performed, including the analysis of the following documents:

- Reports from the H2020 projects, such as EU-SysFlex [8], MIGRATE [9] and OSMOSE [10];
- Public documents from TSOs and utilities, such as ENTSO-E [11], EirGrid [12], SONI [13] and National Grid [14];
- Discussion paper from ISGAN regarding flexibility [3].

The collaborative work developed among the WP2 partners is pivotal for the success development of the foreseen activities within Task 2.1. This collaborative work allows to address two important domains: 1) the detailed characterization of the existing environment with respect to flexibility in EPS for the countries hosting demonstrations, involving some interaction with national TSOs, and 2) the identification of EU-level initiatives with respect to the definition/standardization of flexibility services.

With respect to EU-level initiatives, the following EU regulations are taken in consideration:

- EU Regulation 2017/1485 [15] (the Network Code on System Operation, also named System Operation Guideline and hereafter named SOGL);
- EU Regulation 2016/631 [16] (establishing a network code on requirements for grid connection of generators, hereafter named NC RfG);

- EU regulation 2017/2195 [17] (establishing a guideline on electricity balancing, hereafter named EGBL).

Furthermore, the ENTSO-E FCR cooperation project [18] is also included in this report, since Switzerland and France are already participating in the FCR exchange platform (an outcome of the ENTSO-E FCR cooperation project) that should increasingly include more countries of Continental Europe (CE).

Regarding chapter 6, which provides an overview of the project demos with respect to flexibility partners contributed for the characterization of each demo and the technologies to be implemented and/or evaluated. This characterization is done with the direct support of the demo owners and equipment manufacturers of each HPP.

The contents from chapter 4, chapter 5 and chapter 6, with respect to the categorization of typical and current flexibility services, future trends in the European area as well as the characterization of the demonstrators and the technologies to be implemented and/or evaluated, are crucial to develop and outline the "Flexibility Matrix" described in chapter 0. The current capabilities of each HPP in providing the identified flexibility services are characterized with the support of the demo owners and equipment manufacturers of each HPP.

To prepare the next tasks of the XFLEX HYDRO project, an identification is performed about the renewable integration scenarios with insights/views on the future trends regarding the European HPP fleet, towards the adoption of flexibility solutions under development in the XFLEX HYDRO project. With this aim, a literature review is performed in chapter 7 regarding future energy scenarios for Europe, namely by including the outcomes from the following institutions: European Commission [19], ENTSO-E [20], other Horizon 2020 projects (EU-SysFlex [21] and HydroFlex [22]), IRENA [23] and the International Hydropower Association (IHA) [24] that is part of the XFLEX HYDRO project consortium.

3 Flexibility needs in future power systems

3.1. Flexibility – an overview

The main focus of work package WP2 is to establish and characterize a framework for the provision of flexibility by hydropower plants within a context of non-dispatchable RES massification in EPS. In this context, it is necessary to clearly define flexibility and what it encompasses. Multiple entities have proposed different definitions of flexibility. In 2018, the Council of European Energy Regulators adopted a more general definition for flexibility as *"the capacity of the electricity system to respond to changes that may affect the balance of supply and demand at all times"* [25]. In the same year, IEA provided a revised version for flexibility: "all relevant characteristics of a power system that facilitates the reliable and cost-effective management of variability and uncertainty in both supply and demand" [6]. Also, in 2018, IRENA defined flexibility taking into consideration Variable Renewable Energy (VRE) generation as: *"the capability of a power system to cope with the variability and uncertainty that VRE generation introduces into the system in different time scales, from the very short to the long term, avoiding curtailment of VRE and reliably supplying all the demanded energy to customers"* [7].

In short, flexibility can be broadly defined as the ability of the overall EPS to manage changes. It has two different dimensions: technical and commercial dimensions. In fact, the flexibility in supply, demand, storage of energy and energy transfer, is restricted by technical and commercial capabilities. The technical capabilities are necessary to support the operation and planning of the EPS, in accordance to commercial capabilities of the market requirements and their regulations, as much as in the present as for the foreseeable future.

In addition, it covers a wide spectrum of needs for the EPS. Depending on the timeframe, flexibility in the system can be divided in needs for power and for energy, regarding the system wide level, and in needs for voltage control and for transfer capacity on the regional level (Figure 1).

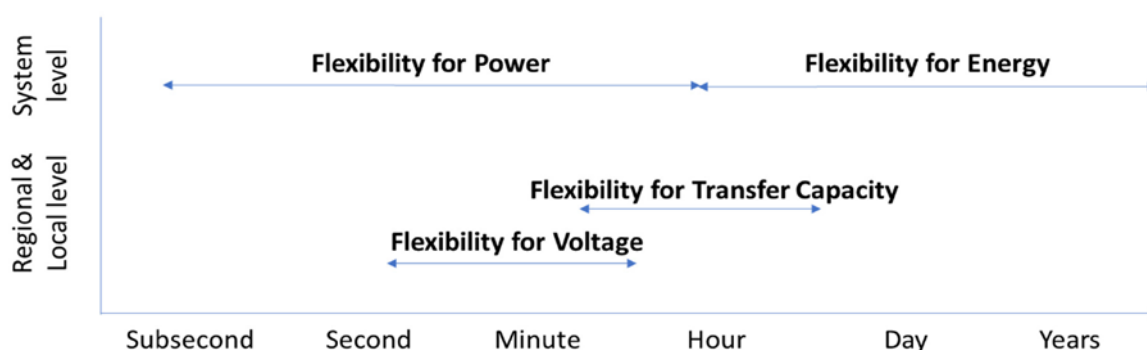


Figure 1 Interrelation of flexibility needs in perspectives of space and time [4]

Flexibility for power is necessary for assuring the short-term equilibrium between power supply and power demand. It is a system wide flexibility that maintains frequency stability in AC systems. This flexibility should be available in the timescale of fraction of seconds up to an hour and is becoming a major concern because of the growing penetration of VRE in the generation mix [4]. In short, flexibility for power is needed to provide a secure power supply while maintaining grid frequency and stability.

Flexibility for energy is a system wide requirement that allows for a medium to long-term balance between energy supply and demand for scenarios over time. It is needed to cover the decreasing

amount of fossil fuel storage-based energy supply in the generation mix and encompasses the hours to several years" timescale [4]. In other words, this flexibility will ensure a future adequacy of supply.

Flexibility for power transfer capacity is a local or regional ability to transfer power between supply and demand to avoid congestions in the grid. It is required to deal with time periods having increased utilization levels (during higher peak demands and/or higher peak supply) and it is a short to medium-term capability with a timescale of min to several hours [4].

Flexibility for voltage is the ability to provide reactive power to the grid to keep the bus voltages within the pre-defined technical limits. As such, it is a local or regional requirement and is short-term capability (timescale of seconds to tens of minutes). The main rationale for the need of this flexibility is closely related with the increased amount of generation in the distribution network, resulting in bi-directional power flows and highly variable operating scenarios [4].

3.2. Power systems evolution and the need for more flexibility

3.2.1. General

In the previous section, a brief overview is provided regarding the presentation and discussion of the flexibility concept. However, a deeper overview is necessary in order to understand the need for augmented EPS flexibility.

Firstly, it is necessary to realize that EPS are going through extreme and profound transformations to become more efficient, decarbonized, and clean. Namely, the following main global trends are driving the evolution of the EPS in terms of planning and operation [4] [26]:

- Elimination of coal as a source of energy, to decrease the carbon footprint of the EPS (decarbonization);
- Significant increase in the number of smaller and RES-based power plants (also known as distributed generation) spread throughout every voltage level of the EPS and geographically dispersed (decentralization);
- Increasing investments in wind and solar power plants (variable and non-dispatchable RES - VRE);
- Increased disconnection of thermal power plants;
- Transition from synchronous rotating machines to power electronic interfaced devices;
- Progressively integrated electricity grid, with larger capacity and more interconnections, as well as with increasingly integrated energy markets;
- Massive integration and reliance on information and communication technologies (digitalization), for successfully operating the evolving EPS such as the deployment of smart and microgrids;
- Consumers are more climate conscious and more aware of their potential to become key players in the evolving EPS, by investing in distributed generation, demand response mechanisms, storage devices and in electric vehicles and by participating in the wholesale markets.

The flexibility in the operation of the EPS has a direct relation to the resulting impacts of increasing shares of VRE. Table 1 presents the impacts of a high share of VRE and resulting system needs, considering a timeframe ranging from sub-seconds to years [5]:

- From subseconds to seconds, the impact of VRE will be mainly on the dynamic response of the system, namely on frequency stability and on Rate of Change of Frequency (RoCoF). The solutions include to ensure a proper level of system inertia and to provide faster power regulation by means of faster frequency services.

- From seconds to minutes, the key issue is to maintain a balance between active power supply and demand, which should be provided by higher volume in active power reserves.
- From min to hours, the key issue is net load¹⁾ following. The technical solution in terms of system operation is to provide proper ramp rates capabilities of active power, in the real time market, to control the consumption balance.
- From hours to days, a high share of VRE will affect the unit commitment plan since it will promote an increased cycling of dispatchable units and a decrease availability of flexible units such as fast thermal generators.
- From days to years, being a wider timescale, the impact of VRE will hinder the scheduling of generating units for seasonal adequacy, which increases the importance of well-planned new investments.

Table 1. Impacts in the EPS of high share of VRE and system solutions [5]

Time Frame	Sub second	Sub minute	Hour	Days	Years
VRE impacts	F. stability & RoCoF	Balancing	Net load following	Unit commitment	Scheduling for seasonal adequacy
System operations	(Fast) power regulation	Increasing volumes of operating reserves	Increasing ramp rates capabilities of active power	Increasing cycling, dispatching fewer flexible units	Planning of new investments

The aforementioned changes will influence drastically the provision of the power grid balancing and challenge the EPS operations and safety, justifying therefore the need for more flexibility.

However, how to increase flexibility in the overall system?

Answering to this question, [7] presents several sources of flexibility while considering also a cost dimension associated to it, see Figure 2.

From this figure, it is possible to conclude that, for medium/high share of VRE, the supply-side flexibility to be achieved by means of more flexible power generation assets has an important role to play. In this sense, the XFLEX HYDRO overarching goal is to demonstrate an innovative methodology for system integration of hydroelectric technology solutions and to draw the roadmap for enabling the European fleet of HPPs to contribute significantly to the increase of the flexibility of the electric power system while achieving an improved average annual overall efficiency of the hydroelectric machinery and further providing high availability of HPP and maximizing its performance.

¹⁾ "Net load" means the considered load for the dispatchable power generation fleet after deducting VRE generation from the load.

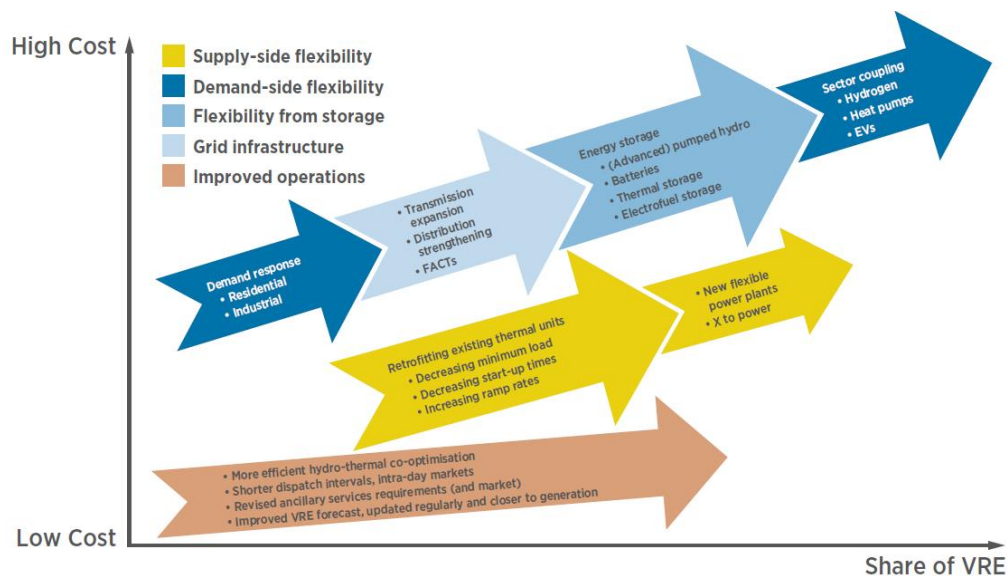


Figure 2 Technical options to increase system flexibility [7]

3.2.2. Challenges for a secure and stable operation of future power systems

It is of upmost importance to provide reliable solutions to support the EPS with more flexibility services. HPP already significantly supports EPS flexibility in terms of regulation capability, power-frequency control, start/stop cycles, generating to pumping transition modes, high ramping rates, synchronous condenser mode of operation, fault ride through capability in variable speed units, etc. XFLEX HYDRO aims to demonstrate an innovative methodology for system integration of hydroelectric technology solutions, to provide further enhanced flexibility services assessed by a crosscutting analysis of their impact on both the technology and the market aspects. First, it is necessary to identify the challenges for a secure and stable operation and planning of future power systems, which according to [3] are:

- Identification of true operational state and limits by quantifying uncertainties in measurements and modelling, to better understand which reserves are required to maintain the critical stability limits of the EPS. The crucial behaviours to tackle are frequency stability, bus voltage stability and rotor angle stability.
- Increasing need of information exchange to be able to characterize the state of the system and to be able to monitor and control from distributed generation (for example, send new set points to dispatchable units).
- A major shift in the dynamic response of the system. In particular, the increasing substitution of rotating machines for power electronic interfaced generation systems will result in significant changes of the dynamic behaviour of the power system.
- New utilization patterns of the system, like more dispersed generation units, new type of demand, increased number and size of interconnections.

To overcome these challenges in future EPS, it is of the most importance to rely on and enhance the flexibility of the system. Several projects have already been deployed or concluded with the objective to provide new and effective ways to enhance and improve the overall flexibility of the system.

From these projects, the following three contributed the most for the work already developed and to be performed in the future of XFLEX HYDRO.

1. EU-SysFlex project [8], an H2020 EU funded project that aims to identify a mix of flexibility and system services to support secure and resilient operation of the power system. The work done

on this project became a foundation to WP2 of XFLEX HYDRO (especially for this report), since it characterizes the future EPS needs and scarcities, specifically the ones with high-share of VRE. It started in November of 2017.

2. The OSMOSE project [10] that started in 2018 and is expected to be concluded by 2021. It is a H2020 EU-funded project that aims for the development of flexibilities, which can be used for a better integration of RES. The project proposes four TSO-led demonstrations (RTE, REE, TERNA and ELES) aiming at increasing the techno-economic potential of a wide range of flexibility solutions and covering several applications:

- synchronisation of large power systems by multiservice hybrid storage;
- multiple services provided by the coordinated control of different storage and FACTS devices;
- multiple services provided by grid devices, large demand-response and RES generation coordinated in a smart management system;
- cross-border sharing of flexibility sources through a near real-time cross-border energy market.

The flexibility solutions identified in OSMOSE are used, as well, as guidelines and inspiration to define the flexibility services that future hydropower stations could deliver to the power grid.

3. MIGRATE project [9], an EU-funded project under the framework of Horizon 2020 that aims to find solutions for the technological challenges that the grid is currently and will be facing in the future due to the massive integration of power electronic interfaced devices and the decommissioning of traditional synchronous machines. The main challenges tackled were:

- the system growing dynamic stability issues for the power system (possibly a new major barrier against future renewable penetration);
- the necessity to upgrade existing protection schemes and measures to mitigate the resulting degradation of power quality due to harmonics propagation.

The MIGRATE was concluded in 2019, after 4 years of work. This project identifies the growing stability issues for the power system and solutions found to deal with them. It should be used as guidelines for the dynamic studies to be done at the last stage of WP2.

3.2.3. Contribution of hydropower to flexibility

Reservoir and pumped storage hydropower are already being used in many countries, providing flexibility, energy storage and ancillary services in the electricity system. To transition towards renewable energy systems, hydropower must also contribute with base load electricity, more demanding flexibility requirements and ensuring security of power supply in many regions of the planet. Another key role played by hydropower reservoirs is to provide a secure supply of energy throughout the year, as plenty of countries have seasonal and inter-annual variations of precipitation and inflow [5].

There are two possibilities to refurbish existing reservoir hydro, in order to increase flexibility at multiple time scales and enable a larger share of VRE in the power system, preventing retrenchment of other renewables without the constructing of new dams or rebuilding existing ones [5]:

- Redesigning the plant to include a pumped storage facility, by installing pumps or reversible pump turbines (only possible if a reservoir hydropower plant discharges to another reservoir or a lake).
- Increasing the turbine capacity in existing power plants.

Both ways require civil works, new machinery and reinforced grid connection in some situations. Nonetheless, no new dams or reservoirs would be required to obtain it and the additional environmental impact would be narrowed. By installing pumps, reservoir hydropower will participate in short to

medium-term flexibility much more recurrently than when just increasing the capacity. The plant will be operated like a battery, allowing the water to be “recycled” several times. Despite of these advantages, these options are site specific and dependent on the plant capacity and layout, active reservoir storage and regulatory permits [5].

A third option is also possible and is closely related to the work being developed in XFLEX HYDRO. Essentially, it consists in enabling existing HPP to become “smarter” by installing sensory equipment and developing software capable of improving the unit operation, namely by being more efficient and controllable. Depending on the hydro technical solution, this will allow for an overall higher operation range and/or better ability to provide faster ancillary services to the grid [5].

Hydropower can guarantee extra flexibility for short-term variations in the power system, having however many competing technologies, such as batteries, flywheels and other types of demand-side and supply-side flexibility, that can also contribute. Hydropower has advantages over conventional thermal resources as it allows to quickly ramp and start at any time, including switching between producing and consuming energy. Besides, although hydropower may experience constraints and inefficiency at partial loads, thermal plants tend to be more expensive and run less efficiently at partial loads.

As the energy system becomes increasingly dependent on weather variability, long-term flexibility plays a much more important role, in addition to ultra-short, short, and medium-term flexibility. Hydropower can provide large quantities of both capacity (driven short-term power flexibility) and energy (driven medium-term and long-term power and energy flexibility) [5]. An increased system value can be identified by providing the right capacity at the right times, instead of providing energy volume that is exactly what VRE sources do. Having the capability to capture this so-called energy-option value will be fundamental in ensuring the profitability of any kind of technology used to consolidate the VRE generation. Hydropower occupies a unique position from a flexibility supplier perspective as it stores primary energy (GWh) with very small losses as the potential energy of water. Moreover, it provides power capacities (GW) at a high degree of predictable availability. This gains even more importance when flexible thermal units are being phased out and when decentralized solutions, such as batteries, electric vehicles and demand response, are expected to provide short-term flexibility, but in a less predictable way [5].

4 Network codes and system operation

4.1. European synchronous areas

The electric power systems across Europe has been evolving towards interconnection from many decades. Nowadays, the European Network of Transmission System Operators for Electricity (ENTSO-E) represents 42 electricity TSOs from 35 countries across Europe and has which are organized in five Synchronous Areas²⁾ (SA) - see Figure 3 and Table 2:

- Continental Europe;
- Nordic countries;
- United Kingdom;
- Ireland (Republic of Ireland and Northern Ireland);
- Baltic Interconnected Power System.

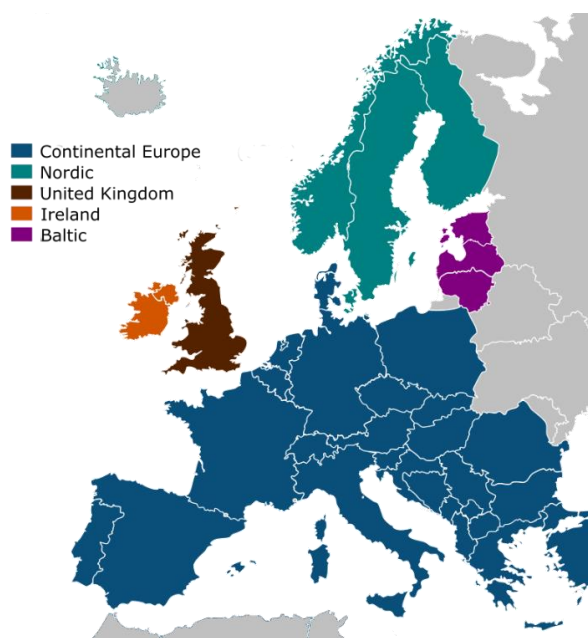


Figure 3 European SA (adapted from [27])

Table 2. Participating countries in each European SA

Synchronous area	Participating Countries
Continental Europe	Albania, Austria, Belgium, Bosnia-Herzegovina, Bulgaria, Czech Republic, Croatia, Denmark (West), <u>France</u> , Germany, Greece, Hungary, Italy, Luxemburg, Montenegro, Netherlands, Poland, <u>Portugal</u> , Romania, Serbia, Slovakia, Slovenia, Spain, <u>Switzerland</u> and Turkey
Nordic	Denmark (East), Finland, Norway and Sweden
Baltic	Estonia, Latvia, Lithuania

²⁾ "Synchronous area" means an area covered by synchronously interconnected TSOs.

Synchronous area**Participating Countries**

United Kingdom

Great Britain

Island of Ireland

Ireland and Northern Ireland

Regarding the context of the XFLEX HYDRO demonstrators, they are geographically integrated in the CE SA, namely, in France, Portugal and Switzerland. Therefore, in order to document the existing and future trends with respect to the definition of system services requirements the CE SA is taken as the main reference.

4.2. System services in Continental Europe – an overview

4.2.1. Scope

This section provides an overview regarding the system services established by the European Commission Regulation, namely the ones described in SOGL [15] and in NC RfG [16]. The focus of this description is to highlight the requirements that are defined by the existing EU Regulation for system service providers. For the sake of objectivity, only the requirements that are expected to have a relevant impact for the XFLEX HYDRO project are described. This means that these requirements are described for the CE SA (the remaining four SA of Table 2 are excluded from the analysis) and for the hypothesis of the provider being a power-generating facility. Demand facilities, distribution systems and High Voltage Direct Current (HVDC) systems are excluded from the analysis. The ongoing developments on system service requirements, performed within the framework for a common European balancing market and the cross-border activation of reserves within CE SA, are described afterwards in chapter 5.

4.2.2. System services

The system services in EU Regulation are separated into the following groups:

1. Active power services, aiming to provide proper load-frequency control and comprising the provision of the following reserves:
 - Frequency Containment Reserve (FCR);
 - Frequency Restoration Reserve (FRR), where a distinction is performed between FRR with automatic activation (aFRR) and with manual activation (mFRR);
 - Replacement Reserve (RR).
2. Voltage/reactive power (Volt/var) services, aiming to provide proper voltage control.

An overview of the main characteristics of these services are described below.

4.2.3. Frequency Containment Reserve process

FCR control target

The main goals of the FCR process are the following:

- Contain system frequency after the occurrence of an active power imbalance. This is implemented by maintaining a balance between active power generation and demand within the entire CE SA.
- Fulfilling pre-specified frequency time domain behaviour requirements after the occurrence of an instantaneous imbalance equal or less severe than the "reference incident" (which is $\pm 3\text{GW}$ for CE SA). The main frequency behaviour requirements, for CE SA, are illustrated in Figure 4 and described next:

- Maximum instantaneous frequency deviation ($|\Delta f(t)|_{\max}$) of 0.8 Hz;
- Maximum steady-state frequency deviation after the "FCR full activation time"³ ($|\Delta f_{ss}|_{\max}$) of 0.2 Hz. "FCR full activation time" is specified in 30 seconds for CE SA. Δf_{ss} is named "FCR full activation frequency deviation".

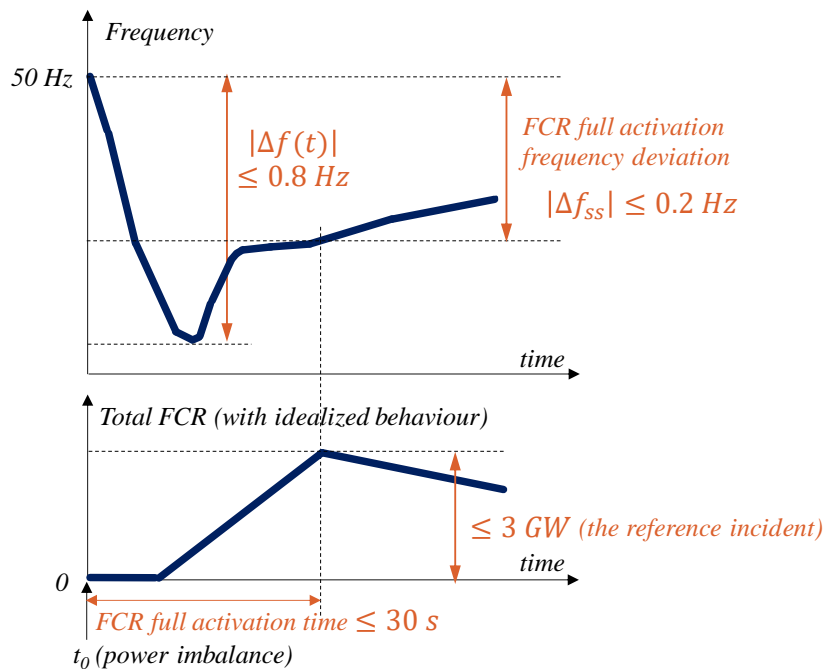


Figure 4 Frequency behavior requirements after a generation loss of 3 GW (in CE SA)

FCR implementation

In CE SA, FCR was formerly named "primary control" [28]. This process is implemented by an automatic and decentralized control of FCR, provided by the speed droop characteristic implemented in the speed governors of generation units from FCR providers. This is a mandatory service and a joint action/responsibility distributed among all the TSOs of the CE SA.

FCR minimum technical requirements to be ensured by the TSOs

Each reserve connecting TSO shall ensure that the FCR fulfils the properties listed for its SA, namely, that the combined reaction of FCR in its control area comply with the following requirements specified for CE SA:

- Minimum accuracy of frequency measurement: 10 mHz or the industrial standard if better.
- Maximum combined effect of inherent frequency response insensitivity and possible intentional frequency response dead band of the governor of the FCR providers (FCR providing units or providing group): 10 mHz.
- "FCR full activation time": 30 s (illustrated in Figure 4).
- "FCR full activation frequency deviation": ± 0.2 Hz (illustrated in Figure 4 for a generation loss).

³⁾ "FCR full activation time" is the time period between the occurrence of the "reference incident" and the corresponding full activation of the FCR.

- The activation of FCR shall not be artificially delayed and must begin as soon as possible after a frequency deviation.
- In case of a frequency deviation $|\Delta f| \geq 0.2$ Hz:
 - at least 50 % of the full FCR capacity shall be delivered, at the latest, after 15 s;
 - 100% of the full FCR capacity shall be delivered, at the latest, after 30 s;
 - the activation time of the FCR capacity shall rise, at least, linearly from 15 s to 30 s (see Figure 5).

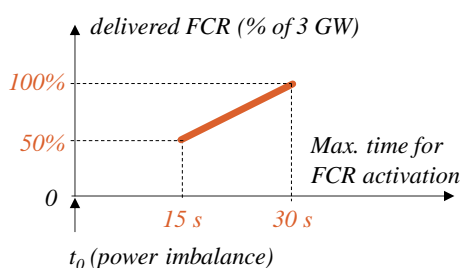


Figure 5 Maximum value for FCR activation time if frequency deviations are equal or larger than 0.2 Hz (in CE SA)

FCR minimum technical requirements to be ensured by the reserve providers

- Each FCR providing unit/group shall comply with the following requirements (these requirements are similar to the ones ensured by the reserve connecting TSO for the combined reaction of FCR in its control area):
 - Minimum accuracy of frequency measurement: 10 mHz or the industrial standard if better.
 - Maximum combined effect of inherent frequency response insensitivity and possible intentional frequency response dead band of the governor of the FCR providing unit/group: 10 mHz.
 - "FCR full activation time": 30 seconds.
 - "FCR full activation frequency deviation": ± 0.2 Hz.
- Besides, FCR providers shall be capable of activating FCR within the frequency ranges specified in Article 13(1)(d) of NC RfG [16] and presented in Table 3.

Table 3. FCR frequency ranges in CE SA

Frequency range	Time period for operation
47.5 Hz ÷ 48.5 Hz	To be specified by each TSO, but not less than 30 min
48.5 Hz ÷ 49.0 Hz	To be specified by each TSO, but not less than the period for 47.5 Hz-48.5 Hz
49.0 Hz ÷ 51.0 Hz	Unlimited
51.0 Hz ÷ 51.5 Hz	30 min

- FCR providers must also comply with any additional properties specified by the TSOs of its SA (in the SA operational agreement) or by the reserve connecting TSO, by means of a set of technical parameters within the ranges in Article 15(2)(d) of NC RfG. In particular, the following can be specified:
 - The power-generating module shall be capable of providing an active power-frequency response, like the one illustrated in Figure 6, within the following ranges:
 - Active power range related to maximum capacity: $(|\Delta P_1|/P_{\max}) \times 100 \in [1.5\%; 10\%]$;

- Speed droop: $s_1 \in [2\%; 12\%]$.
- In the event of a frequency step change, the power-generating module shall be capable of activating full active power response at or above the full line shown in Figure 7 (which shall aim at avoiding active power oscillations for the power-generating module) within the following ranges:
 - Maximum value for the initial delay (t_1) for power-generating modules with inertia: 2 s;
 - Maximum value for the initial delay (t_1) for power-generating modules without inertia: as specified by the relevant TSO (a shorter time than 2 s can be specified);
 - Maximum value for the full activation time (t_2): 30 s.
- The initial activation shall not be unduly delayed.
- The power-generating module shall be capable of providing full active power-frequency response for a period between 15 min and 30 min.

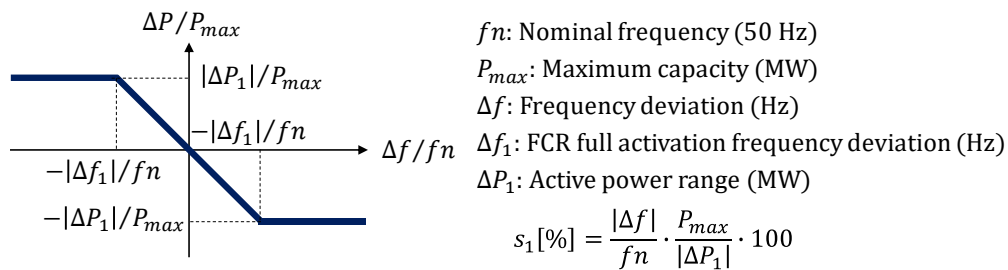


Figure 6 Active power-frequency response characteristic (case of zero dead band and insensitivity)

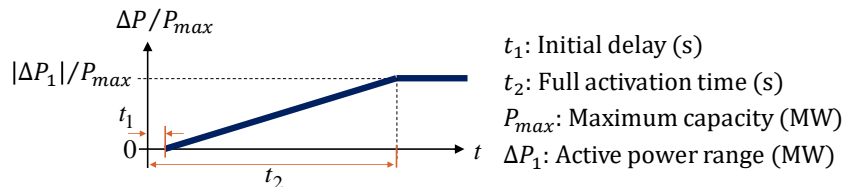


Figure 7 Active power time response capability

4. For the CE SA, all TSOs shall develop a proposal concerning the minimum delivery period to be ensured by FCR providers. This period must be between 15 min and 30 min (being 15 min the "time to restore frequency", which is explained in the next section within the FRR process).
5. To ensure that the loss of an FCR providing unit does not endanger operational security, the share of the FCR provided per FCR providing unit is limited to 5% of the reserve capacity of FCR required for the whole CE area, i.e., it is limited to 150 MW (5% of ± 3 GW).
6. An FCR provider with a limited energy reservoir shall ensure the recovery of the energy reservoirs, in the positive or negative directions, as soon as possible. For the CE SA, this must be obtained within 2 hours after the end of the alert state.

4.2.4. Frequency Restoration Reserve process

FRR control target

The main goal of the FRR process is to restore the Area Control Error (ACE, but also named Frequency Restoration Control Error or FRCE) of each Load-Frequency Control (LFC) area toward zero. In brief,

the computation of the ACE signal for an LFC area is illustrated in Figure 8. From the perspective of power system operation, the goals of the FRR process are the following:

- Restore the system frequency (f) to its set point value (f_{REF}) i.e., restore the signal $\Delta f = f - f_{REF}$ towards zero;
- Restore the balance between the active power generation and demand within the control area, after the occurrence of a power imbalance. This process aims at ensuring that the active power imbalance is corrected only by the generating units of the disturbed control area. This is implemented by restoring the power interchanges with neighbouring control areas (P_{if}) to the programmed value (P_{ifREF}): i.e. restoring the signal $P_{if} - P_{ifREF}$ towards zero.

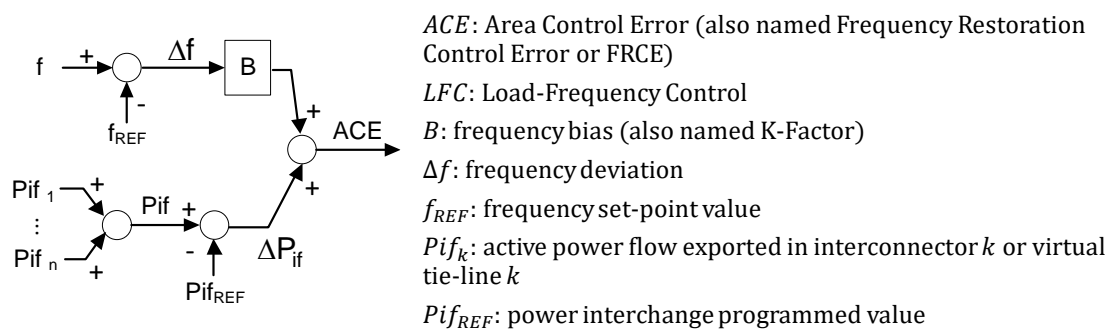


Figure 8 ACE computation for an LFC area

In principle, the active power reserve activated by the FRR process replaces the active power reserve that was previously activated by the FCR process.

FRR implementation

This is a mandatory process, implemented by the TSO of the disturbed LFC area, being distinguished in the following two solutions:

- Automatic FRR process or aFRR (formerly named "secondary control" [28]), being implemented by an automatic and centralized TSO-equipment (a controller with proportional-integral behaviour, named "frequency restoration controller", "Automatic Generation Control" or AGC) that controls the active power of FRR providers in its LFC area.
- Manual FRR process or mFRR (formerly named "directly activated tertiary control" [28]), being implemented by TSO instructions for manual FRR activation in the LFC area.

FRR minimum technical requirements to be ensured by the TSOs

It is up to the TSO to decide having only aFRR, mFRR or a combination of both, however, always having in mind that:

- The process must be finished within the "*time to restore frequency*"⁴⁾, which is 15 min for the CE SA. In other words, the "*FRR full activation time*"⁵⁾ must not exceed 15 min.
- The FRR process must be performed without overshoot.

⁴⁾ "*time to restore frequency*" means the maximum expected time after the occurrence of an instantaneous power imbalance within which the imbalance is compensated.

⁵⁾ "*FRR full activation time*" means the time period between the setting of a new set point value and the corresponding activation/deactivation of FRR.

FRR minimum technical requirements to be ensured by the reserve providers

The following minimum time requirements are defined, in [15], for aFRR providers:

- *"aFRR activation delay"*⁶⁾ must not exceeding 30 s.
- Capable of activating its complete automatic reserve capacity on FRR within the *"automatic FRR full activation time"*⁷⁾, where this time must not exceed the *"time to restore frequency"* (i.e. 15 min).

The following minimum time requirements are specified, in [15], for mFRR providers:

- Capable of activating its complete manual reserve capacity on FRR within the *"manual FRR full activation time"*⁸⁾, where this time must not exceed the *"time to restore frequency"* (i.e. 15 min).

Moreover, the FRR providers must ensure that their FRR providing units/groups fulfil the following:

- availability requirements defined in the *"LFC block operational agreement"*⁹⁾;
- control quality requirements defined in the *"LFC block operational agreement"*;
- ramping rate requirements (maximum ramping rates and/or ramping constraints during hour change) that may exist in the *"LFC block operational agreement"*.

4.2.5. Replacement Reserve process

RR control target

The aim of the RR process is to progressively replace the activated FRR and/or support the FRR control process by activation of RR.

RR implementation

RR implementation consists in optional TSO instructions for manual activation of reserves in the LFC area, usually performed after the *"FRR full activation time"* (and the *"time to restore frequency"*), in a timeframe between 15 min to one hour. Formerly, this process is named *"scheduled activated tertiary control"* [28]. This is a process to be implemented by the TSO of the disturbed control area.

To better understand the time-domain hierarchy of the load-frequency control process, the expected dynamic activation of each type of reserve (i.e. FCR, aFRR, mFRR and RR), after an active power generation shortfall is illustrated in Figure 9.

⁶⁾ *"aFRR activation delay"* means the time period between the setting of a new set point value and the start of physical automatic FRR delivery.

⁷⁾ *"automatic FRR full activation time"* means the time period between the setting of a new set point value by the frequency restoration controller and the corresponding activation or deactivation of automatic FRR.

⁸⁾ *"manual FRR full activation time"* means the time period between the set point change and the corresponding activation or deactivation of manual FRR.

⁹⁾ *"LFC block operational agreement"* means a multi-party agreement between all TSOs of an LFC block if the LFC block is operated by more than one TSO and means an LFC block operational methodology to be adopted unilaterally by the relevant TSO if the LFC block is operated by only one TSO (like the control block of Portugal operated by REN).

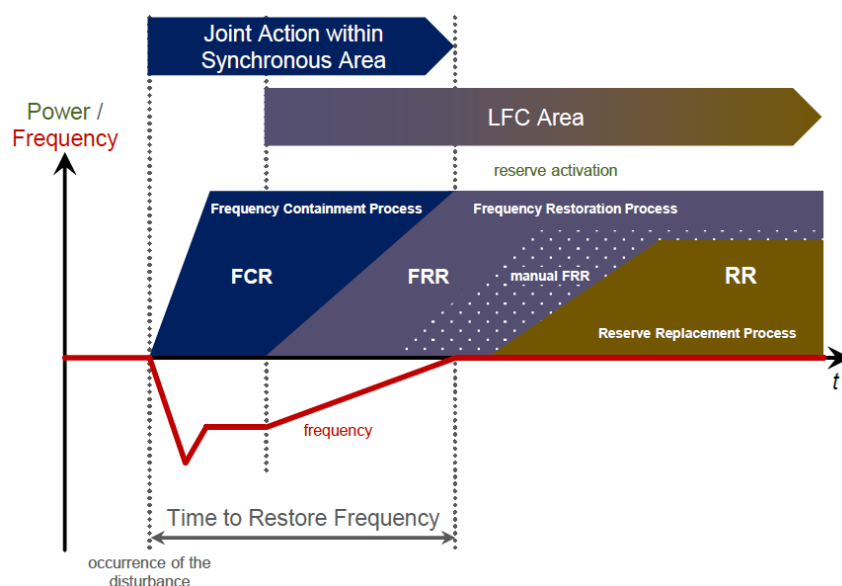


Figure 9 Time domain hierarchy of the load-frequency control process [11]

RR minimum technical requirements to be ensured by the reserve providers

According to SOGL [15], defining the minimum technical requirements of RR providers is a responsibility of the "reserve instructing TSO"¹⁰⁾ and TSO of the same LFC block. In fact, according to SOGL [15], RR providers must comply with the following minimum technical requirements:

- Activation of complete reserve capacity on RR within the activation time defined by the "reserve instructing TSO".
- Control quality requirements defined in the "LFC block operational agreement".
- Availability requirements defined in the "LFC block operational agreement".

4.2.6. Voltage/reactive power control process

Volt/var control implementation

The Volt/var control process is implemented by manual and/or automatic control actions designed to maintain the set values for the voltage levels and/or reactive powers.

Minimum technical requirements to be ensured by the Volt/var service providers

Scope of application

For power-generating facilities, the minimum technical requirements for the provision of voltage/reactive power services are specified in NC RfG [16]. Regarding this EU regulation, it is important to highlight the scope of application, namely the following:

- This regulation shall apply to new power-generating modules and to existing power-generating modules subjected to substantial modifications.
- A distinction is performed for the requirements to be ensured by different unit categories, namely by type A, B, C and D units. The unit category is defined by the voltage level of the connection point and the maximum capacity like described in Table 4.

¹⁰⁾ "Reserve instructing TSO" means the TSO responsible for the instruction of the reserve-providing unit or the reserve-providing group to activate FRR and/or RR.

- A distinction is performed for the requirements to be ensured by *"synchronous power-generating modules"*¹¹⁾ and *"power park modules"*¹²⁾. Within the XYFLEX HYDRO project, it is assumed that the fixed speed hydro power plants fulfil the requirements applicable to *"synchronous power-generating modules"*.
- In NC RfG [16], *"Pump-storage variable speed power-generating modules shall fulfil the requirements applicable to synchronous power-generating modules..."*. Therefore, within the XYFLEX HYDRO project, we may also assume that the variable speed HPP fulfil the requirements applicable to synchronous power-generating modules. However, since variable speed HPP are connected to the network through power electronics, this report also describes the technical requirements, to be provided by *"power park modules"* for the V/Q control.

Table 4. Categories of power-generating facilities, NC RfG [16]

Category	Voltage level of the connection point	Maximum capacity
Type A	<110 kV	≥ 0.8 kW
Type B	<110 kV	\geq threshold (proposed by the relevant TSO), conditioned by threshold ≤ 1 MW (for CE SA)
Type C	<110 kV	\geq threshold (proposed by the relevant TSO), conditioned by threshold ≤ 50 MW (for CE SA)
Type D	<110 kV	\geq threshold (proposed by the relevant TSO), conditioned by threshold ≤ 75 MW (for CE SA)
	≥ 110 kV	any

Volt/var control requirements for type B or C synchronous power-generation modules

In article 17(2)(b), with regard to the voltage control system: a synchronous power-generating module shall be equipped with a permanent automatic excitation control system that can provide constant alternator terminal voltage at a selectable setpoint without instability over the entire operating range of the synchronous power-generating module.

Volt/var control requirements for type C or D synchronous power-generation modules

In article 18(2)(b)(i)-(ii), with regard to reactive power capability at maximum capacity: the relevant system operator shall specify a $U - Q/P_{\max}$ profile that may take any shape within the boundaries of which the synchronous power-generating module shall be capable of providing reactive power at its

¹¹⁾ *"Synchronous power-generating module"* means an indivisible set of installations which can generate electrical energy such that the frequency of the generated voltage, the generator speed and the frequency of network voltage are in a constant ratio and thus in synchronism.

¹²⁾ *"power park module"* or *"PPM"* means a unit or ensemble of units generating electricity, which is either non-synchronously connected to the network or connected through power electronics, and that also has a single connection point to a transmission system, distribution system including closed distribution system or HVDC system.

maximum capacity. Namely, the specified $U - Q/P_{\max}$ profile may take any shape inside the inner envelope presented in Figure 10 (the position, size and shape of the inner envelope are indicative).

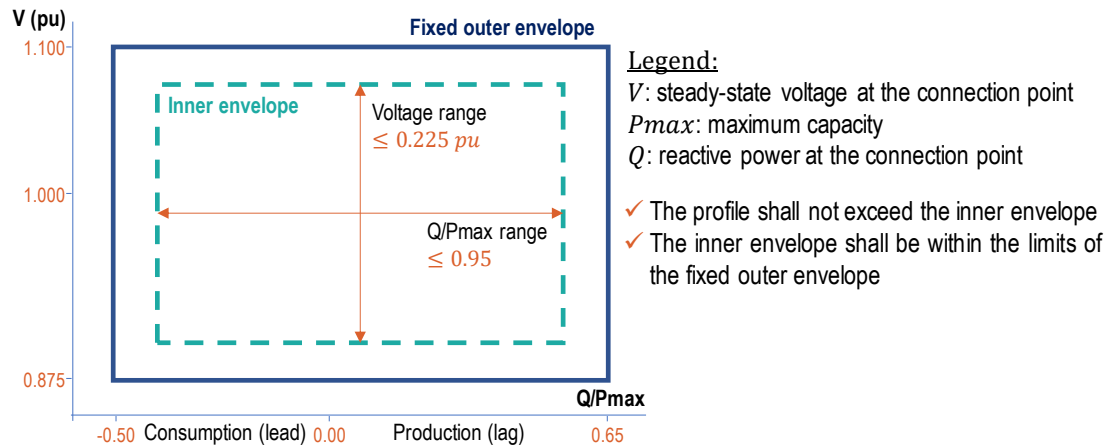


Figure 10 $U - Q/P_{\max}$ profile of a type C or D synchronous power-generation module (with the ranges defined for CE SA)

Volt/var control requirements for type D synchronous power-generation modules:

- In article 19(2)(a), the parameters and settings of the components of the voltage control system shall be agreed between the power-generating facility owner and the relevant system operator.
- In article 19(2)(b), the agreement referred to in subparagraph (a) shall cover the specifications and performance of an Automatic Voltage Regulator ("AVR") with regard to steady-state voltage and transient voltage control and the specifications and performance of the excitation control system. The latter shall include:
 - bandwidth limitation of the output signal (to ensure that the highest frequency of response cannot excite torsional oscillations on other power-generating modules connected to the network);
 - an underexcitation limiter (to prevent the AVR from reducing the alternator excitation to a level which would endanger synchronous stability);
 - an overexcitation limiter (to ensure that the alternator excitation is not limited to less than the maximum value that can be achieved whilst ensuring that the synchronous power-generating module is operating within its design limits);
 - a stator current limiter;
 - a PSS function (to attenuate power oscillations) if the synchronous power-generating module size is above a value of maximum capacity specified by the relevant TSO.

Volt/var control requirements for type B power park module

In article 20(2)(a), regarding reactive power capability, the relevant system operator shall have the right to specify the capability of a power park module to provide reactive power.

Volt/var control requirements for type C or D power park module

- In article 21(3)(b), regarding reactive power capability at maximum capacity: (i) the relevant system operator in coordination with the relevant TSO shall specify the reactive power provision capability requirements in the context of varying voltage. To that end, it shall specify a $U - Q/P_{\max}$ profile that may take any shape within the boundaries of which the power park module shall be capable of providing reactive power at its maximum capacity. Namely, the

specified $U - Q/P_{\max}$ profile may take any shape inside the inner envelope presented in Figure 11 (the position, size and shape of the inner envelope are indicative).

- In article 21(3)(c), with regard to reactive power capability below maximum capacity: (i) the relevant system operator in coordination with the relevant TSO shall specify the reactive power provision capability requirements and shall specify a $U - Q/P_{\max}$ profile that may take any shape within the boundaries of which the power park module shall be capable of providing reactive power below maximum capacity. Namely, the specified $P - Q/P_{\max}$ profile may take any shape inside the inner envelope presented in Figure 12 (the position, size and shape of the inner envelope are indicative) constrained by the following:
 - the active power range of the profile envelope at zero reactive power shall be 1 p.u.;
 - the profile shall include conditions for reactive power capability at zero active power.

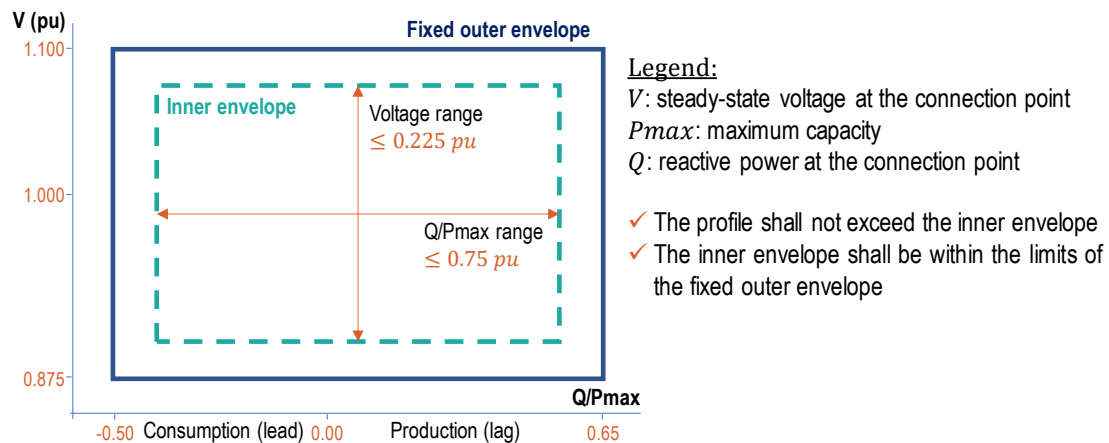


Figure 11 $U - Q/P_{\max}$ profile of a type C or D power park module (with the ranges defined for CE SA)

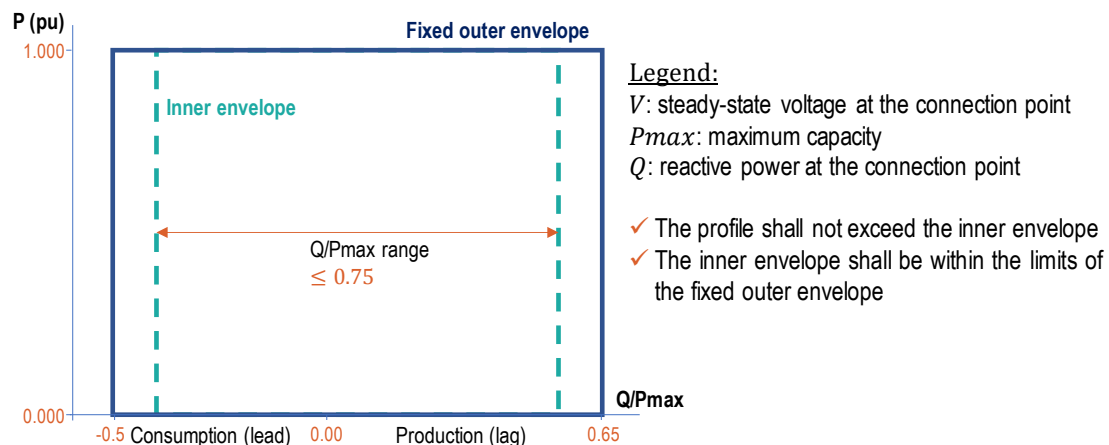


Figure 12 $P - Q/P_{\max}$ profile of a type C or D power park module (with the ranges defined for CE SA)

- In article 21(3)(d), regarding reactive power control modes:
 - The power park shall be capable of providing reactive power automatically by either voltage control mode, reactive power control mode or power factor control mode.

- For the purposes of voltage control mode: the power park module shall be capable of contributing to voltage control at the connection point with a setpoint voltage covering 0.95 p.u. to 1.05 p.u., p.u. in steps ≤ 0.01 p.u., with a slope having a range of at least 2% to 7% in steps $\leq 0.5\%$. The reactive power output shall be zero when the grid voltage value at the connection point equals the voltage setpoint.
- The setpoint may be operated with or without a deadband selectable in a range from zero to $\pm 5\%$ of reference 1 p.u. network voltage in steps $\leq 0.5\%$.
- Following a step change in voltage: the power park module shall be capable of achieving 90% of the change in reactive power output within a time t_1 in the range of 1 s to 5 s, and must settle at the value specified by the slope within a time t_2 in the range of 5 s to 60 s, with a steady-state reactive tolerance $\leq 0.5\%$ of the maximum reactive power. The relevant system operator shall specify the t_1 and t_2 time specifications.
- For the purpose of reactive power control mode: the power park module shall be capable of setting the reactive power setpoint, anywhere in the reactive power range, with setting steps no greater than 5 Mvar or 5% (whichever is smaller) of full reactive power, controlling the reactive power at the connection point to an accuracy within ± 5 Mvar or $\pm 5\%$ (whichever is smaller) of the full reactive power.
- For the purpose of power factor control mode: the power park module shall be capable of controlling the power factor at the connection point, within the required reactive power range, with a target power factor in steps ≤ 0.01 . The relevant system operator shall specify the target power factor value, its tolerance and the period of time to achieve the target power factor following a sudden change of active power output. The tolerance of the target power factor shall be expressed through the tolerance of its corresponding reactive power. This reactive power tolerance shall be expressed by either an absolute value or by a percentage of the maximum reactive power of the power park module.

4.3. Synchronous and Synthetic Inertia

4.3.1. General concept

In classical power systems, "*inertia*" is the physical parameter that represents the inherent capability of rotating machines (including loads, when applicable) to store and inject their kinetic energy to the power system [29]. The level of inertia directly influences frequency transient behaviour in the moments subsequent to an active power imbalance. Namely, it affects the frequency gradient (also named RoCoF) and the maximum value reached by instantaneous frequency deviations. Therefore, an inertia decrease can raise the risk of losing system security by risking load-shedding intervention, generators trip, or, in the worst scenario, by a blackout situation.

To limit the transient frequency deviations and RoCoF, the required inertia is usually obtained by the connected rotating masses (from synchronous generators and the pumps of pump-storage hydro power plants with fixed speed units), being this inertia named "synchronous inertia". Given the trends in inertia reduction, synchronous inertia can also be provided by using synchronous condenser, i.e. synchronous generators being operated in the synchronous condenser mode. Synchronous condensers do not provide any active power to the system but are regularly used for voltage control purposes in many countries by means of their excitation system. Moreover, these are devices that comprise a freely spinning machine connected to the grid so, they can also provide synchronous inertia for supporting grid operation. The aggregated use of inertia as a service and voltage control is a tempting application for synchronous condensers, but using these machines with the sole purpose of providing synchronous inertia does not seem to be a cost-effective solution [30].

Alternatively, power electronic interfaced power sources (the main cause for inertia level reduction in the power systems) can also provide short-term frequency support. These power sources have no inherent inertial response, but are able to swiftly adapt power output, driven by their control system, to provide "*synthetic inertia*". This "*synthetic inertia*" constitutes a synthesized active power response driven by a frequency event in the grid, with a response time much faster than FCR services. Moreover, the ability to provide this response in converter-interfaced units requires some form of energy buffer such that energy is available to be quickly injected to the system when required. As the energy buffer capabilities may be limited – as it is case of the energy that can be extracted from a rotating drive train of a wind turbine without losing mechanical stability – the time during which the service can be provided is usually limited to a few seconds [31]. Being limited in time, the active power response obtained from synthetic inertia is followed by a recovery period where power can drop below the pre-fault value. This recovery period is crucial in wind turbines, since the machine needs to re-accelerate following the speed decrease (due to kinetic energy extraction) occurring during the active power step deployment to the grid as a synthetic inertial response. It follows that the duration and amplitude of the active power recovery depends on this speed reduction, which may have dramatic impacts in the global system stability/frequency response, if not properly accommodated by the response of other sources, [32] and [33].

Furthermore, the "*synthetic inertia*" response might be quite restricted with respect to the available capacity, since the inverters have a very low overload capacity compared to synchronous machines [29]. Another difference between "*synthetic inertia*" and "*synchronous inertia*" is that the emulation requires the frequency to be measured. Therefore, its effect on the grid is delayed, and, for very-fast frequency transients, it may not be enough [34].

A study from the Danish ELETRA IRP project [35] proposed the provision of Fast Frequency Response (FFR) and synthetic inertia control, employing single phase electric vehicles as flexibility resources in a microgrid. The results show that FFR can improve the transient frequency behaviour. However, both on the simulation and on the experimental level, the implementation of synthetic inertia control showed to be more challenging with limited performance when compared with FFR. FFR is further described in section 4.4.

4.3.2. Inertia concerns and mitigation measures in large interconnected systems

In the last years, the level of inertia in the system is gaining an increased attention since it may be significantly reduced mainly due to the increasing integration of non-synchronous renewable generation.

Regarding inertia future capacity requirements in CE this is far away from being quantified/specified, being something that starts now to be evaluated. Several studies of the effects, on inertia reduction, from increasing non-synchronous share are still in progress [30]. From a general perspective, many large power systems – such as CE – have been studied lately, but systems with such levels of installed and interconnected capacity do not show significant vulnerability to low inertia [30]. For instance, Germany, a leading country in the field of renewable energy use, has not identified near future vulnerabilities related to low level of inertia [30]. The Iberian Peninsula is currently assisting to the development of studies to understand the value of synchronous inertia to be provided by synchronous condensers to be used following a conversion of synchronous machines available after the decommissioning of coal-fired power plants (assuming that all the power coal-fired station is dismantled and the generator remains to be operated in the synchronous condenser mode). As far as described in the available literature, providing inertia is not currently foreseen as a near future market service in CE SA.

Studies on the Nordic countries of EU highlighted that maximum instantaneous frequency deviation is the concern in the Nordic SA (RoCoF is not the concern) [36]. These studies concluded that more

efficient mitigation measures are available than increasing or maintaining the system inertia. Based on a cost and benefit analysis, the preferred solution to handle both the present and future low inertia situations in the Nordics are FFR based solutions [36].

Denmark purchased synchronous condensers in 2013, which could be used to provide inertial response, although this is not their primary task. Besides this implemented mitigation measure, Denmark increased the RoCoF threshold for new power plants with a capacity above 1.5 MW (from 2 Hz/s to 2.5 Hz/s). Their regulation also defines that wind turbines and photovoltaic units must withstand such frequency changes for at least 200 ms [30].

4.3.3. Regulatory framework in CE synchronous area

In the exiting ENTSO-E regulation, namely in NC RfG [16], no reference is performed about having synchronous inertia as a system service. Synthetic inertia is mentioned as a possible requirement to avoid a larger RoCoF during high RES production. The definition of synthetic inertia to be a mandatory service and of the associated performance parameters are decisions left to the relevant TSO. In fact, in article 21(2) of NC RfG, EU regulation states that Type C and D power park modules shall fulfil the following requirements:

- The relevant TSO shall have the right to specify that power park modules be capable of providing synthetic inertia during very fast frequency deviations.
- The operating principle of control systems installed to provide synthetic inertia and the associated performance parameters shall be specified by the relevant TSO.

4.3.4. Market framework outside CE synchronous area

Apart from large interconnected systems, several studies have shown urgent operational concerns regarding vulnerability to low inertia, namely in large-scale islands. This is for instance the case of the island of Ireland, of Great Britain and the south-eastern parts of Australia. In these power systems, inertia services were introduced on the market, aiming to provide proper replacement for the nearly instantaneous response of synchronous units.

TSOs of the Irish Island (EirGrid and SONI) have introduced a new synchronous inertia service named "Synchronous Inertial Response" (SIR). SIR is a response in terms of active power output and synchronizing torque that a unit (generator, synchronous condenser and load) can instantaneously provide after a disturbance. According to [30], the service is defined as the kinetic energy of the unit, multiplied by the SIR factor, whereas the SIR factor of a generator is calculated as the ratio of kinetic energy to the lowest sustainable power output at which the unit can still provide reactive power control. The threshold of the factor is between 15 and 45 seconds, where the higher value is considered for condensers and loads.

In UK, National Grid has specified a remunerated system service relying on the provision of inertia [37]. The provision of the service is organized under a tender process that started on 2019, for a service provision to start between April 2020 and April 2021 and for a contract to run until March 2023 or March 2026. Due to the timing and the need of high confidence in service delivery, the tenders are restricted to synchronous compensators and synchronous generators running in a synchronous compensator mode, i.e., are restricted to the provision of synchronous inertia. The main technical characteristics specified for this service are the following:

- As this is a zero MW service, the service will be treated as un-available when a plant is exporting or importing power for purposes other than providing the inertia service.
- Providers are welcome to offer other balancing services in conjunction so long as this does not impact on their availability to provide the inertia service.

- To participate, the minimum technical requirement is to have an inertia contribution of at least 1.5 p.u. of the plant MVA rating.
- Regarding availability, the service needs to be available 24/7 throughout the contract term, with an allowance of 15 calendar days of planned and agreed outages.

Although the specification of system services in other geographies is not in the scope of this report, this is next briefly approached, for the Australian Energy Market Operator (AEMO), in order to exemplify existing situations where synchronous inertia has a framework within a market service. AEMO already has synchronous inertia as a market service [38], being defined as an instantaneous response from synchronous machines, calculated as the stored kinetic energy that is extracted from the rotating mass of the machine after a disturbance (being therefore independent of the active power output of the unit) [30]. In the longer term, the plans in Australia include a wider range of frequency control services from inverter connected resources, like simulated inertia (in this report named synthetic inertia) to simulate the inertial response of a synchronous unit as closely as possible [38]. For now, AEMO states that simulated inertia is not yet commercially demonstrated for power systems with typical large RoCoF, like in South Australia (it can exceed 4 Hz/s, while in high inertia grids the RoCoF rarely exceeds +/- 0.1 Hz/s). The specified characteristics for this service include the following:

- Typical time to full response (including measurement and detection): no more than 10 ms – 20 ms (manufacturers have indicated to AEMO that inverter-connected devices with sub-cycle total response times of the order of 10 ms -20 ms may be feasible).
- Trigger and control type: Local frequency measurement.

4.4. Filling the gap between inertia and FCR – the FFR service

4.4.1. General concept

The Fast Frequency Response (FFR) service is designed to provide a MW response faster than existing operating reserve times and hence provide fast support to the power-frequency balance following a load-generation loss of equilibrium. It requires a rapid shift of active power in the timeframe following inertial response and before the activation of the FCR. It is intended to further reduce frequency excursions after a disturbance and to increase the time that frequency takes to reach nadir (i.e., the lowest frequency value after a disturbance). A general concept of this service can be defined as a fast injection (or absorption) of active power, by generating units or controllable loads, in a timeframe typically less than two seconds after a disturbance that provokes an imbalance of generation/demand equilibrium [39].

In CE, this service is not being implemented for the short/medium term, but it is a trend currently seen in another European SA. In fact, in Europe and outside CE SA, several TSOs are already planning or have already implemented incentives and common trading platforms between TSOs from the same SA, for ensuring enough capacity of FFR reserve to cope with the generation uncertainties from increasing penetration of VRE and the increasingly operational scenarios with reduced system inertia [39], [40]. This list of TSOs includes EirGrid and SONI (from the Ireland SA), National Grid UK (Great Britain SA) as well as the Nordic SA TSOs.

In the EU-SysFlex project [8], is mentioned that an innovative approach to add FFR to the portfolio of services for CE SA *"could include bundling FFR with other frequency response products to create a sustained response service, including specified trajectories into the product definition"* [39].

A FFR service is a relatively new concept that may be required to sustain the dynamic frequency stability of the EPS in face of increasing shares of VRE. In principle, this specific service could be provided by HPPs, more specifically, by the ones connected to the grid via a power electronic conversion stage

(Doubly Fed Induction Machines - DFIM or Full-Size Frequency Converters - FSFC), as it provides a decoupling between the electrical and the mechanical systems of the unit which typically benefits the capability to provide faster responses in comparison to synchronously connected units.

4.4.2. FFR examples from other European synchronous areas

The FFR product on the island of Ireland, and the Enhanced Frequency Response (EFR) product in Great Britain (also being considered an FFR service), are designed to provide a rapid active power response, in the face of sudden power imbalance, in order to promptly arrest frequency excursions. The increase or decrease of active power regarding these products is intended to be faster than the classical operating reserves, such as FCR and aFRR. The FFR product from Ireland Island has a full activation time (FAT)¹³⁾ that should be less than 2 s and requires a duration of at least 8 s. If a market player is capable of delivering both SIR and FFR, it is allowed to participate with both services [41].

The existing requirements for the EFR product existing in Great Britain are more demanding, since the FAT should be less than 1 s and requires a duration of at least 15 min [39]. EFR is a continuous service, aiming to manage system frequency through a droop response characteristic based on locally measured frequency values. National Grid has already launched tenders for EFR, with two types of services, which only differ in the size of the deadband (± 0.05 Hz and ± 0.015 Hz).

Table 5 compares the two earlier referred (fast) frequency responses products, which can be classified in the same bucket of FFR.

Table 5. FFR types of services in UK and Ireland [39]

Products	Jurisdiction	FAT	Duration	Comments
FFR	Ireland and Northern Ireland	2 s	8 s	There is an incentive for responses faster than 2 s. Min and Max provision levels apply.
EFR	Great Britain	1 s	15 min	Providers must be capable of delivering a minimum of 1 MW of response. This may be from a single unit or aggregated from several smaller units. Maximum response of 50 MW.

Another example of a FFR type of service is the one envisioned by the Nordic TSO, called Fast Frequency Reserve, to handle low inertia situations that have become more frequent in the Nordic power system. This kind of new reserve should be in operation by summer of 2020 [40].

To participate in the Fast Frequency Reserve markets in the Nordic SA, it is necessary for the providing units and groups to be prequalified, to ensure that all necessary technical requirements are fulfilled [40].

¹³⁾ "Full Activation Time" or FAT means the time period between the activation request and the full delivery of active power.

There are several combinations for FFR provision regarding not only the FAT but also regarding the support duration¹⁴⁾ of the product. The provider can freely choose the combination of requirements that are best suited for each providing entity [40].

There are three different alternatives regarding the frequency activation level and the time that takes to fully activate (i.e., the FAT value) [40], namely:

- Option A: $FAT \leq 0.7$ s for a frequency activation level of 49.5 Hz;
- Option B: $FAT \leq 1.0$ s for a frequency activation level of 49.6 Hz;
- Option C: $FAT \leq 1.3$ s for a frequency activation level of 49.7 Hz.

The provider may choose any of the three alternatives A, B, or C, but the choice must be specified before the prequalification. The shape of activation is not crucial (see Figure 13): it may be a ramp, a step or something similar [40].

The prequalified FFR capacity and FFR overshoot are determined and defined as illustrated in Figure 13. The prequalified FFR capacity is the minimum support power in MW from the providing entity, within the time slot of the support duration. The maximum acceptable overshoot is 35% of the prequalified FFR capacity.

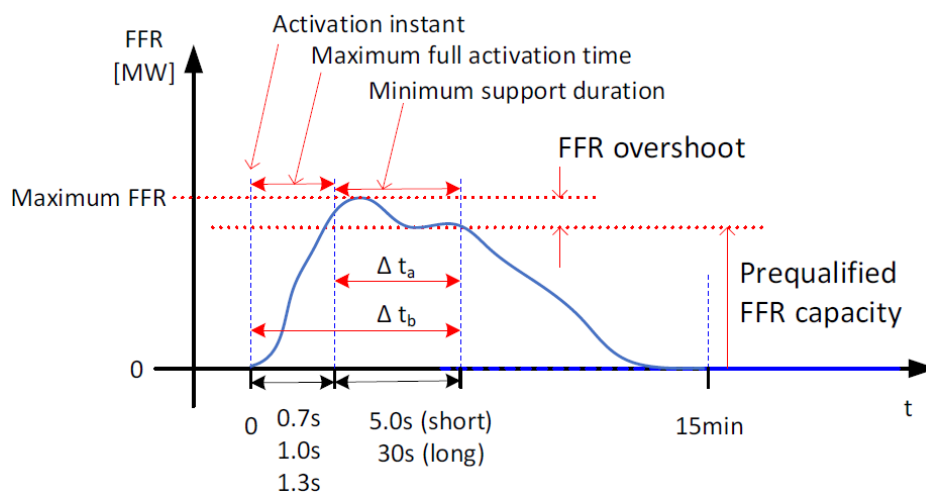


Figure 13 Definition of FFR service characteristics [40]

As illustrated in Figure 13, there are two alternatives for the minimum support duration:

- Short support duration FFR, with a delivery period of at least 5 seconds.
- Long support duration FFR, with a delivery period of at least 30 seconds.

A time evolution diagram illustrating the activation time, support duration, deactivation time, buffer time and recovery period are shown in Figure 14. Depending on the chosen support duration, there exist different alternative requirements for the rate of deactivation that the provider can freely choose to prequalify for [40]. The recovery must not start before a time corresponding to the activation time, plus the support duration, plus the deactivation time, plus 10 seconds after the activation instant (at $t = 0$ s). The activation cycle of the FFR is 15 min, which means that the FFR providing entity must be ready for a new activation cycle within 15 min after the activation instant [40]. The FFR service in the Nordic SA

¹⁴⁾ The "support duration" also named "delivery period" means the time period during which the service provider delivers/withdraws the full requested active power value.

is only defined for negative frequency deviations (underfrequency situations) since these are more severe than positive deviations (over frequency situations) [40].

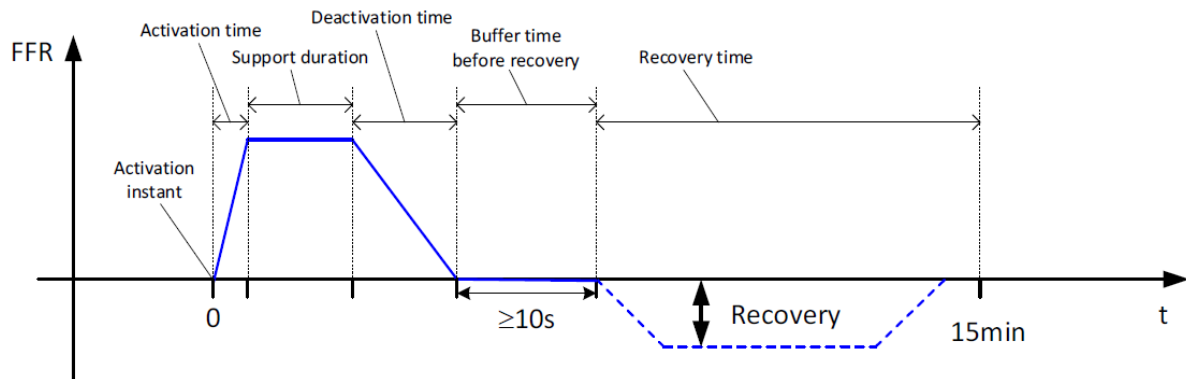


Figure 14 FFR activation and recovery requirements [40]

As described above, there are many different approaches and variations for the FFR product. They all depend on the specific needs of each SA and, as such, further studies are needed regarding the implementation of such a service in CE SA. However, a common characteristic for all the products listed above is that the time that takes fully activate this product should be less than 2 seconds [39].

4.5. Black start

Black start is the process of restarting operation of a power plant, within a blackout system state and from a completely non-energized operating state, in order to power up other plants and loads, aiming to bring the system back to normal operating conditions and to minimize the impact for consumers. A power plant is capable of black start if it can go from a completely shut down state to operational without requiring grid electricity supply.

According to ENTSO-E [42], a "black start unit" shall operate and deliver power without external electrical energy supply. It has island operation capability with the ability to run from shutdown condition to an operation mode. "Island operation capability" means that the generating unit can bring stability into an island and during steps of load pickup, in case of reenergizing the current island. In [42], ENTSO-E recommends TSOs to perform tests of black start capability, where the following behaviours are recommended for the black start units:

- "The generating unit should be able to run to the nominal speed and voltage as quick as possible and operate in this no-load operation state minimum 30 min".
- "... the generating unit should be able to regulate the frequency and voltage on a separated network island connected to the black start unit and balance the active and reactive load switching (on and off) by means of connecting lines and suitable load (e.g. pumps, auxiliaries/house load of units or power plants, contracted load as ancillary services) in some steps."

Besides being able to restart operation and deliver power without external electrical energy supply, according to [43], a black start power plant must also have the following characteristics:

- Reduced starting time (i.e. to bring the black start unit up to rated voltage) after a blackout;
- Reduced needs of station power and switching operations to reenergize the plant;
- Fast up/down MW ramp rate and being able to operate over a wide range of MW power (to provide flexibility to match changing power system demands);
- Enough MW and Mvar capacity to energize the transmission system and start other generators, with minimum transformers in between and with minimum transmission switching operations;

- Being able to withstand the large frequency excursions that usually occur during the early grid restoration operation (not for a long time, but long enough to stabilize an island);
- Being able to provide a proper control for stabilizing the grid frequency (in particular, having high inertia and variability of output) and being able to provide voltage control.
- Adequate on-site primary energy source supply (for instance, for hydropower this means having fuel to power the emergency diesel generators of the power plant and an adequate supply of water in the upper reservoir or from forecast inflows).

In addition, because of routine maintenance or a forced outage, power plants with several self-starting units are more valuable for black start than plants with a single self-starting unit.

In general, the way these characteristics translate into formal technical requirements for black start power plants varies from one system operator to another, due to differences in system characteristics and/or market design/rules. However, usually, the required starting time is equal or higher than 10 min.

Comparing with other power generation technologies that usually provide black start (namely, combustion turbines, combined cycle and fossil fuel power plants), hydropower plants are particularly well suited for black start. According to [43], the most attractive characteristics of hydropower plants to provide black start are:

- Have inherent ability to restart quickly (as fast as 10 min, similar to gas turbines) and with minimal station power needs (typically 0.5% to 1% of its rate capacity [44]).
- Allow fast MW ramp rates.
- Have the ability to operate over a wide range of MW power.
- Have no constraints of availability of primary energy supply (unless impacted by drought conditions).
- Usually have many self-starting units (at larger power plants).

As a possible disadvantage of hydropower, the location of the power plant can be a constraint and a concern for some transmission operators, especially in densely populated areas, since, by its nature, a hydropower plant is usually located on suburban or rural areas [43].

In future scenarios with a massive increase of renewable power production, the availability of thermal power generation technologies with black start capabilities will be very limited because of the decline and decommissioning of traditional thermal black start providers (larger synchronous power stations). Besides, the expected large integration of inverter-based distribution generation may increase the risk of blackout events because of the reduction of system inertia. Regarding these scenarios, investigations have been conducted to evaluate the capability of non-traditional technologies, namely of wind, solar, storage, demand side response and electric vehicles, in the restoration of the power system, in the event of a partial or total system shutdown.

Small-scale solar/wind systems and distribution-level battery energy storage systems (BESS), sited at end-user facilities or on distribution feeders/substations, can be valuable in providing power to facilities during a grid outage, but they are too small in power capacity to energize the transmission grid and serve as black start resources [43]. The creation of small-distributed power islands is of particular interest, with restoration being initiated on distribution networks and grow to energize the transmission network. For instance, the studies in [45] report that, technically, microgrids/power islands with a higher share of renewables and converters can be operated reliably, and have sufficient strength and stability to play an important role in supporting black start of the distribution and transmission power grid. Regarding utility-scale renewable energy sources (solar PV and wind power), if conditions are such that a solar or wind installation can supply power after an outage, and it is equipped with suitable advanced inverters and controls, it could theoretically black start and provide cranking power to other generators. However, like highlighted in [43], solar PV and wind power cannot be considered reliable black start

resources for planning purposes because of the uncertainties associated to the availability of the primary energy resource. In view of these conditions, it is expected that in future scenarios with a massive increase of renewable power production, the black start capabilities of hydropower plants will become of crucial importance to guard system security.

4.6. System services in countries hosting demonstrations

4.6.1. Portugal (PT)

Portugal is one of the three countries hosting demonstrators within the scope of the XFLEX HYDRO project. Therefore, it is important to provide an overview regarding the main services currently being demanded by the local system operator (REN - Redes Energéticas Nacionais, S.A.). These services are specified in the national regulation under the Global Management of the System handbook (hereafter named GMS) [46], the Transmission Network Regulation 596/2010 [47] and Regulation 73/2020 [48] defining non-exhausted national conditions related to the EU regulation 2016/631 NC RfG [16]. The existing services can be generally classified in two different groups: the frequency/active power control and the voltage/reactive power control services. An overview of the main characteristics of the aforementioned services are presented below.

Frequency/active power regulation services in PT

The operational procedures for the Portuguese transmission systems are specified in GMS [46], defining the frequency/active power regulation services in line with the ENTSO-E guidelines, in order to mitigate imbalances between generation and consumption. The required volume of each regulation reserve is defined in accordance with specific rules. Depending on the time scale in which its action takes place and the signal originated by its action, three regulation reserve levels are established: primary regulation reserve, secondary regulation reserve and tertiary regulation reserve. The specified requirements for each of these services are described next.

Primary regulation reserve in PT

The primary regulation reserve is formally equivalent to the new FCR (Frequency Containment Reserve) service defined in EU Regulation 2017/1485 (SOGL) [15]. It is currently constituted as a mandatory and not remunerated service for all power plants (including all kind of hydro power plants, excluding pumping operation mode in pumped storage plants) directly connected to the Portuguese transmission system.

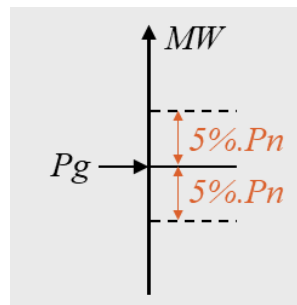


Figure 15 Primary control reserve availability requirement ($\pm 5\%$ around a stable point of operation)

The providers of primary regulation reserve are required to comply with the following requirements:

- Availability and speed droop characteristic: all generation groups must comply with primary reserve provision of, at least, 5% of its nominal power around any stable operational point (Figure 15), together with an adjustable speed droop characteristic between 4% to 6%.
- Frequency response insensitivity: 10 mHz.
- Frequency response dead band: 0 mHz.
- Maximum value for the initial delay (t_i in Figure 7 of section 4.2.3) for power-generating modules without inertia: 500 ms.
- Maximum activation time: For frequency deviations $|\Delta f| < 0.1$ Hz: the required reserve (according to speed droop characteristic) must be activated within the first 15 seconds.
- Maximum activation time: For frequency deviations $|\Delta f| \in [0.1, 0.2]$ Hz: the required reserve must be activated within 15 to 30 seconds and following a linear evolution for intermediate values (being 30 seconds the EU "FCR full activation time"), as it is depicted in Figure 16.

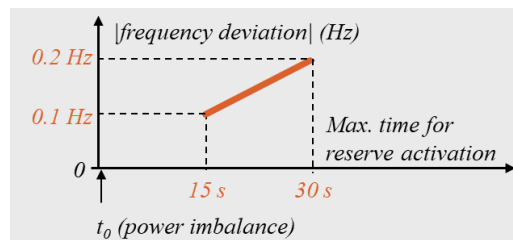


Figure 16 Maximum activation time for primary control reserve

- Minimum delivery period: providers should be able to fully activate primary reserve continuously for at least 15 min (the EU "time to restore frequency").

Secondary regulation reserve in PT

The secondary regulation reserve is formally equivalent to the aFRR (automatic Frequency Restoration Reserve), described in EU Regulation 2017/1485 [15]. Under the current Portuguese regulatory framework, it is procured within the framework of an internal market managed by the local TSO to which qualified providers must submit bids. Upon certification for the provision of the service by the local TSO, providers are then obliged to participate in the corresponding market.

Currently, the providers of secondary regulation reserve are obliged to comply with the following requirements:

- Requirements on the quality control and ramping rate of the product:
 - Activation should be concluded (and eventually completed by the tertiary reserve) in less than 5 min.
- Availability requirements:
 - Thermal groups shall be capable of continuously varying their power within a band corresponding to at least 10% of their rated power, within their operating power range and beyond the band available for primary control.
 - This secondary control band shall be at least 30% of the rated power for hydro power generators (Figure 17).
 - For every period, the system operator determines a ratio between upward and downward reserves, which is usually 2 (2/3 in the upward direction and 1/3 in the downward direction (Figure 17)) and with a tolerance of 5%.

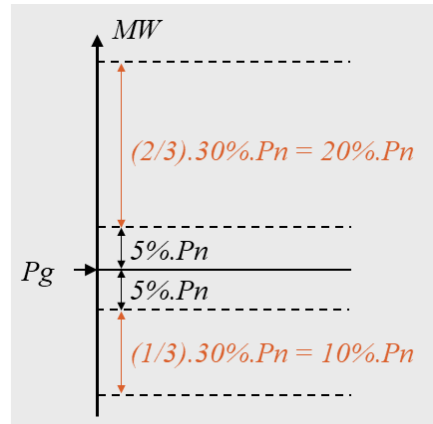


Figure 17 Availability requirement for secondary control reserve in hydropower units (30 % beyond primary reserve)

The upcoming Portuguese regulation, expected to be approved in 2020, will include more detailed national requirements for the provision of this reserve, adapted to EU requirements and the operation of a European platform for the exchange of balancing energy from aFRR.

Tertiary regulation reserve in PT

The tertiary regulation reserve is formally equivalent to a combination of mFRR and RR established in the EU Regulation 2017/1485 [15]. It is not a mandatory service. However, physical units are obliged to bid if they take part in the wholesale market and if qualified to participate in the system services market.

The upcoming Portuguese regulation will include national requirements for provision of this reserve, adapted to EU requirements, after having in operation the European platforms for the exchange of balancing energy from mFRR and from RR.

Volt/var control services in PT

Providing reactive power for voltage control is a mandatory and non-remunerated service, for generating units connected to the Portuguese transmission network. The operating conditions defined in the Portuguese Transmission Network Regulation [47] are defined below and in Figure 18.

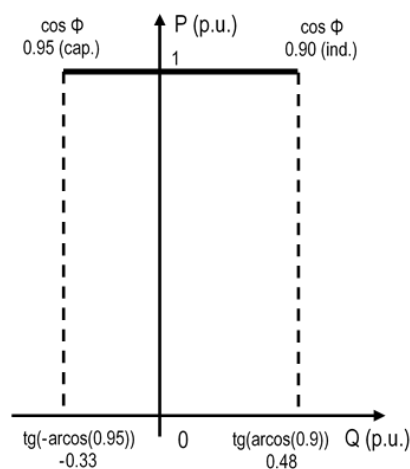


Figure 18 $P - Q / P_{\max}$ profile for synchronous generation modules

Every synchronous generator should be able to stably operate in each point of its P-Q characteristic, with the specified voltage in the high voltage side defined by technical conditions of the point of connection. Moreover, every synchronous generator should be able to guarantee its maximum active power output for:

- $\cos \Phi \in [0.9, 1]$ (inductive)
- $\cos \Phi \in [0.95, 1]$ (capacitive)

A more recent Portuguese legislation 73/2020 [48] specifies a P-Q/P_{max} profile for:

- power park modules of type B, C and D with voltage below 110 kV, which is presented in Figure 19;
- power park modules of type D with voltage greater or equal to 110 kV, which is presented in Figure 20.

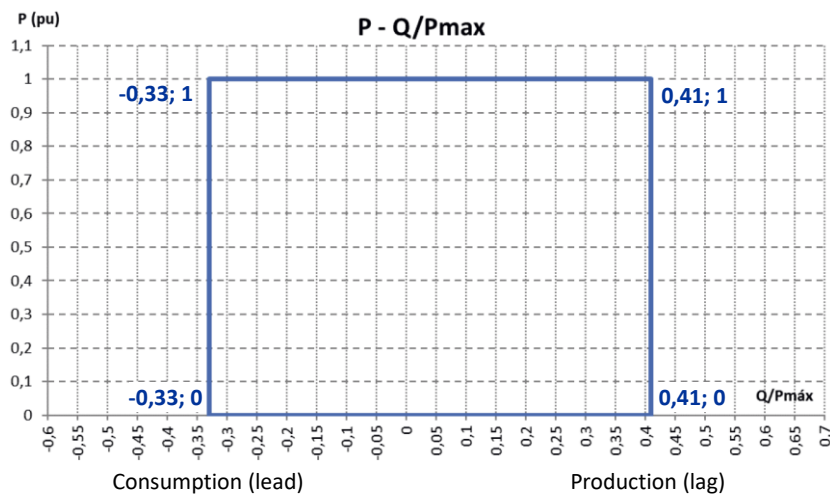


Figure 19 $P - Q/P_{max}$ profile for power park modules of type B, C and D with $U < 110$ kV [48]

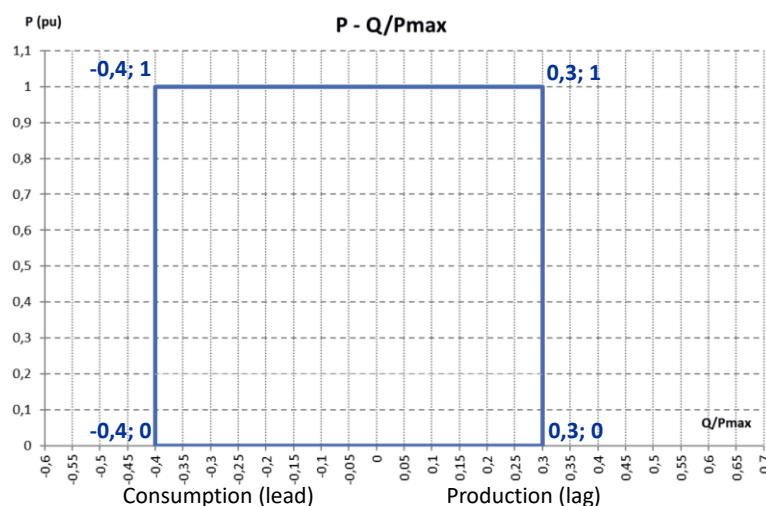


Figure 20 $P - Q/P_{max}$ profile for power park modules of type D with $U \geq 110$ kV [48]

The legislation [48] also specifies the following $U - Q/P_{\max}$ profiles:

- for synchronous generation or power park modules of type B, C and D with voltage below 110 kV, which is presented in Figure 21;
- for synchronous generation or power park modules of D with voltage greater or equal to 110 kV, which is presented in Figure 22.

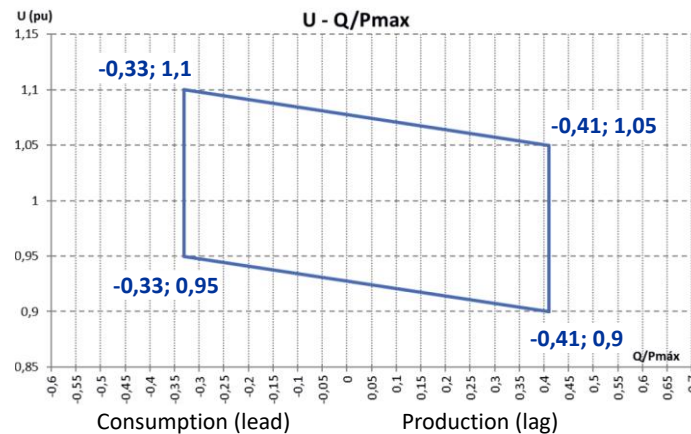


Figure 21 $U - Q/P_{\max}$ profile for synchronous generation or power park modules of type B, C and D with $U < 110$ kV [48]

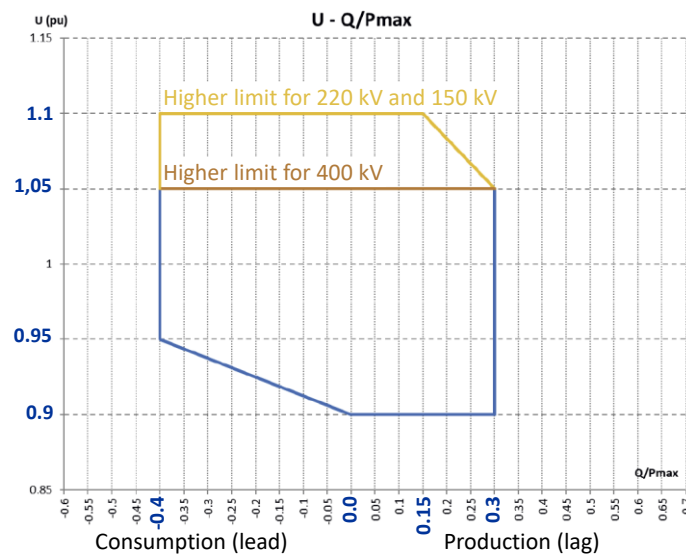


Figure 22 $U - Q/P_{\max}$ profile for synchronous generation or power park modules of type D with $U \geq 110$ kV [48]

Generation units connected to the transmission grid are also responsible for installing appropriated automatic voltage regulation mechanism to assure proper voltage regulation at the generation node, which are remotely set by the system operator. Type D synchronous generating modules must include a PSS function, if connected to very high voltage and if having a capacity of at least 45 MW. Although the reactive power provision is mandatory and non-remunerated for the aforementioned conditions, there can be a remunerated investment if a generator can provide reactive power outside the operating conditions defined in Portuguese regulation [47] and if agreed with the system operator (bilateral contract).

Additionally, it is important to highlight that pump storage HPP are often operate in the synchronous condenser mode, upon request by the local TSO, to provide Volt/var support to the grid.

4.6.2. France (FR)

This section describes the main services currently required by the French system operator (RTE - Réseau de transport d'électricité). These services are described in various technical documents from RTE as well as some contracting document from French regulator (CRE - Commission de régulation de l'énergie). The existing services can be generally classified in two different groups: the frequency/active power control and the voltage/reactive power control services. An overview of the main characteristics of these services is presented below.

Frequency/active power regulation services in FR

The operational procedures to maintain balance between production and consumption at any given time on the French electric network, also called frequency regulation, is divided into automatic reserves (specified in RTE's documentation) and manual reserves (specified in CRE's contracting documentation).

Automatic reserves are made of primary regulation reserve and secondary regulation reserve, while manual reserves are made of rapid reserve and complementary reserve. The aim and the technical description of these four reserves are described in the following sections.

Primary regulation reserve in FR

Primary regulation reserve aims at ensuring automatic participation of consumption and generation units connected to the CE SA to restore immediate balance between production and consumption, maintaining frequency within acceptable limits, following any foreseen event affecting this balance and for any unit able to do so [49]. This reserve is the equivalent to the European FCR as defined in EU Regulation 2017/1485 [15].

Contracting of primary regulation reserve in France goes through a market organized on the FCR cooperation platform [18]. This market is common to Austria, Belgium, France, Germany, the Netherlands and Switzerland. This platform and the corresponding product have evolved along the years, but this product has currently a validity period of 1 day since 1st of July 2019 with auction gate closure two days before real time. On 1st of June 2020, it will change to a four hours product with auction gate closure on the day before real time at 8:00. Since 1st of July 2019, FCR cooperation remunerates all auctions' winners at marginal price for capacity. Finally, FCR cooperation's product has been a symmetrical product since the beginning, meaning that one must be able to offer the same quantity of primary reserve upward and downward.

Consumption entities do not have the obligation to provide symmetrical primary response to be accepted on the FCR cooperation platform, they can be aggregated to reach symmetrical primary response [49]. Generation entities (including reversible generation) must however provide symmetrical primary response by themselves.

In France, all generating entities whose capacity is equal or above 40 MW must be able to provide a symmetrical band of 5% of their nominal power as primary regulation reserve around any given stable operation point (i.e. 2.5% upward and 2.5% downward) [50]. However, there is no obligation to bid on the FCR cooperation platform. The System Operator (RTE) might only require this band by obligation if there are not enough bids to cover primary regulation reserve requirements.

Finally, to be able to offer a capacity on the primary regulation reserve market in France [49]:

- The theoretical response of an entity is expected to be $K \times (50 \text{ Hz} - f)$ where f is the frequency at the connection point of the entity and the gain K is defined such that the entity delivers its full

primary response capacity within 30s for a frequency deviation $|f - 50 \text{ Hz}| = 0.200 \text{ Hz}$. Moreover, the shape of this response between 15 s and 30 s should always be above the line made of the points [15 s; 50% of primary response capacity] and [30 s; 100% of primary response capacity].

- The entity may have a dead band up to $\pm 10 \text{ mHz}$ around 50 Hz.
- The entity must be able to hold full capacity for a minimum of 15 min. Moreover, if the entity has limited storage it must be available again at least two hours after the end of the last activation period.

Secondary regulation reserve in France

Secondary regulation reserve aims at automatically restoring balance between production and consumption within RTE's control area after the intervention of primary regulation reserve. Thus, it aims at zeroing deviations to exchange programs with all other control areas and restore frequency to its target value [49]. This reserve is the equivalent of the European aFRR as defined in EU Regulation 2017/1485 [15].

In France, all generating entities whose capacity is equal or above 120MW must be able to provide a symmetrical band of 9% of their nominal power as secondary regulation reserve around any given stable operation point (i.e. 4.5% upward and 4.5% downward) [50].

Contracting of secondary regulation reserve is accomplished through obligation for the entities mentioned in the above paragraph. All these entities must send their forecasted generation program at 16:00 on D-1. At 17:00 on D-1, RTE sends out secondary reserve obligations to these entities for the following day. Their contribution to secondary reserve is proportional to their contribution to France's generation on each market time step [49].

Secondary response reserve in France has the following characteristics:

- It is symmetrical [49].
- Theoretical response of an entity is proportional to a reference signal periodically sent by RTE (referred to as N_{RSFP}) going from -1 to 1. The entity having to deliver 100% of the attributed upward secondary response capacity corresponds to a signal's value of 1 and 100% of the attributed downward secondary response capacity corresponds to a value of -1. The response should be proportional to the reference signal in between these extreme values [49].
- The slope of the N_{RSFP} signal might be equivalent to the one of a variation from -1 to 1 in 133 seconds in case of emergency but should generally not exceed the equivalent slope necessary to vary between these two extreme values in 800 s [50].
- The actual response of the entity should not differ from the theoretical response described above by more than 60 s [49].

Rapid reserve in France

Rapid reserves aim at overcoming potential shortcomings in secondary regulation reserve in case of fast rise of imbalance between generation and consumption, but it also aims releasing secondary regulation reserve while restoring balance in the system in case of slow rise of imbalance between generation and consumption [50] [51]. This reserve is the equivalent of the European mFRR as defined in EU Regulation 2017/1485 [15].

Contracting of rapid reserve is done through annual tendering for a period of 1 year [51].

Since 2020, all rapid reserve products of 9min activation time have been abandoned. Four products defined by activation time of 13 min remain. Since 2020, some of these products include minimum delivery period of 15 min. RTE stated that the grid did not need rapid reserve with the quicker activation time but rather products with shorter minimum delivery period [52]. The four remaining rapid reserve products are technically described as follow [51]:

- FAT in 13 min, minimum delivery period of 15 min, maximum delivery period of 30 min
- FAT in 13 min, minimum delivery period of 15 min, maximum delivery period of 60 min
- FAT in 13 min, minimum delivery period of 60 min, maximum delivery period of 90 min
- FAT in 13 min, minimum delivery period of 60 min, maximum delivery period of 120 min

RTE currently estimates a lead-time of 2 min between an event and the decision and manual transmission of reserve activation orders, hence the FAT of 13 min to make this reserve available 15 min after an event as prescribed by [53].

Complementary reserve in France

Complementary reserves aim at overcoming potential shortcomings in rapid reserves. This reserve is the equivalent of the European RR as defined in EU Regulation 2017/1485 [15].

Contracting of complementary reserve is done through annual tendering for a period of 1 year [51].

The three complementary reserve products are technically described as follow [51]:

- FAT in 30 min, minimum delivery period of 30 min, maximum delivery period of 30 min
- FAT in 30 min, minimum delivery period of 60 min, maximum delivery period of 60 min
- FAT in 30 min, minimum delivery period of 60 min, maximum delivery period of 90 min

Volt/var regulation services in FR

The purpose of Volt/var services is to ensure the maintenance of voltage of the power system. All users connected to this network benefit from these services, which not only ensure the proper functioning of their electrical equipment and their consumption or production processes, but also the maintenance of safe operating conditions for the French and European power grid. High instabilities in frequency or voltage can lead to large-scale incidents, such as blackouts, depriving entire regions or countries of electricity for periods of several hours or even several days. Voltage/Reactive Regulation Services are obtained through automatic control.

To meet the above challenges, RTE applies a strategy for voltage management on the Public Transmission System based on two main lines:

- Seeking high-voltage operation of generation facilities located on the upstream network, particularly at 400 kV, while preserving their reactive power supply capacity for the needs of dynamic voltage control and, above all, for responding to control contingencies and incidents.
- Limit voltage drops on the downstream network as much as possible by minimizing the flows of reactive power circulating on the Public Transmission System thanks to static compensation means distributed over the network and as close as possible to the loads.

The application of this strategy requires prior voltage studies to determine the "target voltage" at each network node, considering the network topology and the location of the sources.

In view of these considerations, RTE organizes voltage control on the Public Transmission System around four types of complementary actions:

- Controlling source voltages by requiring generation facilities to make their voltage control capacities available to RTE.
- Determination of the most relevant operating schemes to ensure power transits.
- Installation on the Public Transmission System of reactive power compensation devices and on-load tap changers on transformers intended to ensure, as far as possible, the decoupling of voltages between the different levels (EHV1, EHV2 and EHV3).
- Encouraging consumers and distributors to install, as close as possible to their loads, passive means of reactive power compensation (capacitors in most cases and inductors in some cases)

and to make efficient use of the reactive power capacities of the generating installations at their disposal.

The operators of Generation Facilities with a constructive capacity for automatic voltage regulation are required to make their constructive capacities available to RTE (in application of Article L. 321-11 of the Energy Code and in accordance with the provisions of RTE, Règles Services Système Tension, 2017 [54]).

Actors who have facilities with a regulation capacity that does not necessarily have to be made available to RTE (in application of Article L. 321-11 of the Energy Code) may make it available to RTE by signing a Participation Agreement for the System Services Rules. As soon as this Participation Agreement is signed, the Participant is required to make his balancing capacities available (in accordance with the provisions of RTE, Règles Services Système Tension, 2017 [54]).

Voltage is a local variable, notably influenced by variations in consumption and reactive power transits at the interface between the Public Transmission Network and the Public Distribution Networks.

Limitations in the supply and absorption of reactive power are defined by the diagrams $[U, Q] = f(P)$ of each installation, and are known to RTE.

The voltage regulation scheme includes primary and secondary response as described below, and the contribution to Primary and/or Secondary Voltage Adjustments is assessed at the Delivery Point of each Voltage Adjustment Entity.

Primary voltage regulation in FR

The primary voltage regulation can be of one of the following three types:

- Type 1: setting at constant reactive power at the connection point, or a constant value for $\tan(\Phi)$ at the connection point.
- Type 2: reactive power control proportional to the difference between the voltage at the connection point U_{cp} , and a constant set point voltage U_{sp} .

$$Q = \frac{1}{\lambda} \times (U_{sp} - U_{cp})$$

- Type 3: Voltage regulation at the terminals of the generating set according to a set point. This set point can be slaved to the orders coming from the secondary control, in the case of installations participating in secondary voltage control.

Secondary voltage regulation in FR

The secondary voltage regulation can be of one of the following two types:

- The RST ("*Réglage Secondaire de la Tension*" = Secondary voltage regulation)

Its principle consists of organizing the network into control "zones" and regulating the voltage from a particular point in each area, called a "pilot point". The pilot point is chosen to have a voltage representative of the voltage level of the whole area.

A centralized device located at RTE's regional control center generates a control signal K, called level, for each control zone. For each zone, the corresponding K level is sent to all the control groups in the zone. It is transformed locally into set-point voltage variations, applied to the primary voltage regulator (type 3).

- The RSCT ("*Réglage Secondaire Coordonné de la Tension*" = Coordinated Secondary voltage regulation)

As the evolution of the power system has accentuated the interactions between RST zones, this has also led to the development of another system, the RSCT, capable of considering these interactions and based on a different functioning from that of the RST. The RSCT is currently installed only in the Western Region, which is particularly sensitive to voltage problems.

The RSCT makes it possible to adjust the voltage plan globally over an entire region by the voltage of a set of pilot points (and not locally on a single pilot point as in the case of RST) to set point values.

Response time in FR

To guarantee the performance of the secondary voltage regulation in terms of response time and stability, the response of the Voltage Regulating Entity must meet the following requirements:

- When the variations in the set point require it, the maximum variation slope in secondary voltage control must comply with the value declared for the Voltage Control Entity concerned within the framework of the performance commitment or connection agreement (a minimum of 6% Q_n /min where Q_n is the rated reactive power at the stator of the Voltage Control Entity);
- When the Voltage Control Entity is requested in the form of a ramp whose slope is below the declared maximum slope ($=12\% \times Q_n/\text{min}$), the Voltage Control Entity's response must present a time lag error less than or equal to either $T_r = 60$ s, or to the value specified in accordance with Article 4.2.1 of the DTR [55].

4.6.3. Switzerland (CH)

Switzerland is one of the three countries hosting a hydropower plant for demonstration within the scope of the XFLEX HYDRO project. Therefore, it is important to provide an overview regarding the main services currently being demanded by the local system operator (Swissgrid). Swissgrid organizes the following ancillary services as part of its legal obligations:

- Frequency control (primary, secondary and tertiary control);
- Voltage support;
- Compensation of active power losses;
- Black start and island operation capability;
- System coordination;
- Balance group management;
- Operational measurement.

An overview of the main characteristics of the aforementioned services is presented below and based on references [56] [57].

Ancillary services regulation in CH

Switzerland is part of the European interconnected grid and is connected to neighbouring countries via 41 lines. In accordance with Article 22 of the Electricity Supply Ordinance, Swissgrid has been purchasing ancillary services since 1st January 2009 in accordance with a transparent, non-discriminatory, and market-based procedure. The invitations to tender take place daily, weekly, or monthly, depending on the product.

It does this in accordance with the technical specifications of the ENTSO-E. Swissgrid draws up the details of ancillary service provision. The contract scenario with the providers envisages signing a framework agreement following a technical and operational appraisal (prequalification) of providers and their power stations. On this basis, providers are then eligible to bid for the ancillary service in question.

The following overview describes the individual ancillary services and summarizes the intended procurement processes and procedures.

Frequency/active power control in CH

This balance guarantees the secure operation of the electricity grid at a constant frequency of 50 Hz. Technically this is achieved within the ENTSO-E by using a three-stage control procedure (primary, secondary, and tertiary control). The following example assumes a power station failure. Primary control is activated directly in the entire SA. After 30 seconds, secondary control power is automatically called up, which is replaced by tertiary control after no more than 15 min.

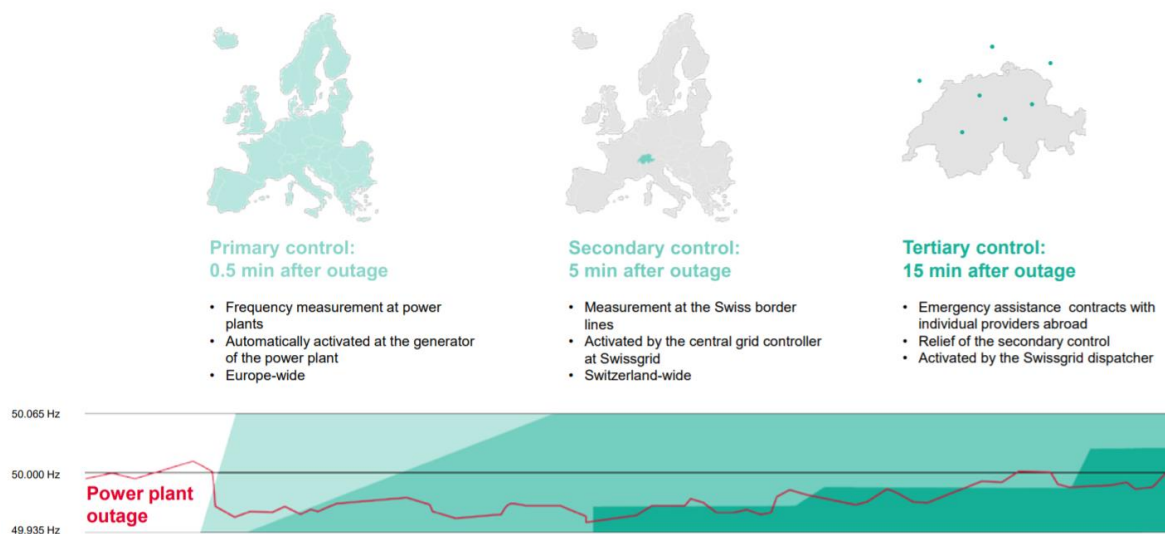


Figure 23 Example of a power plant outage

Primary regulation reserve in CH

The procurement of the primary control power required for Switzerland is realized by a combined auction between Belgium, Denmark, Germany, France, Netherlands, Austria and Switzerland. This common cooperation is called "*FCR Cooperation*" and procures about half of the FCR of the synchronous continental European 50 Hz system.

All TSOs represented in the SA must fulfil the requirements in their country in accordance with the ENTSO-E rules: the primary control power capacity which must be kept in reserve at all times is adjusted annually in November in accordance with ENTSO-E requirements (in Switzerland this is always approximately 70 MW with a frequency deviation of ± 200 mHz). Major characteristics of this reserve for Switzerland are:

- Volume of primary control power required for Switzerland and the cooperation: ± 61 MW (year 2019)
- 1473 MW procurement for the whole cooperation (year 2019);
- Maximum award within Switzerland: Approx. 161 MW (year 2019);
- Product: Symmetrical control power bands;
- Tender period: Daily;
- Bidders: All prequalified bidders;
- Bid structure: Minimum output windows of ± 1 MW, Prices are in €/MW, Divisible or indivisible bids;
- Maximum offer size: 25 MW per bid;
- Request: Frequency controller with droop set on site for each machine;
- Remuneration of capacity: One clearing price for all contracted primary control power;
- Remuneration of energy: No remuneration for primary control energy delivered.

Secondary regulation reserve in CH

The secondary control reserve is formally equivalent to the aFRR, described in EU Regulation 2017/1485 [15]. In the event of an imbalance between production and consumption, secondary control power in the connected power stations is automatically actuated by the central grid controller. As a prerequisite, these power stations must be in operation but must not be generating the maximum or minimum possible nominal capacity to meet the requirements of the central load frequency controller at all times. Secondary control is activated after a few seconds and is typically completed within a maximum of 15 min. If the cause of the control deviation is not eliminated after 15 min, secondary control gives way to tertiary control. Major characteristics of this reserve for Switzerland are:

- Volume of secondary control power required for Switzerland: Approx. ± 400 MW.
- Product: Separate control power bands according to direction (SRL+, SRL-).
- Tender period: Weekly.
- Bidders: All prequalified bidders.
- Bid structure:
 - minimum output windows of ± 5 MW;
 - multiple volume/price combinations per bid are permitted (multilevel bids), each incrementally ± 1 MW at different prices (multi-level bids - a multi-level bid can contain levels for both positive control power (SRL+) and for negative control power (SRL-));
 - prices are in CHF/MW;
 - only indivisible bids.
- Maximum offer size: 100 MW per bid.
- Request: Proportional to the provider contracted service in the corresponding delivery direction by control signal.
- Remuneration of capacity: Bid price for procured secondary control power.
- Remuneration of energy: In accordance with the control signal, with separate delivery direction, averaged over 15 min.
- Energy settlement: In accordance with the subsequent timetable ("*Post Scheduling*") determined from the control signal, separated by delivery direction, averaged over 15 min (in 0.001 MWh).

Tertiary regulation reserve in CH

The Tertiary Regulation Reserve (TRE) is formally equivalent to a combination of mFRR and RR established in the EU Regulation 2017/1485 [15].

The Swissgrid dispatcher activates this reserve by sending special electronically transmitted messages to the providers, who must then intervene in power plant production to ensure the supply of tertiary control power within a maximum of 30 min, depending on the product. Major characteristics of this reserve for Switzerland are:

- Volume of tertiary control power required for Switzerland: Approx. +400 MW and -260 MW.
- Product: Asymmetric control power bands.
- Tender period: Daily.
- Bidders: All prequalified bidders.
- Bid structure:
 - minimum output windows of +5 MW or -5 MW;
 - multiple volume/price combinations per bid are permitted (multilevel bids), each incrementally ± 1 MW at different prices;
 - prices are in CHF/MW;
 - only indivisible bids.

- Maximum offer size: 100 MW per bid.
- Remuneration of capacity: Bid price for procured tertiary control power.
- Activation: Request by e-mail or telephone call.

In addition to the power tendering process, tertiary energy is put out to tender. In the energy tenders, all bidders, who receive a contract in the power tendering process, must submit TRE-bids up to the awarded volume of tertiary control power. Additional TRE bids can also be offered voluntarily, independently of the results of the power tendering process.

Volt/var control services in CH

Swissgrid specifies reference voltages for the feed-in and withdrawal points for generation units and distribution grid operators in the transmission grid. The controlled exchange of reactive power allows the voltage at the feed-in point to be brought to the specified reference voltage. Active participation in voltage support is mandatory for all operating power plants directly connected to the transmission grid. Distribution grids and end customers are obliged to participate in the voltage support at a semi-active level. However, they can prequalify for active voltage support. The provision of reactive energy is contractually regulated in the company agreements. For the time being, no invitation to tender is planned. The replaced reactive energy is remunerated via a fixed tariff in addition to a uniform fee for participants. For mandatory voltage support, power plants have the option of participating in the extra mandatory voltage support. Specific standard contracts regulate the provision of reactive power capacity. In addition to the remunerated reactive energy, specific remuneration is defined per start and operating hour for each power plant.

Mandatory voltage support: Every directly connected partner to the transmission grid is obliged to participate in voltage support. Power plants are obliged to participate in active voltage support. All other participants such as distribution grids, neighbouring system operators or customer plants are obliged to participate in semi-active voltage support. However, they may participate in active voltage support upon successful prequalification.

Regarding the compensation of compliant reactive energy, the operating agreement foresees the following compensation: Compliant reactive energy exchange is compensated with the compensation rate (CHF / Mvarh).

Regarding the charging for non-compliant reactive energy, the operating agreement provides for the following charging components: a) non-compliant reactive energy exchange is charged at the ind. tariff reactive energy (CHF / Mvarh); b) non-compliant reactive energy exchange is additionally charged with the penalty for non-compliant reactive energy (CHF / Mvarh).

Extra-mandatory voltage support: For power plants, distribution systems and end customers connected directly to the transmission system.

Regarding compensation, the standard extra-mandatory reactive power provision agreement provides for the following compensation components:

- remuneration of exchanged reactive energy equal to that in the mandatory range (tariff in CHF/Mvarh);
- additional remuneration for starting up a machine to provide reactive power at Swissgrid's request (CHF per start, individual for each machine);
- additional remuneration for every hour of operation commenced for a machine requested by Swissgrid (CHF per hour commenced, individual for each machine).

Compensation for active power losses in CH

For physical reasons, any transport of electrical energy using a grid leads to losses, i.e. less energy can be withdrawn than is fed into the grid. These active power losses are proportional to the transported energy and amount to between 1% and 7% of the transmitted energy. It is primarily thermal energy that is emitted due to resistances in the environment. The longer a transport line and the lower the voltage, the higher the active power losses. The active power losses for the metrologically separate transmission grid can be determined by the difference between all measured feed-ins and withdrawals. Swissgrid is responsible for procuring active energy on the electricity market to compensate for transmission losses on the extra-high voltage grid. The average active power losses in the Swiss transmission grid amount to approx. 110 MW (with a range of approx. 60 to 200 MW). Inadvertent deviation is charged using the daily active power loss forecast and procured on the exchange. Until the delivery period December 2020, a call for tender with month-ahead delivery will be issued monthly on the fourth Wednesday. Bids are accepted for each 5 MW delivery. From November 2019 (delivery period year 2021) on, the new aforementioned conditions apply.

Black start and island operation capability in CH

Black-start-enabled power stations ensure the restoration of the grid after major incidents. Special operational sequences and procedures are applied to coordinate the restoration of voltage to the grid. This necessitates a certain number of appropriately equipped power stations with the necessary auxiliary installations, which switch themselves on to the grid in the appropriate operational sequence at the grid operator's request and, in so doing, help to restore the grid. A power plant is capable of black start if it can go from idle to operational without requiring the injection of grid-connected electricity. A power plant is able to operate in isolation (island operation capability) if it can achieve and maintain a certain operating level without requiring activation of the outgoing lines to the synchronous grid. Four build-up cells have been defined for the «Black Start and Island Operation Capability» ancillary service for Switzerland. Each build-up cell must be able to independently initiate grid restoration measures. The ancillary services are provided by Swissgrid via an invitation to tender.

System coordination in CH

System coordination covers all higher-level services required at the transmission system level in order to coordinate and ensure the reliable, orderly operation of the transmission grid in Switzerland, which also involves guaranteeing the integration of the Swiss transmission grid in European grid operations. In particular, system coordination includes overall monitoring of the grid, grid management and control, the coordination of international energy exchange programs, congestion management, as well as various other coordination activities within Switzerland and in the international grid. In terms of technical operations, essential tasks of system co-ordination include calculations to determine grid reliability, operation of the Swiss load frequency controller and billing/settlement with neighbouring countries, monitoring the provision of system services and coordinating grid restoration following a major incident. All these tasks are essential for secure and stable operation of the grid, serve all grid customers and are performed by the Swiss grid company Swissgrid.

Balance group management in CH

Balance group management for the Swiss control area is provided by Swissgrid. This is the task of providing and operating a system so that generation and consumption are in equilibrium at all times. This is done using balance groups, which must be balanced using a scheduling system also provided for this purpose (balance group and schedule management). If this is not the case, balancing energy is used to compensate, and the imbalance of the respective balancing group is invoiced (balance compensation management). For this to be possible, a balance group must clearly assign its measuring points (measurement data management).

Operational measurement in CH

This includes installation, operation and maintenance of the measuring and metering devices and data transmission equipment and systems (communication) in the grid, as well as the provision of information (measuring data) to ensure the smooth operation of the grid. This also includes power handover measurements for neighbouring foreign integrated grids. Operational measurements represent an important interface between the different grids. The respective grid operator guarantees installation and maintenance of the measuring and metering devices, measuring and metering data acquisition as well as transmission.

5 European initiatives

The Commission Regulation (EU) 2017/2195 from 23 November 2017 [17], establishing a guideline on electricity balancing (hereafter named EBGL), aims at creating a common European balancing market where countries can share the resources used by their TSOs and allow new players such as demand response, storage operators and renewables to take part in this market. The main purpose of the EBGL is to integrate the markets for balancing services, and by doing so enhance the operational security and efficiency of the European balancing system [58]. In order to achieve this, EBGL aims to foster effective competition, non-discrimination, transparency and effective integration of new participants [11]. The EBGL foresees the implementation of European platforms for the exchange of balancing energy from:

- replacement reserves (RR) - according to article 19;
- restoration reserves with manual activation (mFRR) - according to article 20;
- frequency restoration reserves with automatic activation (aFRR) - according to article 21.

Besides, in article 22, EBGL also foresees the implementation of a European platform for Imbalance Netting (IN) process, which consists on a coordinated process among TSO aiming to avoid the simultaneous counter-activation of aFRR. To comply with EBGL, a certain level of harmonization is essential in both technical requirements and market rules among all participating TSOs. To provide this level of harmonization, the EBGL sets out some requirements for the implementation of the platforms for the exchange of balancing energy and for the balancing markets. Besides, EBGL sets up the essential concepts for the definition of a **"standard product"** for the aFRR, mFRR and RR balancing services.

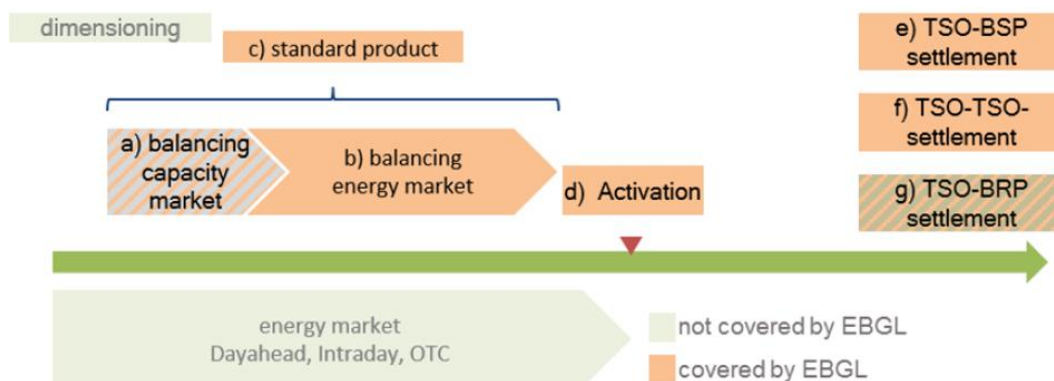


Figure 24 Scope of the EBGL, [58] [59]

Within this context, balancing means all actions and processes through which the TSOs assure the stability of the power system in terms of frequency that needs to be continuously adjusted within a predefined range, as well as the needed amount of energy reserves to ensure the quality of supply. Balancing the system requires three different main actions from the TSO: dimensioning of balancing reserves, procurement of balancing capacity and procurement of balancing energy. Like indicated in Figure 24, the main focus of the EBGL is on the balancing energy markets through the exchange of balancing services "standard products", on the activation of the "standard products", on the TSO-BSP settlement (BSP is an abbreviation for "balancing service provider") and on the TSO-TSO settlement [58] [59], where:

- *"balancing service provider"* (BSP) means a market participant with reserve-providing units or reserve-providing groups able to provide balancing services to TSOs [17];
- *"standard product"* means a harmonized balancing product defined by all TSOs for the exchange of balancing services [17];

- *"balancing market"* means the entirety of institutional, commercial and operational arrangements that establish market-based management of balancing [17].

The **balancing** market operates after the intraday market and considers all the results of the previous electricity markets (namely, day-ahead and intraday). In this market, the TSOs ensure that supply and demand stays balanced by operating the system close to real time. The BSPs, such as generators, storage operators and demand response facilities can offer balancing services to the TSOs, who in turn use them to balance the system [11].

According to ENTSO-E [11], all balancing processes in CE follow a similar functioning principle like synthesized in Figure 25. This is a multilateral TSO-TSO model for the exchange of balancing services, whereas a "TSO-TSO model" means that the BSP delivers services to its connecting TSO, which then provides these services to the requesting TSO [17].

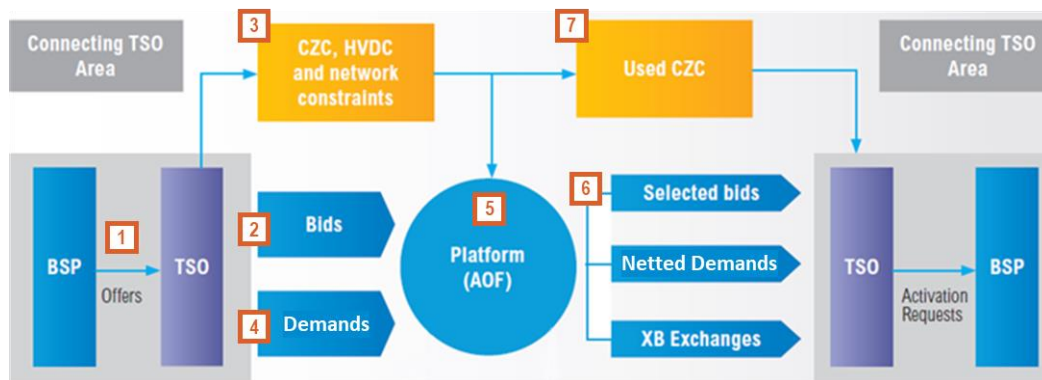


Figure 25 General functioning principles of the balancing process [11] [58]

The process starts by the BSPs sending "balancing standard product bids" or update the price of these bids to their connecting TSOs until the balancing energy gate closure time (1 in Figure 25) [11].

Until the TSO energy bid submission gate closure time, the TSOs forward to the relevant balancing exchange platform (one for each balancing service) the following information [11]:

- balancing standard product bids provided by their BSPs (2 in Figure 25);
- available Cross-Zonal Capacity (CZC, 3 in Figure 25);
- relevant network constraints (3 in Figure 25);
- TSO balancing energy demands of its LFC area or bidding zone (4 in Figure 25).

The Activation Optimization Function (AOF, 5 in Figure 25) of each respective platform generates or accepts, as input data, the common merit order lists¹⁵⁾ (one per direction of activation) and calculates and provides the following output data to the concerning TSOs [11]:

- selected bids to be activated (6 in Figure 25);
- netted demands (6 in Figure 25);
- cross-border (XB) exchanges, if there are any (6 in Figure 25);
- used cross-zonal capacity (7 in Figure 25).

According to the outputs of the activation optimization function of each platform, the TSOs send the activation requests of the accepted balancing standard product bids to their BSPs [11].

¹⁵⁾ Common merit order list is a list of balancing energy bids sorted in order of their bid prices, used for the activation of those bid [17].

To achieve the EBGL goals of developing of a European platform for each of balancing market process (namely for the IN, aFRR, mFRR and RR processes), European TSOs have established the following implementation projects:

- Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation (PICASSO), for the aFRR process [60];
- International Grid Control Cooperation (IGCC), for IN process [61];
- Manually Activated Reserves Initiative (MARI), for the mFRR process [62];
- Trans-European Replacement Reserves Exchange (TERRE), for the RR process [63].

Before EBGL entry into force (November 2017), a European regional project named *"FCR Cooperation"* [18] was launched, in 2015, aiming for a common market for procurement and exchange of FCR being, therefore, also in line with the objectives of EBGL.

In the next sections, each one of these projects is briefly described. Then, section 5.6 provides the up to now characterization of an aFRR, mFRR and a RR "balancing standard product".

5.1. FCR Cooperation

About half of the total CE SA FCR procurement is realized in a common market between Austria, Belgium, Denmark, France, Germany, Netherlands and Switzerland. This market is integrated in the regional project called "FCR cooperation" [18] that promotes the integration of FCR procurement in central Europe. The FCR Cooperation is organized with a TSO-TSO model, where the FCR is procured through a common merit order list where all TSOs pool the offers they have received. The interaction with BSPs and the contracts between the TSOs and BSPs are handled on a national basis along with the responsibility of delivery. The current member and observers of this regional project are presented in Table 6 and Figure 26.

Table 6. List of members and observers in the FCR Cooperation [18]

Members	RTE (France)	Elia (Belgium)
	Amprion (Germany)	Tennet NL and Tennet DE (Netherlands and Germany)
	TransnetBW (Germany)	Swissgrid (Switzerland)
	APG (Austria)	50Hertz (Germany)
Observers	Energinet (Denmark)	-



Figure 26 Map with members and observers of the FCR Cooperation [18]

The FCR product on the FCR Cooperation follows the guidelines of the Operational Handbook [53] for all CE SA. Consequently, the FCR product of the FCR Cooperation follows the same requirements as any primary control product in the CE SA, which are properly described in section 4.2.3.

Regarding the market rules and product bids that are being applied on the FCR Cooperation platform, a description is performed in section 4.6.2, within the discussion of the primary regulation reserve currently existing in FR. The characteristics of these bids follow the "TSOs" proposal for the establishment of common and harmonized rules and processes for the exchange and procurement of balancing capacity for Frequency Containment Reserves (FCR) [64] (from April 2016). In brief, the product characteristics in the FCR cooperation are as follows [18]:

- Symmetric product (meaning that upward and downward FCR are procured together);
- Duration of product delivery: daily;
- TSOs allow divisible and indivisible bids;
- Indivisible bids can have a maximum bid size of 25 MW in all the participating countries;
- Minimum bid size is 1 MW and bid resolution is 1 MW as well;
- Core shares and export limits exist as limitations in the FCR Cooperation market.

5.2. PICASSO

PICASSO, Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation, is the implementation project to establish the European platform for the exchange of balancing energy from FRR with automatic activation (i.e. for the exchange of aFRR) [60]. The objectives to create this European platform are aligned with the ones described in EBGL regulation. The main objectives of the PICASSO initiative are to:

- Design, implement and operate an aFRR-Platform compliant with the approved regulations;
- Enhance economic and technical efficiency within the limits of system security;
- Integrate the European aFRR markets while respecting the TSO-TSO model.

This platform is expected to go live until December 2021 [60].

The list of the TSOs that, as far as the authors know, are currently members or observers of the PICASSO project is presented in Table 7 and Figure 27.

Table 7. List of members and observers in the PICASSO initiative [60]

Members	MAVIR (Hungary)	ELES (Slovenia)
	Terna (Italy)	Red Eléctrica de España (Spain)
	PSE (Poland)	Svenska kraftnät (Sweden)
	REN (Portugal)	Tennet NL and Tennet DE (Netherlands and Germany)
	Transelectrica (Romania)	50Hertz (Germany)
	Statnett (Norway)	Amprion (Germany)
	SEPS (Slovak Republic)	TransnetBW (Germany)
	RTE (France)	Fingrid (Finland)
	Energinet (Denmark)	HOPS (Croatia)
	ČEPS (Czech Republic)	Elia (Belgium)
	APG (Austria)	-
	ESO (Bulgaria)	IPTO/ADMIE (Greece)
	Swissgrid (Switzerland)	ENTSO-E
Observers		



Figure 27 Map with members and observers of the PICASSO initiative [60]

5.3. IGCC

The International Grid Control Cooperation (IGCC) is the implementation project, chosen by ENTSO-E in February 2016, to become the future European Platform for the Imbalance Netting (IN) process (the IN-Platform). IGCC performs IN of aFRR. The IN process is a TSO-TSO activity that aims to improve the

overall efficiency of the balancing energy market by avoiding the simultaneous activation of aFRR in opposite directions between adjacent participating LFC areas. It is a process agreed between the TSOs of two or more LFC areas that considers the frequency restoration control errors (named FRCE or ACE), as well as the activated aFRR, to properly correct the input of the involved frequency restoration controllers (also named AGCs) accordingly [11] [61].

The implementation of this process is exemplified in Figure 28. The communication of the power-frequency control of a single TSO enables online balancing of the different power imbalances: for each optimization time step, the aFRR optimization system first receives the aFRR demand of participating LFC areas and then transmits a correction signal to the frequency restoration controllers (or aFRR optimization systems) of each IGCC operational member. By following this procedure, it is avoided the counter-activation of aFRR balancing energy and therefore the use of aFRR is optimized [61].

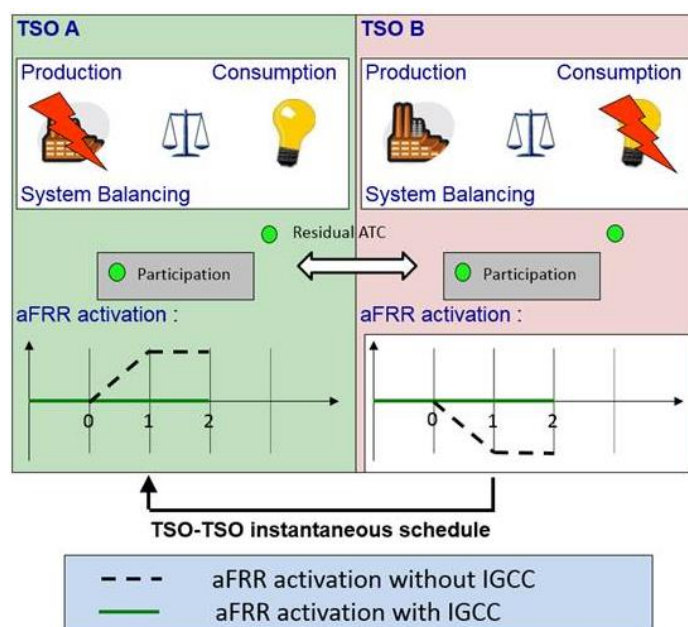


Figure 28 Basic principle of imbalance netting in IGCC [61]

The IGCC implementation project already involves 27 TSOs from 24 different countries across the CE region [61]. The TSOs members of the IGCC can be classified as either operational members (also called as participating TSOs) or non-operational members. The operational members are TSOs that perform the IN process through the IN-platform and are physically connected to the IGCC via the communication infrastructure. Non-operational members are the ones that, although, not yet physically participating in the IN-platform are officially taking part of the IGCC decision-making process [61]. The list of the TSOs that, as far as the authors know, are members (operational and non-operational) or observers of the IGCC project is presented in Table 8 and Figure 29.

Table 8. List of members and observers in the IGCC project [61]

Members	MAVIR (Hungary)	ELES (Slovenia)
	Terna (Italy)	Red Eléctrica de España (Spain)
	PSE (Poland)	Svenska kraftnät (Sweden)
	REN (Portugal)	Tennet NL and Tennet DE (Netherlands and Germany)
	Transelectrica (Romania)	50Hertz (Germany)

Observers	Statnett (Norway)	Amprion (Germany)
	SEPS (Slovak Republic)	TransnetBW (Germany)
	APG (Austria)	Elia (Belgium)
	ČEPS (Czech Republic)	HOPS (Croatia)
	Energinet (Denmark)	Fingrid (Finland)
	RTE (France)	-
	ESO (Bulgaria)	IPTO/ADMIE (Greece)
	Swissgrid (Switzerland)	Swissgrid (Switzerland)



Figure 29 Map with members and observers of the IGCC project [61]

5.4. MARI

MARI (or Manually Activated Reserves Initiative) is the European implementation project for the creation of the EU platform for the exchange of balancing energy from FRRs with manual activation (i.e., for the exchange of mFRR) [62]. The objectives to create this European platform are aligned with the ones regarding the implementation of the EBGL. This project is where all technical details, common governance principles and business processes are being developed by the involved TSOs in the project [58]. The expected deadline for the go-live date of the platform is December 2021 [62].

The list of the TSOs that, as far as the authors know, are members or observers of the MARI initiative is presented in Table 9 and Figure 30.

Table 9. List of members and observers in the MARI initiative [62]

Members	PSE (Poland)	AST (Latvia)	APG (Austria)
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Observer	REN (Portugal)	Litgrid (Lithuania)	Elia (Belgium)
	Transelectrica (Romania)	Elering (Estonia)	ČEPS (Czech Republic)
	Statnett (Norway)	IPTO/ADMIE (Greece)	HOPS (Croatia)
	SEPS (Slovak Republic)	Swissgrid (Switzerland)	Energinet (Denmark)
	ELES (Slovenia)	Tennet NL and Tennet DE (Netherlands and Germany)	Fingrid (Finland)
	Red Eléctrica de España (Spain)	50Hertz (German)	RTE (France)
	Svenska kraftnät (Sweden)	Amprion (German)	MAVIR (Hungary)
	National Grid (UK)	TransnetBW (German)	Terna (Italy)
	ESO (Bulgaria)	EirGrid (Ireland)	EMC (Serbia)
	SONI (Northern Ireland)	ENTSO-E	-

■ Member ■ Observer

Figure 30 Map with members and observers of the MARI initiative [62]

5.5. TERRE

TERRE (or Trans-European Replacement Reserves Exchange) is the European implementation project for the creation of the EU platform for the exchange of balancing energy from replacement reserves (i.e., for the exchange of RR) [63]. The objectives to create this European platform are aligned with the ones regarding the implementation of the EBGL. The participant TSOs are developing an IT platform (and optimization algorithmic), named LIBRA, which will support the European "RR market" and can be used in other balancing processes frameworks [63].



Figure 31 Map with members and observers of the TERRE initiative [63]

This platform has been launched on 6 January 2020 and ČEPS (from Czech Republic) was the first TSO to connect. The following timeline is defined for further TSOs connections to the TERRE platform:

- REE and REN connection in the first quarter of 2020;
- Swissgrid, Terna, National Grid, ESO and RTE connection in the second quarter of 2020;
- PSE (from Poland) connection is expected at the end of 2021/ beginning of 2022 [63].

The list of the TSOs that, as far as the authors know, are members or observers of the TERRE initiative is presented in Table 10 and Figure 31.

Table 10. List of members and observers in the TERRE initiative [63]

Members	National Grid (UK)	Transelectrica (Romania)
	RTE (France)	ČEPS (Czech Republic)
	REN (Portugal)	PSE (Poland)
	Red Eléctrica de España (Spain)	Swissgrid (Switzerland)
	Terna (Italy)	-
Observers	MAVIR (Hungary)	Svenska kraftnät (Sweden)
	IPTO/ADMIE (Greece)	ESO (Bulgaria)
	Statnett (Norway)	ENTSO-E

5.6. Products standardization

5.6.1. Characteristics of a balancing standard product

To facilitate the exchange of balancing energy across borders, the EBGL requires the definition of a "standard product" for the aFRR, mFRR and RR to be exchanged using the pan-European platforms. EBGL sets up the essential concepts for the technical parameters of these standard products, being the detailed characterization and harmonization of a balancing standard product left open to be progressively updated, namely through the implementation frameworks of the aFRR, mFRR and RR pan-European platforms. More recently, in December 2019, aiming to meet the objectives of the EBGL regulation, all TSO provided a common proposal [65] for defining the requirements of the Standard Product for Balancing Capacity (SPBC) for aFRR, mFRR and RR (an ENTSO-E publication named as the SPBC proposal). By following the EBGL regulation and the SPBC proposal, a "balancing standard product" bid must be, at least, characterized by the following characteristics:

- static characteristics of a balancing standard product (listed and described in Table 11);

characteristics to be defined by TSOs for a balancing standard product bid (listed and described in

- Table 12);

Characteristics for a balancing standard product bid submitted by each BSP are described in Table 13.

To help the interpretation of these listed properties, the ones characterizing the active power time behaviour are illustrated in Figure 32.

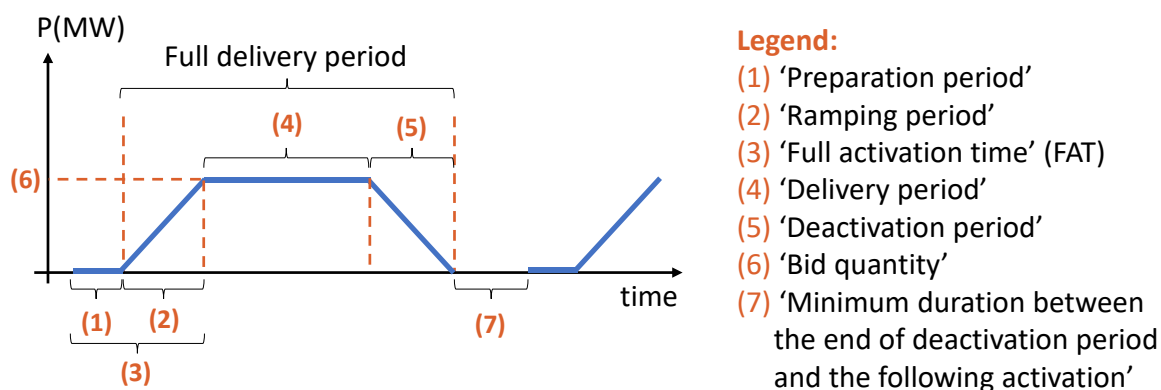


Figure 32 Time domain characteristics of a balancing standard product

Table 11. Static characteristics of a balancing standard product [17], [65] and [66].

"Preparation period"	Means the period between the activation request and the start of ramping, during which no energy is delivered.
"Ramping period"	Means the period defined by a fixed starting point and a length of time during which the active power (P) will increase/decrease.
"Full activation time" (FAT)	Means the period between the activation request and the full delivery of active power.
"Minimum and maximum duration of delivery period"	"Delivery period" means the period during which the BSP delivers/withdraws the full requested change of P.
"Deactivation period"	Means the period for ramping from full delivery/withdrawal to a set point.
"Minimum and maximum bid quantity"	<p>Bid quantity means the active power offered in a bid and which must be reached by the end of FAT (also named "bid size" or "bid volume").</p> <p>According to the SPBC proposal:</p> <ul style="list-style-type: none"> – The minimum bid value shall be 1 MW. – The maximum bid value shall be defined by the TSOs.
"Mode of activation"	Can be "manual" (by an operator) or "automatic" (in a closed-loop manner).

Table 12. Characteristics to be defined by TSOs for a balancing standard product bid [17], [65] and [66].

"Validity period"	<p>Means the time period when the balancing energy bid can be activated, where all the characteristics of the product are respected.</p> <p>In the SPBC proposal, standard product options are 15 min, 1 hour, 4 hours, 1 day or 1 week.</p>
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"Minimum duration between the end of deactivation period and the following activation"

In SPBC proposal, specific values are defined for aFRR, mFRR and RR standard products.

For a TSO, a bid with a minimum duration is intuitively less valuable than another without a minimum duration.

"Direction"

According to the SPBC proposal, "direction" can be upward or downward (these are two separate bid products).

Table 13. Characteristics for a balancing standard product bid submitted by each BSP [17], [65] and [66].

<i>"Bid quantity"</i>	According to the SPBC proposal, this must be submitted in MW.
<i>"Bid price"</i>	According to the SPBC proposal, this must be submitted in (€/MW)/h, with a resolution of 0.01 (€/MW)/h. The price shall be positive or zero and the payment shall be from the TSO to the BSPs only.
<i>"Minimum duration between the end of deactivation period and the following activation"</i>	<p>This requirement strongly depends on BSP asset technical characteristics and on the pre-qualification requirements defined by each TSO in the terms and conditions for BSPs.</p> <p>"Capacity bid divisibility" means the possibility for a TSO to use only part of the balancing capacity bids in terms of power activation.</p>
<i>"Capacity bid divisibility"</i>	<p>According to the SPBC proposal, BPS may submit "indivisible capacity bids" as well as "divisible capacity bids" with a bid granularity of 1 MW. For indivisible bids, the bid quantity submitted by each BSP shall not exceed the value defined by the TSOs. The possibility to submit indivisible balancing capacity bids by BSPs is determined in the national terms and conditions.</p> <p>Indivisible bids will introduce complexity in the auction clearing algorithm, which may lead to unwanted effects such as unforeseeably rejected/accepted bids. However, allowing indivisible bids is considered to have a positive impact on the volume of bids offered and will ensure that the maximum range of providers and technology types can participate.</p>
<i>"Bid location"</i>	According to the SPBC proposal, at least the smallest of LFC area or bidding zone in which the providing units/groups are connected to must be provided. More detailed location information may be required under national responsibility.
<i>"Additional characteristic"</i>	The SPBC proposal leaves room for additional characteristics that may be defined by TSOs, such as the possibility to link bids or to submit mutually exclusive bids.

In Table 12, "validity period" should not be confused with the "time of the auction" (time when the contracting is done in advance of the provision of the balancing capacity) or the "contracting period". For example: the balancing capacity validity period of a capacity product could be 4 hours. The contracting period can be 1 day = 24 hours, meaning a BSP has to submit at least 6 bids of 4 hours. The auction itself could take place week-ahead and means that the contracting is done 7 days in advance of the provision of the balancing capacity.

According to the SPBC proposal, each connecting TSO is responsible for the prequalification for the provision of balancing standard product from the reserve-providing units/group in the LFC area under its responsibility.

According to EBGL, the harmonization of the described characteristics of a balancing standard product bid is left optional. Due to differences in the existing balancing markets, TSOs foresee a progressive harmonization, with only the essential concepts being harmonized before the launch of the pan-European platforms [11]. More detailed specifications about the standard products are being defined within the framework of the ENTSO-E pilot initiatives named PICASSO, MARI and TERRE. Based on the outcomes of these initiatives, in the following sections, a description is performed about the specific characteristics defined, so far, for each one of the aFRR, mFRR and RR balancing services.

5.6.2. aFRR standard product

The characteristics for an aFRR standard product bid are specified on the SPBC proposal [65] (from December 2019) and on "All TSOs" proposal for the implementation framework for the exchange of balancing energy from aFRR" [67] (an ENTSO-E publication from December 2018, named as the aFRRIF proposal). This aFRRIF proposal was performed in close coordination with the PICASSO project. According to the SPBC and aFRRIF proposals, an aFRR "balancing standard product bid" includes the specific characteristics described in Table 14. The ones regarding to the active power time behaviour are illustrated in Figure 33.

Table 14. Static characteristics of an aFRR standard product [59], [65] and [67]

<i>"Preparation period"</i>	This requirement remains at national level (depends on the local generation structure), but it is very short since aFRR is an automatic process.
<i>"Ramping period"</i>	Until 17/Dec/2025, each TSO defines the FAT of its aFRR balancing energy product, but the FRCE adjustment process must have a maximum ramping period of 7.5 min. This creates an incentive for TSOs that currently have a longer FAT to foster a fast reaction of their local BSPs.
FAT	Starting from 18/Dec/2025, the FAT shall be set at 5 min.
<i>"Minimum and maximum duration of delivery period"</i>	No minimum delivery time shall be permitted. The bid can be activated and deactivated at any moment within the validity period.
<i>"Deactivation period"</i>	Shall not be longer than the full activation time.
<i>"Minimum and maximum bid quantity"</i>	According to the SPBC proposal: Minimum bid value shall be 1 MW.

"Mode of activation"

Maximum bid value shall be defined by the TSOs (set to 9999 MW justified by IT limitations).

"Automatic" due to the nature of the aFRR process. The frequency restoration controllers automatically send setpoint for activated bids. During the validity period of their offered bids, the setpoint signals sent to BSP can constantly change their values, depending on the aFRR demand.

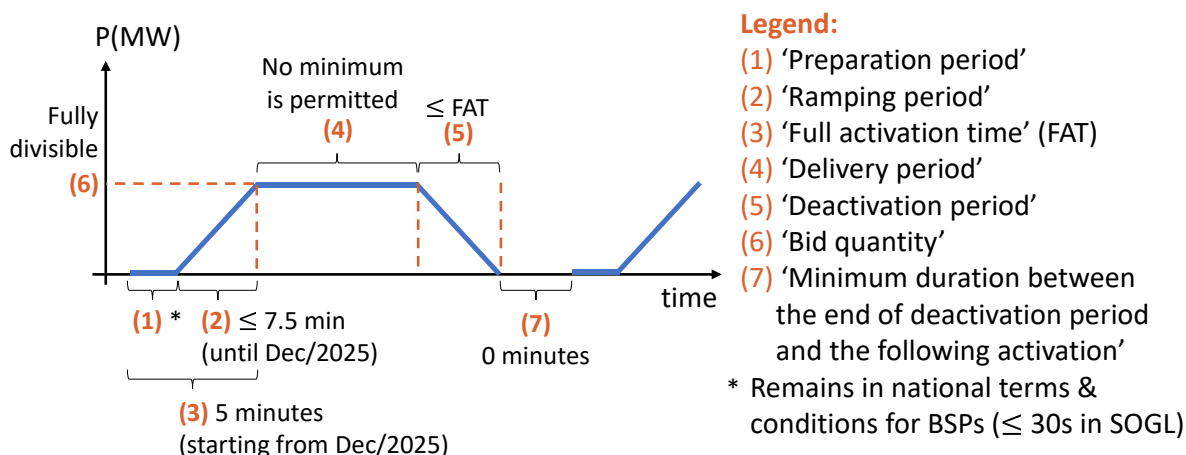


Figure 33 Time domain characteristics of an aFRR standard product

Table 15. Characteristics to be defined by TSOs for an aFRR standard product bid [59], [65] and [67].

"Validity period"

In the SPBC proposal, standard product options are 15 min, 1 hour, 4 hours, 1 day or 1 week.

The first validity period of each day shall begin right after 00:00 CET. The validity periods shall be consecutive and not overlapping.

"Minimum duration between the end of deactivation period and the following activation"

In SPBC proposal, this duration is set to 0 min (since aFRR product is considered to be continuously available for activation).

"Direction"

According to the SPBC proposal, "direction" can be upward or downward.

Table 16. Characteristics submitted by each BPS or an aFRR standard product bid [59], [65] and [67].

<i>"Bid quantity"</i>	According to the SPBC proposal, this must be submitted in MW.
<i>"Bid price"</i>	According to the SPBC proposal, this must be submitted in (€/MW)/h, with a resolution of 0.01 (€/MW)/h. The price shall be positive or zero and the payment shall be from the TSO to the BSPs only.
<i>"Minimum duration between the end of deactivation period and the following activation"</i>	In SPBC proposal, this duration is set to 0 min.
<i>"Capacity bid divisibility"</i>	The bid is always "divisible", in order to be activated continuously. The activation request can be lower than the minimum quantity and minimum granularity (according to the SPBC proposal, "divisible capacity bids" have a bid granularity of 1 MW).
<i>"Bid location"</i>	According to the SPBC proposal, at least the smallest of LFC area or bidding zone in which the providing units/groups are connected to must be provided. More detailed location information may be required under national responsibility.
<i>"Additional characteristic"</i>	TSOs do not foresee the possibility of handling complex bids directly by the aFRR-Platform, such as linked or exclusive bids. Considering such bids in the aFRR optimization would make unfeasible solving the optimization problem within the time needed for the aFRR.

5.6.3. mFRR standard product bid

The characteristics for an mFRR standard product bid are specified on the SPBC proposal [65] (from December 2019) and on "All TSOs" proposal for the implementation framework for a European platform for the exchange of balancing energy from mFRR" [68] (an ENTSO-E publication from December 2018, named as the mFRRIF proposal). This mFRRIF proposal was performed in close coordination with the MARI project. According to the SPBC and mFRRIF proposals, a mFRR "balancing standard product bid" includes the specific characteristics described from Table 17 to

Table 19. The ones regarding to the active power time behaviour are illustrated in Figure 34.

"Mode of activation"

Activated manually by an operator with "scheduled activation" (to solve forecasted imbalances) or with "direct activation" (to solve real-time large imbalances).

- "Scheduled activation" can only take place at the "point of scheduled activation" (at 7.5 min before beginning of the quarter hour for which the BSPs place the respective product bid, i.e. at T-7.5 min of Figure 35).
- "Direct activation" can be activated at any point of time following the point of scheduled activation of the quarter hour for which the bid is submitted and until the point of scheduled activation of the next quarter hour (i.e., between T-7.5 min and T+7.5min of Figure 35). Such a bid must be activated and exchanged between TSOs shortly after an incident happens.

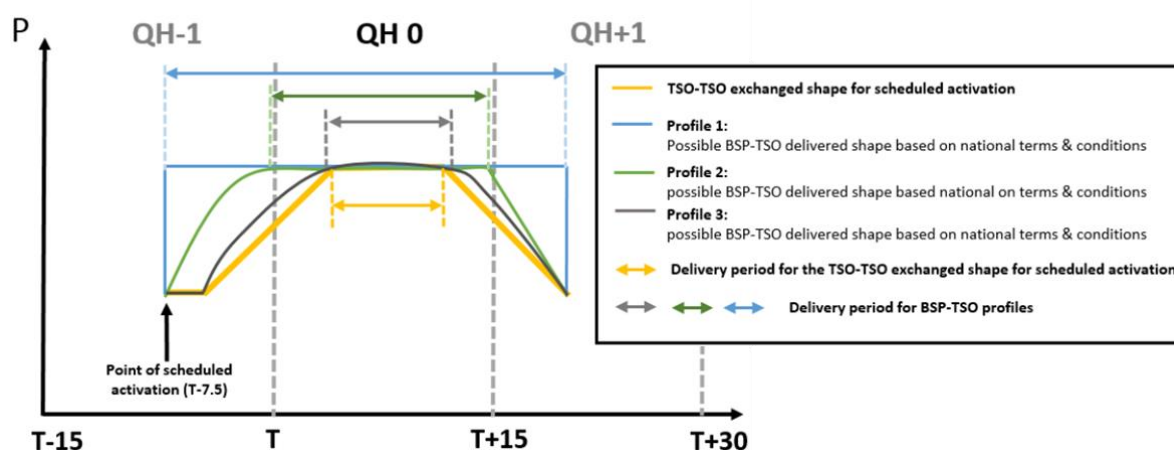


Figure 35 Illustration of some possible BSP-TSO delivered shapes for a cross-border scheduled activation of mFRR (the TSO-TSO exchanged shape) [58].

Table 18 Characteristics to be defined by TSOs for a mFRR standard product bid [58], [65] and [68].

"Validity period"

In the SPBC proposal, validity period options are 15 min, 1 hour, 4 hours, 1 day or 1 week.

"Minimum duration between the end of deactivation period and the following activation" ("Minimum duration between activations" in short)

The following possible mFRR products are defined in SPBC proposal:

- A product for which the BSP must not submit a restrictive value for the "Minimum duration between activations": this value is set to 0;
- A product for which the BSP may submit a restrictive value for the "Minimum duration between activations" between 0 and 8 hours. This option is only valid for a validity period of 15 min or 1 hour.

To support these options, TSOs claim that they may decide to include a mix of capacity products with different minimum duration between activations, in order to optimize the procurement cost while still ensuring the dimensioning requirement. TSOs assume that they may

"Direction"

apply economic incentives to make the BSP reduce the restrictions of their bid.

According to the SPBC proposal, "direction" can be upward or downward.

Table 19. Characteristics submitted by each BPS for a mFRR standard product bid [58] [65] [68]

"Bid quantity"	According to the SPBC proposal, this must be submitted in MW.
"Bid price"	According to the SPBC proposal, this must be submitted in (€/MW)/h, with a resolution of 0.01 (€/MW)/h. The price shall be positive or zero and the payment shall be from the TSO to the BSPs only.
"Minimum duration between the end of deactivation period and the following activation"	Must be consistent with the values defined by TSOs.
"Capacity bid divisibility"	According to the SPBC proposal, BPS may submit "indivisible capacity bids" as well as "divisible capacity bids" with a bid granularity of 1 MW. For indivisible bids, the bid quantity submitted by each BSP shall not exceed the value defined by the TSOs.
"Bid location"	According to the SPBC proposal, at least the smallest of LFC area or bidding zone in which the providing units/groups are connected to must be provided. More detailed location information may be required under national responsibility.
"Additional characteristic"	<p>BPS are required to provide information on <i>"technical links"</i> between bids submitted in consecutive quarter hours or in the same quarter hour, needed to avoid the underlying asset performs unfeasible activations. More details about <i>"technical links"</i> can be found in [58].</p> <p><i>"Parent-child linking"</i> and <i>"exclusive group orders"</i> will be allowed within the same quarter hour. These are economic links, i.e., links between bids with the purpose of economic optimization. "Parent-child linking" means a bid (the child) that can only be activated if another specific bid (the parent) is activated as well, not vice-versa. This is useful, for instance, to reflect start-up costs and power limits of their BSP units more correctly. "Exclusive group orders" means that only one specific bid can be accepted from the list of bids part of the exclusive group orders. More details about allowed "economic links" can be found in [58].</p>

5.6.4. RR standard product

The characteristics for a RR standard product bid are specified on the SPBC proposal [65] (from December 2019) and on "The proposal of all TSOs" performing the reserve replacement for the

implementation framework for the exchange of balancing energy from RR" [69] (an ENTSO-E publication from June 2018 and approved on December 2018, named as the RRIF proposal). This RRIF proposal was performed in close coordination with the TERRE project. According to the SPBC and RRIF proposals, a RR "balancing standard product bid" includes the specific characteristics described from Table 20 to Table 22. The ones regarding to the active power time behavior are illustrated in Figure 36. According to the RRIF proposal, in case of under or over delivery of RR balancing energy, the BSP will have financial consequences.

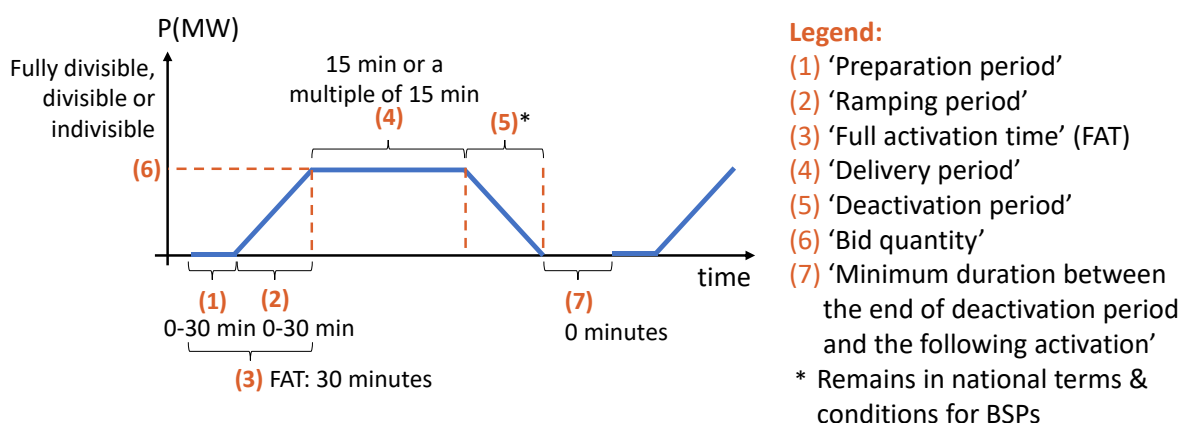


Figure 36 Time domain characteristics of a RR standard product bid

Table 20. Static characteristics of a RR standard product bid [65], [69] [70].

"Preparation period"	Can be from 0 to 30 min.
"Ramping period"	Can be from 0 to 30 min.
FAT	FAT is set to 30 min. Minimum: 15 min.
"Minimum and maximum duration of delivery period"	Maximum: it depends on the number of daily gates. The RR-platform is defined to go-live with 24 daily gates, meaning that each optimization covers 60 min balancing duration and that the maximum delivery period is also 60 min (in case of moving to 48 gates, the maximum delivery period will be 30 min, and if moving to 96 gates, this maximum period will be 15 min).
"Deactivation period"	Under national responsibility. According to the SPBC proposal:
"Minimum and maximum bid quantity"	Minimum bid value shall be 1 MW. Maximum bid value shall be defined by the TSOs. In case of divisible bid, no maximum is requested (only technical limit apply). In case of indivisible bid, national rules will be implemented.
"Mode of activation"	"Scheduled with manual activation".

"Time frame resolution"

RR can be activated for a fixed quarter hour or a multiple of a fixed quarter hour respecting the minimum and maximum duration of the delivery period.

15 min

Table 21. Characteristics to be defined by TSOs for a RR standard product bid [65], [69] and [70]

"Validity period"

In the SPBC proposal, validity period options are 15 min, 1 hour, 4 hours, 1 day or 1 week.

"Minimum duration between the end of deactivation period and the following activation"

In SPBC proposal, this value is set to 0 min.

"Direction"

According to the SPBC proposal, "direction" can be upward or downward.

Table 22. Characteristics submitted by each BPS for a RR standard product bid [65], [69] and [70]

"Bid quantity"

According to the SPBC proposal, this must be submitted in MW.

"Bid price"

According to the SPBC proposal, this must be submitted in (€/MW)/h, with a resolution of 0.01 (€/MW)/h. The price shall be positive or zero and the payment shall be from the TSO to the BSPs only.

"Minimum duration between the end of deactivation period and the following activation"

In SPBC proposal, this value is set to 0 min.

"Capacity bid divisibility"

According to the SPBC proposal, BPS may submit "indivisible capacity bids" as well as "divisible capacity bids" with a bid granularity of 1 MW. For indivisible bids, the bid quantity submitted by each BSP shall not exceed the value defined by the TSOs.

"Fully divisible bids", "divisible bids" and/or "indivisible bids" are allowed (explained in Figure 37).

"Bid location"

According to the SPBC proposal, at least the smallest of LFC area or bidding zone in which the providing units/groups are connected to must be provided. More detailed location information may be required under national responsibility.

"Additional characteristic"

Other possible formats for the bids are the following:

- "Linked bids in time" (explained in Figure 38).
- "Exclusive bids" in time or in volume, meaning that only one or none of the exclusive bids can be activated. "Exclusive bids in time" are illustrated in Figure 39, whereas "exclusive bids in volume" are illustrated in Figure 40.
- "Multi-part bids" meaning bids that have variable prices for variable quantities (better explained in Figure 41). These bids allow BSPs to internally model their fixed costs (e.g. start-up costs).

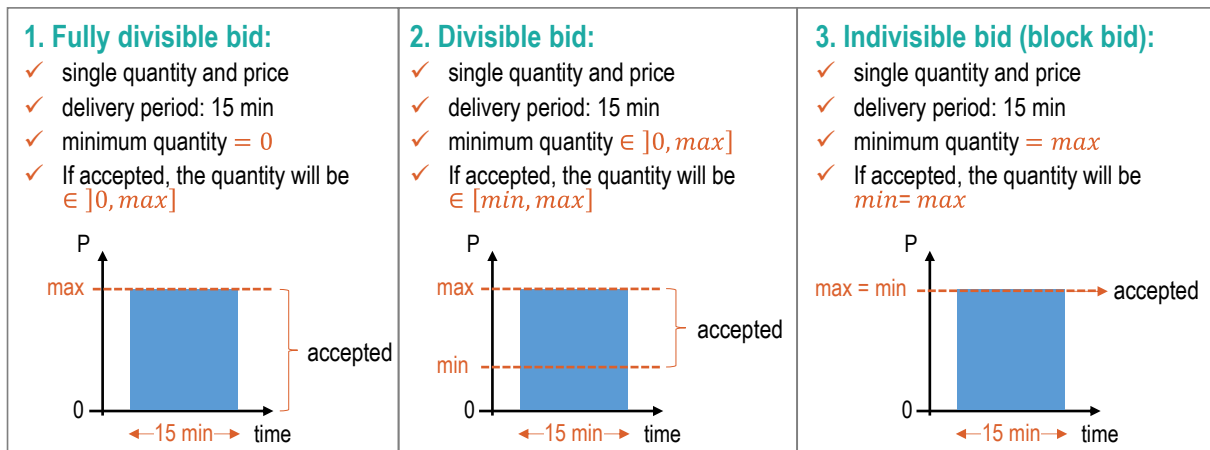


Figure 37 Fully divisible, divisible or indivisible bid [62].

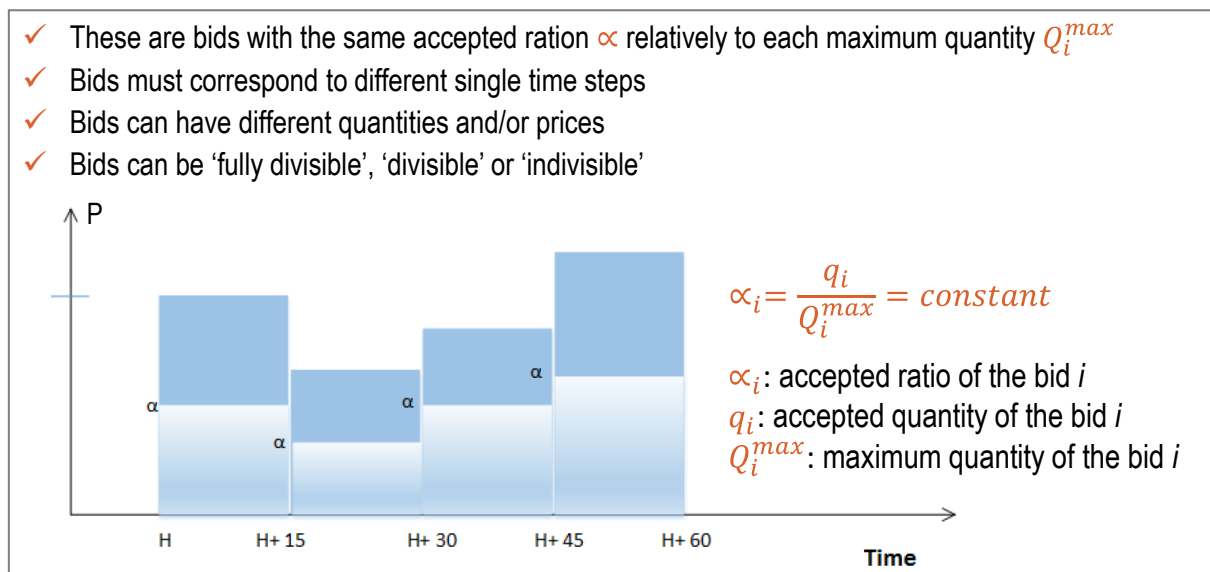


Figure 38 Linked bids in time [62]

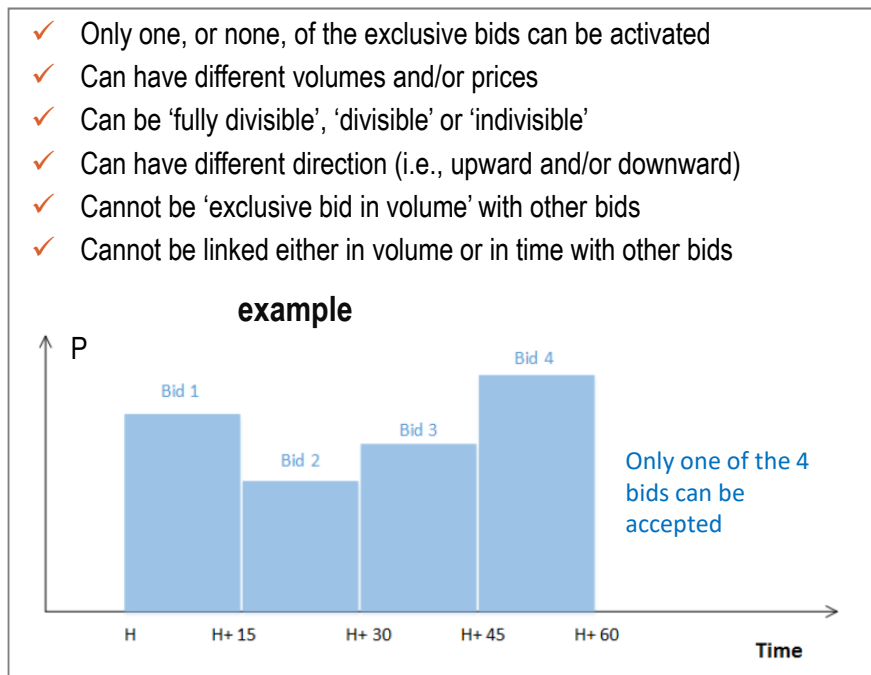


Figure 39 Exclusive bids in time [62].

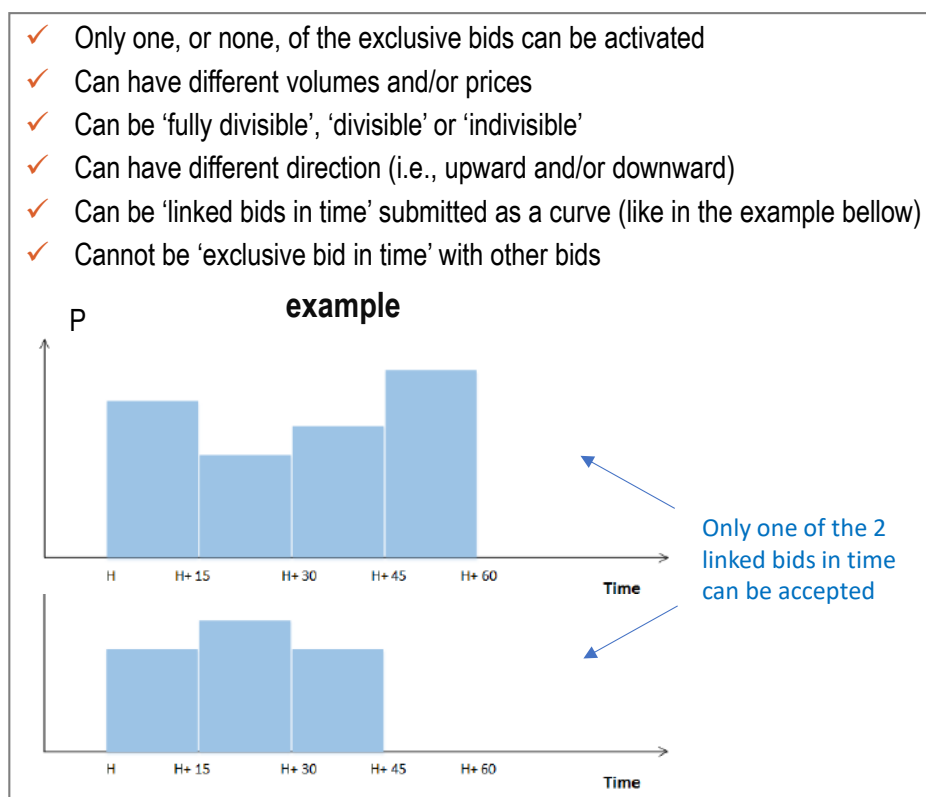


Figure 40 Exclusive bids in volume [62].

- ✓ The price can only increase with the quantity of P
- ✓ Can be 'fully divisible', 'divisible' or 'indivisible'
- ✓ P can only have a single direction (i.e., upward or downward)
- ✓ A starting time and an ending time has to be defined in order to indicate the delivery period

example

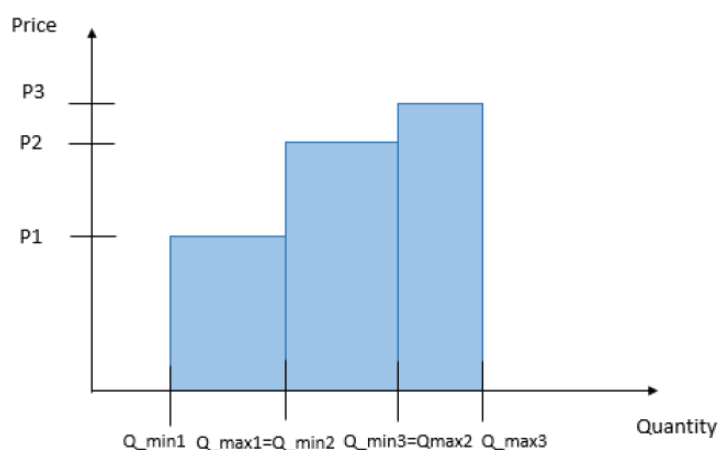


Figure 41 Multi-part bids [62].

6 Demonstrators and technological solutions

This section aims to provide a preliminary overview of XFLEX HYDRO demonstrators, addressing in particular the technological solutions tackled within the scope of each one in the light of their capability to improve the provision of flexibility/ancillary services as well as through the overall improvements in the hydroelectric machinery existing in the HPPs. The technological solutions to be assessed and/or implemented within the scope of the XFLEX HYDRO project are as follows:

- **Fixed speed** units;
- **Variable speed**, through the installation/conversion to:
 - Doubly Fed Induction Machine (DFIM);
 - Full Size Frequency Converter (FSFC);
- **Smart Power Plant Supervisor** (SPPS), a methodology to provide an adequate monitoring and extensive knowledge of the machine that will enable the plant owner to manage the risks and costs associated to a temporary off-design operation according to the potential benefits it offers. SPPS provides plant health information (monitoring of wear & tear of critical components) that will allow an asset management module to reduce the need of maintenance. It is also important to note that in this report the SPPS methodology is considered as an umbrella of all the actions, studies and control measures performed to increase operation controllability and monitoring of the HPP without the installation of significant hardware.
- **Hydraulic Short Circuit** (HSC), which allows the HPP to generate power at the same time it is pumping water for storage. This enables the simultaneous pumping at rated power and controlling the turbine power generation, varying continuously the consumption of the plant.
- **Hydro-Battery-Hybrid** (HBH). Hybridization of the HPP through the installation of a Battery Energy Storage System (BESS).

These technologies have different applicability and specificities according to each demonstrator characteristic and allow for different improvements in terms of hydroelectric machinery and provision of flexibility. In the coming subsections is presented a general characterization of each demonstrator and its expected evolution regarding hydroelectric machinery and flexibility/ancillary services portfolio evolution.

6.1. Demonstrator – Z'Mutt

6.1.1. General characterization

Z'Mutt is a Pumped Storage Plant (PSP), which is currently equipped with 5 storage pumps and is part of the Grande Dixence hydroelectric scheme located in Canton Valais, in Switzerland. The current unit 5 is in the process of being replaced by a new variable speed reversible Francis pump-turbine (replacement process is done in parallel with XFLEX HYDRO activities) and the commissioning is scheduled for May 2021. Table 23 and Table 24 summarize the main data of the power plant with the new Francis pump-turbine.

Table 23. Z'Mutt hydraulic features

Head	Rated: 110 m
Type of turbine	Vertical reversible Francis pump-turbine
Number of units & unit size	1
Turbine rotational speed range	Reversible [600 min ⁻¹ ; 1200 min ⁻¹]

Mechanical power 4.5 MW

Table 24. Z'Mutt power generation features

Type of power generator	Asynchronous motor generator
Variable speed	FSFC
Rotational speed	Min:10 Hz, Rated:16.67 Hz, Max:20 Hz

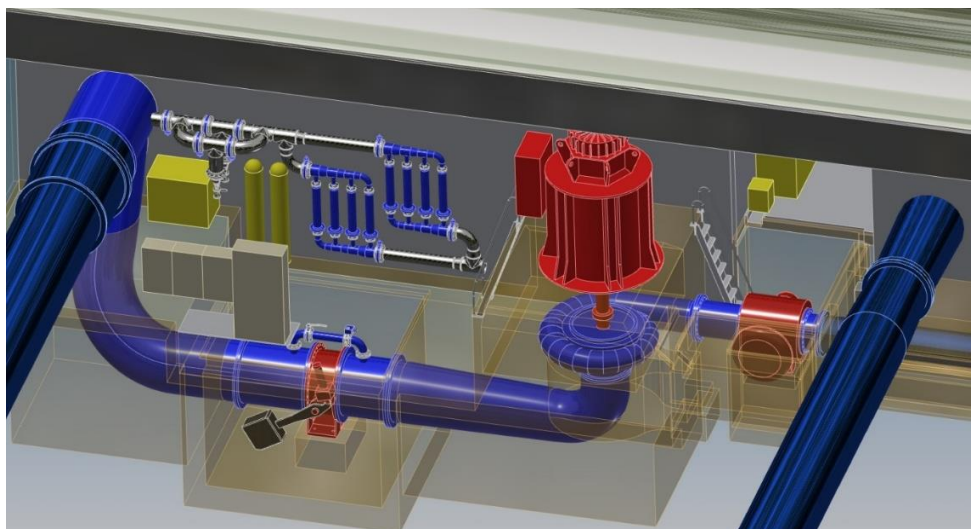


Figure 42 3D view of the future variable speed pump-turbine unit 5 of Z'Mutt pumping station owned by Grande Dixence SA.

6.1.2. Services portfolio and expected evolution

The current services portfolio, regarding both the improvement of the hydroelectric machinery operation and the EPS flexibility services, is detailed in Table 25 and

Table 26 and compared to the future portfolio after the implementation of the XFLEX HYDRO project.

Table 25. Improved hydroelectric machinery in Z'Mutt

Improvements	Today	Tomorrow	Justification
Average annual efficiency	Pump average efficiency of 85%	Pump average efficiency of 88.5%	New Francis reversible pump-turbine replacing old Dériaz pump-turbine
High availability hydropower plant	Interval between two consecutive starts of 15 min Limited number of starts per day	No interval between two consecutive starts Increased number of starts per day	Severe direct start in pumping mode inducing motor generator overheating replaced by soft start with torque and speed control of motor generator
Maximized performances	Constant power in pumping mode	Power control in pumping mode (50%-100% of P_n)	Variable speed with FSFC

Improvements	Today	Tomorrow	Justification
		Additional 11 GWh power production annually	Additional > 4 million m3 will be pumped to Grande Dixence + new Francis pump will turbine some water
Optimized maintenance intervals	Every 2 years	Every 4 years (5 times more starts until same electrical and mechanical maintenance)	Severe direct start in pumping mode replaced by soft start with torque and speed control of motor generator Coating of parts
Minimized outage time	-	Reduced unplanned outage	Severe direct start in pumping mode replaced by soft start with torque and speed control of motor generator
Digitalization measures	Few operation and maintenance digital platforms installed	SPPS (and Hydro-Clone)	-

Table 26. Improvement in Z'Mutt provision of flexibility service

Flexibility Services	Today	Tomorrow	Justification
Synthetic Inertia	No	Yes	Inertia emulation control loop will be implemented in the hydro unit governor
Synchronous inertia	Yes	No	Compensated by synthetic inertia
FCR	+/-20% of P_n in 10 s in generating mode	+/-20% of P_n in 0.2 s in generating and pumping mode and continuously thanks to fast transition mode	FSFC enable fast active power injection and absorption as well as fast transition between pumping and generating mode and vice-versa
FRR	No	Extended operating range in generating mode (40%-100% of the nominal power P_n) and available in pumping mode (50%-100% of P_n)	FSFC enable to provide control in pumping mode and extended operating range in generating mode
RR	(No generating mode) 15 s in pumping mode	P_n available after 15 s in generating and in pumping mode	FSFC enable smooth start-up sequence from zero speed (speed and torque control)

Flexibility Services	Today	Tomorrow	Justification
	with direct start (transient overload)	pumping mode with soft start	
Volt/var control	Not available (asynchronous MG)	Available during operation and at standstill	Grid side converter enable to provide reactive power

As previously described, both the hydroelectric machinery operation and the EPS flexibility services are expected to be substantially improved thanks to the implementation of the variable speed technology and the SPPS. The main expected results, which will be demonstrated in Z'Mutt power plant, are:

- High flexibility of variable speed unit equipped with a FSFC and advanced control:
 - fast power injection or absorption in pump and generating mode and inertia emulation for contribution to primary, secondary and tertiary control services (FCR, FRR, RR);
 - fast start and stop sequences in turbine and in pump as well as fast transition modes.
- Maintenance optimization by unit components lifetime prediction methods at prototype scale and safe long-term operation under high flexibility operation.
- New control strategies (electrical breaking) in fast transient phenomenon (load rejection).

6.2. Demonstrator – Frades 2

6.2.1. General characterization

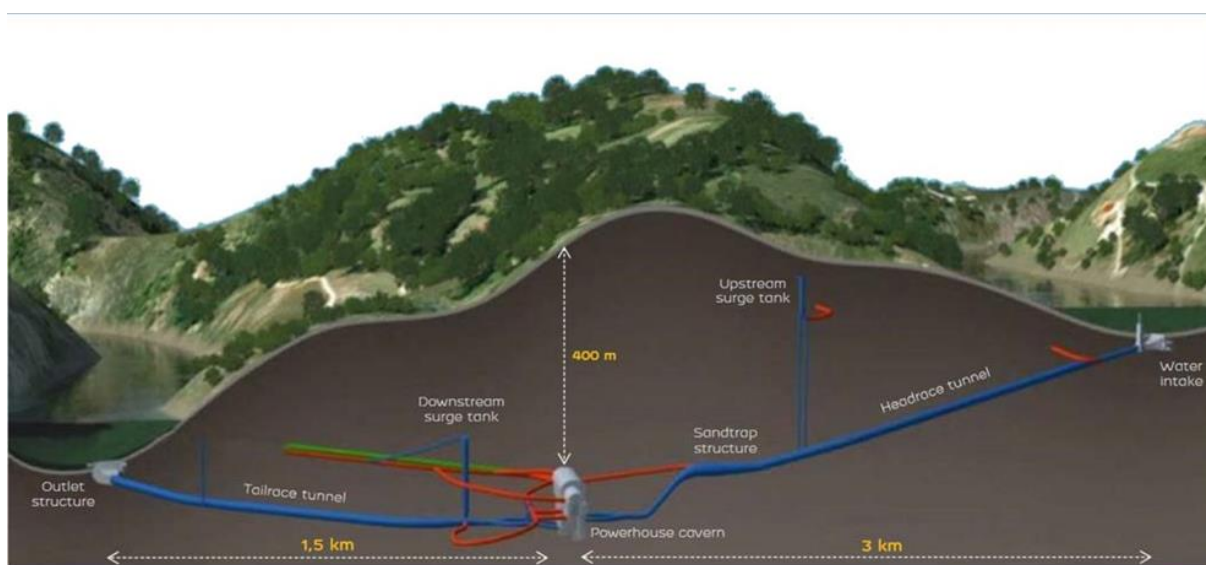
Frades 2 hydroelectric plant is a PSP built between 2010 and 2017 on the Rabagão river in the north of Portugal. The plant is composed of two high head, variable speed units made of two reversible pump turbines, coupled with 420 MVA DFIM) which are currently Europe largest and most powerful machines. The following tables include the main hydraulic and power generation features.

Table 27. Frades 2 hydraulic features

	Maximum 431.80 m, Minimum 413.64 m
Head	Rated Pumping mode: 414 m Rated Generating mode: 426 m
Type of turbine	Francis type single stage reversible pump-turbine
Number of units & unit size	2 units, 4.500 m
Turbine rotational speed range	350 min ⁻¹ ; 381.2 min ⁻¹
Mechanical power	Generating mode: 400 MW, 390 MW, 190 MW Pumping mode: -300 MW, -381 MW, -390 MW

Table 28. Frades 2 power generating features

Type of power generator	Asynchronous machine
Variable speed	DFIM
Rotational speed	350 min ⁻¹ , 375 min ⁻¹ , 381.2 min ⁻¹
Other features	420 MVA rated power

**Figure 43 Frades 2 PSP layout**

6.2.2. Services portfolio and expected evolution

The main hydroelectric machinery operation characteristics for Frades 2 PSP are listed in Table 29 below and are compared to the future expected improvements after the implementation of the XFLEX HYDRO project.

Table 29. Improved hydroelectric machinery in Frades 2

Improvements	Today	Tomorrow	Justification
Average annual efficiency	average auxiliary power consumption of 900 kW	Reduction of average auxiliary power consumption by 10%	Implementation of condition-based control of auxiliary equipment
High availability hydropower plant	350 h/month	Depending on trading market, estimated at least 400h/month	Enhanced SPPS monitoring & analysis of steady-state and transient operation will allow monitoring and operating the generator in a wider range of power regulation, especially in pumping mode

Maximized Performances	FRR: 300 MW-390 MW + 600 MW-780 MW in pumping mode; 190 MW-800 MW in generating mode.	FRR: Extended 0-200 MW in pumping mode; Extended 0-100 MW in generating mode	Implementation of variable speed HSC operation to extend power regulation capability
Adapting to variable speed generation	Already variable speed. This enables pumping / generating power in the range of 319 MW to 383 MW	-	-
Optimized maintenance intervals	According to OEM suggested schedule, every 4000 h operating hours	Condition-based maintenance for critical components assessed with SPPS, estimated at least every 4500 h	SPPS will provide plant health information (monitoring of wear & tear of critical components) that will allow an asset management module to reduce the need of maintenance
Digitalization measures	No	SPPS (and Hydro-Clone)	-

Frades 2 demonstrator will validate the improvement in performances and maintenance intervals for DFIM variable speed PSPs. To achieve that, the following technologies will be integrated and tested:

- HSC aiming at maximizing the performance and increasing the flexibility through extending the power plant power range.
- Implementation of the SPPS to improve the maintenance intervals and minimize outages.

The demonstration will allow or improve the provision of several flexibility services compared to the current condition. FRR will be enhanced through the HSC implementation. Furthermore, the demonstrator will also allow virtual inertia emulation and FCR provision. Table 30 illustrates the current flexibility services provided as well as the expected improvements provided by Frades 2.

Table 30. Improvement in Frades 2 provision of flexibility services

Flexibility Services	Today	Tomorrow	Justification
Synthetic Inertia	No	Yes	Inertia emulation control loop will be implemented in the hydro unit governor
Synchronous inertia	No	No	Compensated by synthetic inertia
FCR	No	Yes	Implementation of FCR functionality in the master turbine controller

FRR	Available within normal operating range in generating and pumping mode	Available in additional pumping range: 0-200 MW and additional turbine range: 0-100 MW	Implementation of variable speed HSC operation
-----	------------------------------------------------------------------------	----------------------------------------------------------------------------------------	------------------------------------------------

6.3. Demonstrator – Grand Maison

6.3.1. General characterization

Built in the mid-80s, in the French Alps, Grand Maison PSP features the largest 1800 MW installed capacity in Europe. The headwater and tailwater reservoirs feature 150 million m³ and 15 million m³ capacity, respectively, Pelton runners being uprated to 170MW. The following tables summarize the main data of the power plant.

Table 31. Grand Maison hydraulic features

Head	Min 837 m; Rated 900 m; max 923 m
Type of turbine	Pelton / Multistage pump turbine
Number of units & unit size	4 Pelton turbines 156 MW uprating in progress to 170 MW 8 pump-turbines 156 MW each
Turbine rotational speed range	Fixed speed: Pelton 428 min ⁻¹ ; pump turbine 600 min ⁻¹
Mechanical power	156 MW / unit

Table 32. Grand Maison power generation features

Type of power generator	12 units: synchronous
Variable speed	Fixed speed
Rotational speed	428 min ⁻¹ and 600 min ⁻¹ as per turbine

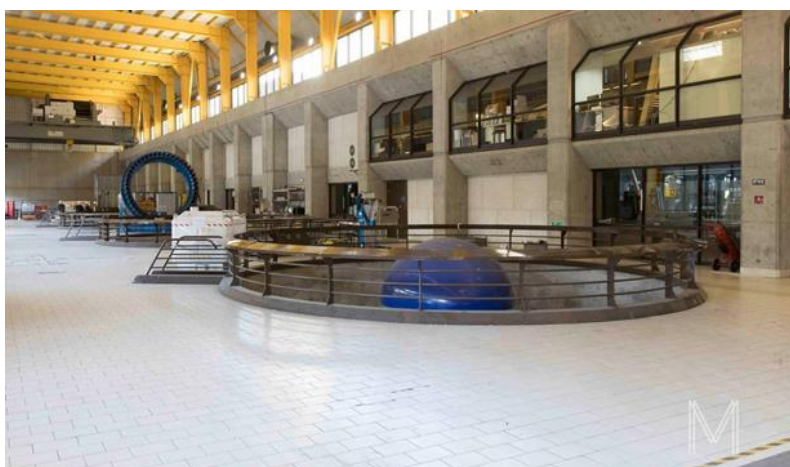


Figure 44 Grand Maison Pelton units floor

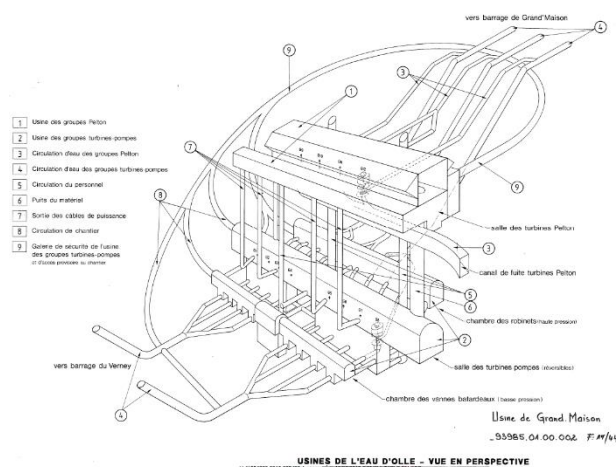


Figure 45 Grand Maison power plant scheme

6.3.2. Services portfolio and expected evolution

Today, grid frequency support is only available when the units are operated in generating mode, while EPS flexibility services cannot be provided in pumping mode.

The current services portfolio, regarding both the improvement of the hydroelectric machinery operation and the EPS flexibility services, is detailed in Table 33 and

Table 34 and compared to the future portfolio after the implementation of the XFLEX HYDRO project.

Table 33. Improved hydroelectric machinery in Grand Maison

Improvements	Today	Tomorrow	Justification
Average annual efficiency	Pelton efficiency 1980 design	Pelton efficiency to be increased by 1.5% to 2%	New Pelton Runner with 2010 design
High availability hydropower plant	Pelton units run 6 h to 10 h daily	Pelton units will run 9 h to 15 h daily	Pelton units will also be used when the scheme is in pumping mode
Maximized performances	Constant power in pumping mode; no frequency support in pumping mode (0 MW)	Power control in pumping mode (50%-100% of P_n); contribution of the scheme (aFRR) to around 60 MW per Pelton x 4 runners (20% of France secondary reserve)	Pelton units will run together with the pumps and provide the power adjustment
Optimized maintenance intervals	Pelton runners are checked every 1000 h	New runners are checked every 4000 h	Pelton bucket attachment is less stressed with the new design

Improvements	Today	Tomorrow	Justification
Minimized outage time	-	Reduced unplanned outage	Severe direct start in pumping mode replaced by soft start with torque and speed control of motor generator
Digitalization measures	E-monitoring based on trending	SPPS and Hydro-Clone	

Table 34. Improvement in Grand Maison provision of flexibility services

Flexibility Services	Today	Tomorrow	Justification
Synthetic Inertia	No	No	-
Synchronous inertia	Yes	Yes, 1.5 to 2 times more	As Pelton units will run in pumping mode their inertia will be added up to the pump units
FCR	None in pumping mode	5% to 10% of Pelton power	Pelton runner are equipped with turbine governors
FRR	None in pumping mode	20% to 40% of Pelton unit power can be allocated to FRR	Pelton unit will be controlled by the PSP controller which shall adjust unit set point according to FRR need
RR	Yes (takes 120 s)	Yes, it will be almost instantaneous	Pelton units will be operating already
Volt/var control	Yes	Yes with 1.5 to 2 times more regulation	Pelton units being equipped with voltage controller

As previously described, both the hydroelectric machinery operation and the EPS flexibility services are expected to be substantially improved thanks to the implementation of the HSC technology and the SPPS. While the power plant is operating in pumping mode, one Pelton unit is operated at partial load, depending upon the request of the grid frequency support. This technology, together with the implementation of the smart control, will enhance the EPS frequency control services and the inertia during low demand with an increase of 30% compared to the current situation.

Maintenance optimization by unit components lifetime prediction methods at prototype scale and safe long-term operation under an extended operating range will also be performed to boost the flexibility and availability of the power plant for the EPS services.

6.4. Demonstrator – Alqueva

6.4.1. General characterization

Alqueva hydroelectric plant is a PSP located in the Guadiana river in the south of Portugal. It is owned by EDP and it is part of the Alqueva Dam complex, an infrastructure that created the Europe largest artificial lake. The power plant includes two separate powerhouses, Alqueva I, commissioned in 2004 and Alqueva II, commissioned in 2017. Two fixed speed reversible groups with a total nominal power of 520 MW compose each powerhouse. Table 35 and Table 36 include the main hydraulic and power generation features.

Table 35. Alqueva hydraulic features

Head	Alqueva I: 76 m (max), 50.2 m (min) Alqueva II: 72 m (max)
Type of turbine	Francis reversible pump-turbine
Number of units & unit size	Alqueva I: 2 units, $D_{\text{runner}} = 6$ m Alqueva II: 2 units, $D_{\text{runner}} = 6$ m
Turbine rotational speed range	Alqueva I: fixed 136.4 min^{-1} Alqueva II: fixed 136.4 min^{-1}
Mechanical power	Alqueva I: Max. 129.6 MW in generating mode and 106.9 MW in pumping mode. Alqueva II: Max. 130 MW in generating mode and 110 MW in pumping mode.

Table 36. Alqueva power generation features

Type of power generator	Synchronous motor generator
Variable speed	Fixed
Rotational speed	Alqueva I: 136.4 min^{-1} Alqueva II: 136.4 min^{-1}
Other features	Alqueva I: 147 MVA Alqueva II: 143 MVA

6.4.2. Services portfolio and expected evolution

The main hydroelectric machinery operations for Alqueva PSP are listed in Table 37. Moreover, they are compared to the future expected operational improvements after the implementation of the XFLEX HYDRO project.

Table 37. Improved hydroelectric machinery in Alqueva

Improvements	Today	Tomorrow	Justification
Average annual efficiency	will be monitored at the beginning of the project	Improved	Thanks to specific efficiency strategy in the advanced joint control

Improvements	Today	Tomorrow	Justification
High availability hydropower plant	95%-98% over last 10 years	Improved 1%	Thanks to specific damage management strategy in advanced joint control
Maximized performances	40%-100% operation range in generating mode	+/-100% operation range	Thanks to extended operation range and simultaneous pumping and generating.
Optimized maintenance intervals	-	Improved 10%	Thanks to specific damage management strategy in advanced joint control
Digitalization measures	Condition monitoring system under installation	Some additional sensors and analytics	Condition monitoring feeding advanced joint control

Alqueva demonstrator will evaluate reduced low CAPEX opportunities to improve the hydroelectric machinery operation and consequently, extend the flexibility services provided. The following technologies will be integrated:

- The advanced joint control technology will be tested to allow to adopt the dispatching rules according to the criteria to optimize (efficiency, wear and tears, maintenance plan).
- HSC operation will be tested to allow simultaneous pumping and generating from the four generators.
- Extended operating range will be tested to reach an almost continuous power output from zero to rated power in generating mode.

Thanks to extended operation range and simultaneous pumping & generating, the performance will be maximized to continuous operation from -100% to +100%.

Furthermore, flexibility services will also be enhanced thanks to simultaneous pumping and generating. More in detail, synchronous inertia will be doubled, FCR will be offered at any time, FRR will be accessible in pumping mode and increased in generating mode, and the time for RR will be six times faster compared to the current condition.

Table 38 gives an overview of the expected improvements on the flexibility services that will be obtained after the implementation of the XFLEX HYDRO project.

Table 38. Improvement in Alqueva provision of flexibility services

Flexibility services	Today	Tomorrow	Justification
Synchronous inertia	Yes	Extended: increased two times	Inertia of turbine will be added to pumps inertia thanks to simultaneous pump & generating mode
FCR	None in pumping mode	+/- 20% of P _n in 30 s	Thanks to simultaneous pumping and generating
FRR	None in pumping mode (fixed speed)	+/- 30% of P _n in pumping mode +/-	Thanks to large operating range in generating mode

Flexibility services	Today	Tomorrow	Justification
	+/- 30% in generating mode	40% in generating mode	and simultaneous pumping & generating
RR	Yes (takes 120 s to start one unit)	Yes, in less than 20 s	Thanks to simultaneous pumping & generating (time to shut down the pump)
Volt/var Control	Yes (compulsory and non-remunerated)	Extended	The 2nd turbine is providing voltage control thanks to simultaneous pumping & generating

6.5. Demonstrator – Alto Lindoso & Caniçada

6.5.1. General characterization

Alto Lindoso hydroelectric plant is a high head Storage Hydro Plant (SHP) located in the north of Portugal and owned by EDP. Alto Lindoso is in operation since 1992 and it is one of the largest hydro plants in Portugal in terms of installed capacity.

Caniçada is a small size with medium head SHP, located in Cávado river in the north of Portugal, also owned by EDP. It is in operation since 1954 and it has been refurbished in 2017. Caniçada being a small size with medium head unit is used as to complete the study conducted on Alto Lindoso to cover a wide range of unit size and head. The main hydraulic and power generation features for Alto Lindoso and Caniçada are presented Table 39 and Table 40.

Table 39. Alto Lindoso and follower Caniçada hydraulic features

HPP	Alto Lindoso	Caniçada
Head (max./nom./min.)	288 m / 275.6 m / 227 m	121 m / 77 m
Type of turbine	Francis	Francis
Number of units & unit size	2 units, $D_{\text{runner}} = 3770$ mm	2 units, $D_{\text{runner}} = 2020$ mm
Turbine rotational speed range	214.3 min ⁻¹	300 min ⁻¹
Mechanical power	2 x 317 MW	2 x 35 MW

Table 40. Alto Lindoso and follower Caniçada power generation features

HPP	Alto Lindoso	Caniçada
Type of power generator	Synchronous motor generator	Synchronous motor generator
Variable speed	Fixed	Fixed
Rotational speed	214.3 min ⁻¹	300 min ⁻¹

Other features 2 x 350 MVA

2 x 37 MVA

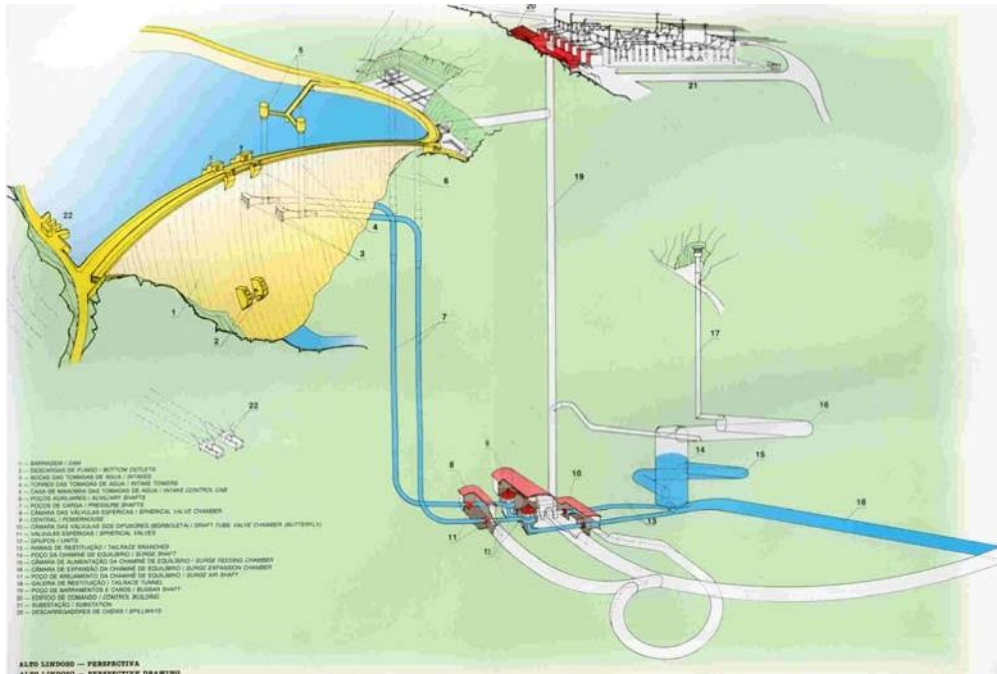


Figure 46 Alto Lindoso SHP layout

6.5.2. Services portfolio and expected evolution

The main hydroelectric machinery operations for Alto Lindoso and Caniçada are presented in Table 41 and are compared to the expected future operational improvements after the implementation of the XFLEX HYDRO project.

Table 41. Improved hydroelectric machinery in Alto Lindoso and follower Caniçada

Improvements	Today	Tomorrow	Motivation
Average annual efficiency	To be monitored	Improved	Specific efficiency strategy in advance joint control
High availability hydropower plant	98% over the last 10 years	Improved 0.5%	Specific damage control strategy in advance joint control
Maximized performances	50 - 100% operation range	Near 0 to 100% operation range	Thanks to extended operation range
Optimized maintenance intervals	-	Improved 10%	Specific damage control strategy in advance joint control
Digitalization measures	Condition monitoring system under installation	Some additional sensors and analytics	Condition monitoring feeding advanced joint control

Alto Lindoso and Caniçada demonstrator goal is to extend the existing operating range to achieve an almost continuous power output from zero to rated power, without the implementation of variable speed turbines. Therefore, the two following low CAPEX opportunities will be evaluated during the demonstration:

- Extension of the operating range will be tested to allow an almost continuous power output, implementing the recent progress in understanding deep partial load behavior.
- Advanced joint control allowing to adapt the dispatching rules according to the criteria to optimize (efficiency, wear and tears, maintenance plan, etc.).

Flexibility services will also be enhanced thanks to the extension of the operating range, in particular, FRR will be doubled compared to the current situation.

Overview of the current and expected improvement on the flexibility services is given in Table 42.

Table 42. Improvement in Alto Lindoso and follower Caniçada provision of flexibility services

Flexibility services	Today	Tomorrow	Justification
Synchronous inertia	Yes	Yes	-
FCR	+/-20% of P_n in 30s	+/-20% of P_n in 30s	-
FRR	+/-25% of P_n	Doubled +/-50% of P_n	Thanks to the extended operation range (0-100%)
RR	Yes (takes 90s to start one unit)	Yes (takes 90s to start one unit)	-
Volt/var control	Yes (compulsory and non-remunerated)	Yes (compulsory and non-remunerated)	-

6.6. Demonstrator – Vogelgrün

6.6.1. General characterization

Vogelgrün demonstrator is a 142 MW Run-of-River (RoR) HPP in France, situated near the border with Germany along the river Rhine. The plant has four low head Kaplan turbines, in service since 1959, and during XFLEX HYDRO one of the units will be hybridized with a battery. Complementing the turbine operations, the hybridization of the system with the installation of a battery will add energy capacity and power converter rating to improve the HPP capacity of providing FCR and use a master control to optimize both flexibility and wear and tear effects.



Figure 47 Photography of Vogelgrün RoR HPP in FR

The main hydraulic and power generation features for Vogelgrün are presented in Table 43 and Table 44, respectively.

Table 43. Vogelgrün hydraulic features

Head (max./nom./min.)	12.5 m / 11.7 m / 10.5 m
Type of turbine	Kaplan
Number of units	4 units
Turbine rotational speed range	214.3 min ⁻¹
Mechanical power	4 x 35 MW

Table 44. Vogelgrün power generation features

Type of power generator	Synchronous motor generator
Variable speed	Fixed
Rotational speed	83 min ⁻¹
Other features	4 x 39 MVA

6.6.2. Services portfolio and expected evolution

The evolution of the actual hydro power plant has several objectives described below:

- Hybridize the turbine unit with a battery of suitable energy capacity and power converter rating, to improve capability of providing primary frequency response.
- Contribute to frequency response with high-dynamic response.
- Significantly reduce turbine wear and tear and quantify it.
- Evaluate the possibility of upgrading fixed speed double-regulated Kaplan turbine units by enhanced variable speed single-regulated propeller unit.

The BESS specifications are defined in terms of power converter rating and energy storage through a technical study performed as part of another WP, but it is expected the installation of battery system in the range of 200 kWh of storage with the inverter power rating in the range of 800 kW.

The main hydroelectric machinery operations for Vogelgrün are presented in Table 45 and are compared to the expected future operational improvements after the implementation of the XFLEX HYDRO project.

Table 45. Improved hydroelectric machinery in Vogelgrün

Improvements	Today	Tomorrow	Motivation
Average annual efficiency	-	Refined monitoring procedures	Due to a better detection of incipient failures
High availability hydropower plant	50 - 100% operation range	Expected 0.5% higher energy production	Due to reduced outage times
Optimized maintenance intervals	Maintenance intervals: every 10 years Wear and Tear of mechanical equipment: 1 move every 5 sec	Maintenance intervals: every 20 years expected, by Predictive maintenance methods Mech. movements reduced to 10%: 1 move every 50 sec	Based on actual (improved) operation of the unit
Digitalization measures	-	Hydro-Clone; Metris DiOMera ¹⁶⁾ , SPPS	SPPS will be developed for optimization of operation, Metris DiOMera provides capabilities for data-based prediction of health and trends of machine components and will be adapted to this specific pilot

The hybridization of the HPP with a BESS will enhance the availability and promptness to answer to the EPS flexibility needs in comparison with hydraulic unit alone. More specifically, the installation of a BESS will allow for much a faster response in terms of FCR because of the very quick time constants associated to the power electronics involved in the converter of the battery. FCR is already provided by Vogelgrün but with a very slow response of 300 s (there is an agreement for Vogelgrün to provide it in 300 s) and after the installation and implementation of the BESS, the provision of FCR it should be much faster than the FAT of 30 s regulated.

An overview of the current and expected improvement on the provision of flexibility services is given in Table 46.

Table 46. Improvement in Vogelgrün provision of flexibility services

Flexibility services	Today	Tomorrow	Justification
Synchronous Inertia	Yes	Yes	Rotating machine remains unchanged
Synthetic Inertia	No	No	Power electronics too small to be efficient

¹⁶⁾ Metris DiOMera is digital platform developed by ANDRITZ to improve HPP overall performance

Flexibility services	Today	Tomorrow	Justification
FCR	Yes, but slow (300 s)	Yes, faster (< 30s)	Power electronics time response is very quick
FRR	No	No	Out of the scope of RoR plants with navigation constraints
RR	No	No	Not achievable with RoR plants
Volt/var control	Yes	Yes	Voltage control remains unchanged

Flexibility matrix

7 Concept

7.1. General

As previously mentioned, the decarbonization process of the economy is largely based on the massification of renewable-based energy production, which is characterized by high temporal variability and reduced controllability. Bearing in mind that the operating philosophy of any electrical system is based on the constant balance between supply and demand, the growth in renewable production strongly disrupts this condition and demands greater availability of flexibility services.

In this sense, the main objective of XFLEX HYDRO is the development of new technological solutions that will integrate HPPs of various types, aiming to improve their performance and efficiency, and thus actively contribute to the decarbonization of the EPS. As part of this exercise, it is important to understand more clearly the set of flexibility (or ancillary¹⁷⁾ [71]) services expected for the electricity sector, from which new opportunities will emerge for HPP. Based on this rationale, the first concept of a "Flexibility Matrix" in Figure 48 is designed. This matrix aims to combine the different flexibility services and their evolution, the flexibility markets that are inherently associated with it, as well as, the different technologies to be integrated in the HPPs to endow them with enhanced capacity to provide these flexibility services. It is also intended that the development of the project will make possible to show an indication of the level of adequacy of each demonstrator, equipped with a new technological solution, to provide flexibility services and to play in their markets. It is understood that this matrix will be extremely important for the various stakeholders in the hydroelectricity industry, providing a synthetic mapping of new opportunities in the decarbonization plans of the economy.

¹⁷⁾ According to [71], "ancillary service" means a service necessary for the operation of a transmission or distribution system, including balancing and non-frequency ancillary services, but not including congestion management; 'non-frequency ancillary service' means a service used by a transmission system operator or distribution system operator for steady state voltage control, fast reactive current injections, inertia for local grid stability, short-circuit current, black start capability and island operation capability.

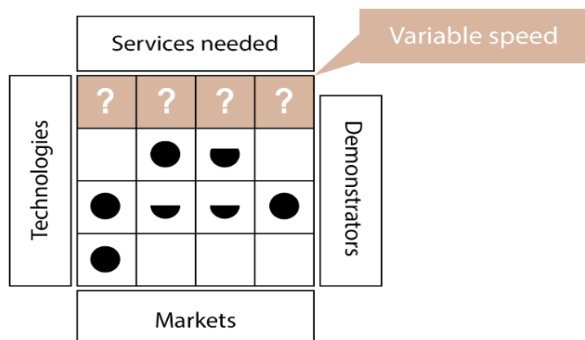


Figure 48 First concept of the Flexibility Matrix

However, this initial concept of the "*Flexibility Matrix*" would leave out significant information about the improvements expected to be achieved within the XFLEX HYDRO project in terms of the HPP overall operation and maintenance and capabilities to provide flexibility that do not fall back into the envisaged basket of ancillary services for the future EPS. Therefore, the summary of the overall contributions expected to be drawn from the XFLEX HYDRO project are proposed to be organized in two matrixes:

- The "*Ancillary Services Matrix*" (ASM) that holds the same concept envisioned for the flexibility matrix and addresses a wide basket of ancillary services to which HPP are expected to contribute in the short to long term range (a first stage of the ASM is presented in subchapter 7.2).
- A Key Performance Indicators matrix, named the "*KPI Matrix*", envisioned to highlight the improvements provided in terms of the HPP overall operation/maintenance/efficiency and in terms of the capabilities to provide flexibility that do not fall back into the envisaged basket of ancillary services for the future EPS. A general overview of the framework of this matrix is introduced in subchapter 7.3.

This arrangement aims at providing a common link along the overall project development: from the innovation phase (which includes work package 2 and 3), inclusion of the set of work packages dealing specifically with several demonstrators (4 to 9) and the deployment phase where a roadmap for HPP is to be developed (work package 10) followed by a market uptake study (work package 11). These matrixes are expected to be continuously populated alongside the project development, constituting a summary of the main achievements in terms of HPP capabilities towards EPS provision of services and associated efficiency and availability.

7.2. Ancillary Services Matrix

7.2.1. Types of Ancillary Services

By combining the most recent power balancing/ancillary services products, the emerging market supporting mechanics associated to them and the hydropower technologies under evaluation in several demonstrators within the scope of this project an ASM is created. This final version of this matrix, when fully populated, is intended to provide an overview regarding the adequacy of each technology in each demonstrator to the existing/expected ancillary services.

The first stage of the ASM is displayed in Figure 50 (first milestone of WP2) and it already presents the baseline characterization of each demonstrator with respect to the envisioned ancillary services. Following the XFLEX HYDRO project development, the ASM will be progressively populated, thus mapping the most recent outcomes/conclusions being drawn under several dimensions: on-site studies and tests, as well as dynamic simulations of hydraulic, mechanical and electrical responses on small-scale test benches and/or digital models.

The breakdown of the technological solutions per demo portrayed in the matrix follows a preliminary rational considering demo owners and associated equipment manufactures view regarding the envisioned development plan for each demo, either in terms of engineering/simulation studies, reduced scale models tests and on-site live tests. For each demo, the set of technological solutions to be assessed is as follows:

Z'Mutt:

- Fixed speed (baseline – synchronous machine);
- Variable speed with a FSFC;
- Variable speed and SPPS.

Frades 2:

- Fixed speed;
- Variable speed with a DFIM (baseline);
- Variable speed, SPPS and HSC.

Grand Maison:

- Fixed speed (baseline);
- Fixed speed, SPPS and HSC.

Alqueva:

- Fixed speed (baseline);
- Fixed speed and SPPS;
- Fixed speed and HSC;
- Fixed speed, SPPS and HSC;
- Variable speed with a FSFC and SPPS.

Alto Lindoso and Caniçada:

- Fixed speed (baseline);
- Fixed speed and SPPS;
- Variable speed and SPPS.

Vogelgrün:

- Fixed speed (baseline);
- Fixed speed, SPPS and HBH;
- Variable speed (FSFC);
- Variable speed, SPPS and HBH.

In most demonstrators, the baseline situation corresponds to a technological solution based on a fixed speed machine, being Frades 2 the outlier since this HPP includes a state-of-the-art variable speed machine (DFIM type) already installed. Regarding the specific case of Frades 2, a hypothetical solution based on a fixed speed unit is also considered to be addressed under simulation/engineering studies in the benefit of better understand the expected benefits/limitations of each technological solution for the specific typology of this HPP. With respect to the Z'Mutt demonstrator, it is important to notice that unit 5 of this HPP is in the process of being converted to a variable speed machine (FSFC type), which is being done in parallel to XFLEX HYDRO activities. As such, the baseline chosen for this demo to be portrayed in the matrix is fixed speed technology (a synchronous machine is considered in line with other demos, which will be addressed by means of simulation studies).

For populating the ASM with respect to the considered baseline technological solution of each demo with respect to the envisioned services, an approached adapted from a traffic light system is followed. The system from Figure 49 is composed of three differently coloured circles with the following meaning (top to bottom of Figure 49):

- The amber circle means that the HPP with the technological solution that is being evaluated is not currently capable of providing a specific ancillary service;
- The light green circle means that the HPP with the current technological solution is already technically capable to provide a specific service, but its performance can be enhanced taking into consideration the technology portfolio envisioned for the demonstrator;
- The darker green circle means that the HPP with the current technology is already fully capable of providing the specified service, being not expected improvements to it.

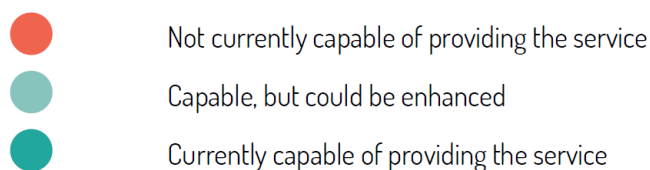


Figure 49 Adaptation of a traffic light system to populate the first stage of the ASM

For the PSPs, two circles with either a “T” (meaning turbine operation mode) or a “P” (meaning pump operation mode) are used to put in evidence that the provision of flexibility services may not be symmetrical. For example, in Grand Maison with the fixed speed technology, the provision of mFRR is only possible (and already at full capability) in turbine mode and not in pump mode.

7.2.2. Ancillary services and market framework

A key aspect of the ASM is to define the basket of ancillary services to be portrayed. The rational that is followed consists in selecting the services that are already envisioned by the TSOs (in Europe) for the current/future operation of the EPS and/or have specific requirements for their provision and that have also existing/emerging market frameworks for their deployment, exchange and remuneration. In this sense, the selected ancillary services along with the existing and/or emerging markets displayed in the AMS are as follows:







- **Synchronous inertia.** The lack of synchronous inertia will become a significant issue with the decommissioning of several synchronous generators of thermal (fossil-fuel based) power plants. It is not currently a remunerated service in CE but it starts to be remunerated, for example, in the UK market, with a tendering process held in 2019 for the start of the provision of this service during 2020 and 2021 [37]. Outside of Europe, there is also the example of Australia [38] that is introducing the service under their market framework.
- **Synthetic inertia.** Although not technically specified in Europe, it is also not foreseen to be remunerated service in the short to medium term (it will probably follow a similar pathway with respect to the conditions for the provision of synchronous inertia – (mandatory provision or contracted in tendering markets). Considering the significant deployment of RES-based sources connected to the grid via power electronics capable of providing such a service and the gradual decommissioning of fossil-fuel based generators (traditionally responsible for providing synchronous inertia), it is expected the technical specification of the service as well as of some sort of regulation/market framework for the deployment of synthetic inertia. In fact, as mentioned in section 4.3.4, in the long term, AEMO (in Australia) plans to include synthetic inertia in its basket of frequency system services [38].
- **Fast Frequency Response (FFR).** This service is designed to provide an active power response faster than existing operating reserves, typically in less than 2 secs in the timeframe following inertial response and before activation of FCR. Although not yet considered in the

basket of system services in the CE SA, FFR is already being explored in Europe (outside of CE SA) in the following markets: UK, Irish Island [39] and Nordic countries [40].

- In CE SA the emerging trends in balancing energy services come from the EBGL implementation and the subsequent exchange platforms/projects:
 - **FCR** (in the original terminology called primary frequency control) is already exchanged in the FCR Cooperation platform of central Europe [18].
 - **aFRR** (in the original terminology called secondary frequency control) has already a standard product defined [59] to be traded in the aFRR platform from the PICASSO [60] initiative as well as in the IN process related to the IGCC [61].
 - **mFRR** and **RR** (in the original terminology called tertiary frequency control) also have standard products defined to be exchanged in the common platforms, respectively MARI [62] and TERRE [63].
- **Volt/var control** is a local technical issue, which nowadays is typically mandatory and not remunerated. In some countries there are also bilateral contracts held between BSP with TSO for the provision of extra Volt/var control that is remunerated according to each specific contract.
- **Black start** is not foreseen to have its own market framework and nowadays is contracted through bilateral agreements and this is expected to be maintained for the future.






To allow for a better reading of the matrix, the services are ordered, firstly, by active power/frequency control services, which includes inertia (synchronous and synthetic), FFR, FCR, aFRR, mFRR and RR, secondly, by reactive power/voltage control services that includes Volt/var control and, thirdly, by other services that includes black start. The active power/frequency control services are also ordered according to their timescale of activation: from instantaneous deployment (synchronous inertia) to higher than 15 min activation times (RR).

The proposed ASM is presented in Figure 50. The intention is to gradually populate the ASM throughout the programme of technology demonstration, testing and modelling planned in the project. The goal is to evaluate the impact of the various technologies, and their combinations, at each demonstrator.






ANCILLARY SERVICES										
	SYNCHRONOUS INERTIA	SYNTHETIC INERTIA	FAST FREQUENCY RESPONSE (FFR)	FREQUENCY CONTAINMENT RESERVE (FCR)	AUTOMATIC FREQUENCY RESTORATION RESERVE (aFRR)	MANUAL FREQUENCY RESTORATION RESERVE (mFRR)	REPLACEMENT RESERVE (RR)	VOLTAGE/VAR CONTROL	BLACK START	
Sites/Timescale	0 s	< 500 ms	0.5-2 s	< 30 s	30 s - 15 min	< 15 min	> 15 min	< 1 s	N/A	
DEMONSTRATIONS	Z' MUTT 	T P	T P	T P	T P	T P	T P	T P		FS
										VS (FSFC)
										VS & SPPS
	FRADES 2 	T P	T P	T P	T P	T P	T P	T P		FS
										VS (DFIM)
										VS & SPPS & HSC
	GRAND MAISON 	T P	T P	T P	T P	T P	T P	T P		FS
										FS, SPPS & HSC
	ALQUEVA 	T P	T P	T P	T P	T P	T P	T P		FS
										FS & SPPS
										FS & HSC
TECHNOLOGICAL SOLUTIONS	ALTO LINDOSO & CANIÇADA 									FS
										FS & SPPS
										VS (FSFC/DFIM) & SPPS
	VOGELGRUN 									FS Kaplan
										FS, SPPS & HBH
										VS (FSFC) Propeller
										VS, SPPS & HBH
Original terminology	Inertia	Primary frequency control (FC)	Secondary (FC)	Tertiary (FC)	Voltage control	System re-start				
Emerging frameworks	BILATERAL CONTRACTS (GB)	-	GB/IR/NORD	FCR coop.	PICASSO/IGCC	MARI	TERRE	BILATERAL CONTRACTS	BILATERAL CONTRACTS	
MARKET FRAMEWORK										

LEGEND

TYPES OF HYDROPOWER STATIONS

-  Pumped storage plant
-  PSP turbine mode
-  PSP pumping mode
-  Reservoir storage hydropower
-  Run-of-river hydropower

TYPES OF HYDRO EQUIPMENT

-  Reversible Francis unit(s)
-  Francis unit(s)
-  Pelton unit(s)
-  Kaplan/propeller unit(s)
-  Electro-chemical battery

FLEXIBILITY TECHNOLOGY

- SPPS Smart Power Plant Supervisor (XFLEX product)
- FS Fixed speed
- VS Variable speed
- VS (FSFC) VS with full size frequency converter
- VS (DFIM) VS with doubly fed induction machine
- HSC Hydraulic short circuit (PSP)
- HBH Hydro-battery-hybrid

MARKET FRAMEWORKS

- CE Continental European market
- GB UK market
- IR Rep. & Northern Ireland market
- NORD Nordic market
- EBGL EU Electricity Balancing Guideline (2007/2195)
- IGCC International Grid Control Cooperation
- PICASSO Platform for International Coordination of Automated Frequency Restoration and Stable System Operation (aFRR)
- MARI Manually Activated Reserves Initiative (mFRR)
- TERRE Trans European Replacement Reserves Exchange (RR)

CAPABILITY OF ANCILLARY SERVICE




-  Not currently capable of providing the service
-  Capable, but could be enhanced
-  Currently capable of providing the service

Figure 50 Ancillary Services Matrix (first stage)

7.3. KPI matrix

As aforementioned, having a "Flexibility Matrix" mapping only the existing/emerging ancillary services is not capable to fully capture the overall enhancements expected to be achieved in the project, to which the issues related to operation, maintenance and availability of HPPs are also aggregated. Therefore, and having in mind a more detailed characterization of referred improvements, a first draft regarding the identification of Key Performance Indicators (KPI) is also identified under a matrix arrangement and envisioned the overall fleet of demonstrators. The KPI matrix is then presented in Figure 51.

		KPI												
		Extended operation range	Extended/faster FCR	Extended/faster FRR	Extended Volt/var control	Fast Start and Stop	Fast Ramp-up/Ramp-down	Fast turbine-pump / pump-turbine transition	Optimised maintenance intervals	Extended availability	Increased annual efficiency			
Technological Solutions	FS											Z' Mutt	PSP	
	VS (FSFC)													
	VS & SPPS													
	FS											Frades 2		
	VS (DFIM)													
	VS & SPPS & HSC													
	FS											Grand Maison		
	FS, SPPS & HSC													
	FS											Alqueva		
	FS & SPPS													
	FS & HSC													
	FS, SPPS & HSC													
	VS (FSFC) & SPPS													
	FS											Alto Lindoso & Caniçada		RSH
	FS & SPPS													
	VS (FSFC/DFIM) & SPPS													
FS Kaplan											Vogelgrun	ROR		
FS, SPPS & HBH														
VS (FSFC) Propeller														
VS, SPPS & HBH														

Figure 51 First draft of KPI matrix framework

The list of identified KPI to be evaluated are presented next (from left to right), which constitute a basis for further detailing under the scope of each work package demos:

- **Extended operation range.** With the implementation of the SPPS and HSC it is expected that most of the HPP will show significant improvements in terms of operating range, which in turn will increase the availability to provide balancing services bids. For example, in Alqueva it is foreseen an improvement from an operating range of 40% – 100% to an almost continuous operation range of [-100%; 100%].
- **Extended and/or faster FCR and FRR.** In addition to the extension of the operating range, the envisioned technological solutions may provide services with faster response times in comparison to the existing standardized products. The extension of the operation range will result in an increase capability for bids" divisibility. As an illustrative example, in the Vogelgrün

demonstrator, the conversion to a HBH will allow a full provision of FCR in a couple of seconds, which currently is provided in 300 s.

- **Extended Volt/var control.** The possibility of operating in HSC will allow PSP plants to use a second turbine to provide Volt/var regulation, and as such increasing the capability to provide voltage/reactive power support to the grid.
- **Faster start and stop, ramp-up/ramp-down and transition from turbine to pump and pump to turbine.** Improvements related to these three KPI will consequentially reduce the technical restrictions for the provision of RR services (increase the speed of the response and reduce the waiting times between activations).
- **Extended availability of HPP** due to reduced outage times because of a more detailed analysis of the unit conditions as per the expected digitalization capabilities of the SPPS.
- **Optimization of maintenance intervals.** SPPS will provide plant health information (monitoring of wear & tear of critical components) that will allow an asset management module to reduce the need of maintenance.
- **Improvement of the average annual overall efficiency** of the hydroelectric machinery by reducing the power consumption of auxiliary equipment.

It is important to note that the KPI matrix present in this report is only a first draft that needs to be further developed and clearly filled during the XFLEX HYDRO activities/demonstrators WP (4 to 9). However, this KPI matrix will incorporate relevant information regarding the project outcomes will have a relevant role regarding the deployment phase where a roadmap for HPP is to be developed (WP10) followed by a market uptake study (WP11).

8 Future scenarios

8.1. Storylines

Following the characterization of the framework for the provision of flexibility by HPP (assessment of current services and the respective markets for the provision of such services), scenarios for the future integration of the proposed solutions are also identified, encompassing the knowledge of the players involved in the project as well as the main targets defined at EU level.

Future scenarios and "storylines" describe how Europe energy system could develop over the coming decades and characterize the energy mix required to meet national and international decarbonization targets for the power sector by 2030, 2040 and 2050. For XFLEX HYDRO, future scenarios will help provide a framework for modelling the hydropower technologies at system-scale and wider context, for example in WP2 (task 2.5), WP10 and WP11.

A brief literature review showed several institutions publish future energy scenarios for Europe, including the European Commission [19], the ENTSO-E [20], other Horizon 2020 projects [21] [22], and IRENA [23]. It was decided the storylines published by ENTSO-E in their latest 2020 Ten Year Network Development Plan (TYNDP) Scenario report will be taken forward. ENTSO-E developed the scenarios in consultation with stakeholders and national TSOs, also to be consistent with latest national and EU-level policies, as well as regional network development plans. Note ENTSO-E develops the scenarios in an ongoing process every two years, so updates may be periodically released and the next set will be published in the 2022 TYNDP Scenarios.

The three storylines selected by ENTSO-E are presented in Figure 52, sourced from the final storylines report published in 2019 and showing the evolution towards 2050.

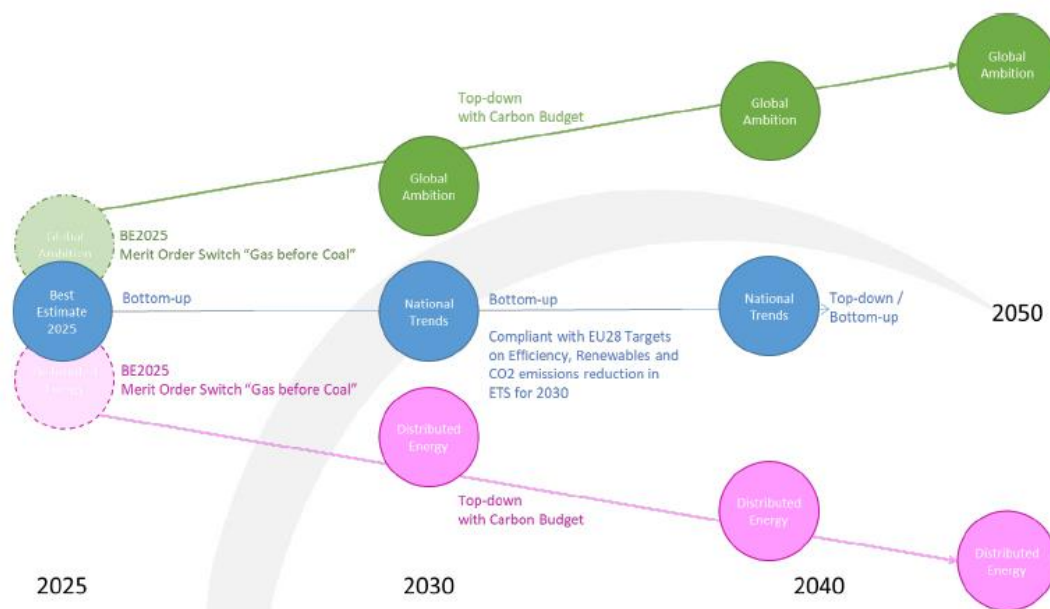


Figure 52 ENTSO-E 3 storylines and future scenarios [20]

National Trends

National trends scenario is the central policy scenario and reflects the most recent National Energy and Climate Plans submitted by EU member states. The National Trends pathway tracks market trends, EU

and national policies including the Commission EUCO 32/32.5 policy (32% energy from renewables, 32.5% energy efficiency by 2030) and assumes "minimum effort" to achieve the long-term climate target of 80-95% CO₂ reduction by 2050 compared to 1990 levels. National Trends is based on bottom-up data for 2025, and starts to use top-down policy assumptions to meet targets by 2030.

Global Ambition

Global Ambition scenario complies with the Paris Agreement 1.5°C climate targets, and characterizes a future driven largely by centralized generation, benefitting from economies of scale for example in offshore wind and power-to-X (including renewable gases), and also cheaper energy imports. Global Ambition represents a "carbon budget" scenario as a transition pathway that aims for carbon neutrality by 2050 and uses top-down assumptions starting from 2030.

Distributed Energy

Distributed Energy scenario also complies with the Paris Agreement 1.5°C climate targets, but takes a de-centralized approach, assuming more active participation of consumers in the market and growth in small-scale technologies such as distributed solar PV. Distributed Energy is another transition pathway that uses top-down assumptions including carbon neutrality by 2050.

ENTSO-E publishes scenario data based on market modelling to quantify each storyline, including annual generation (TWh) and installed capacity (GW) in 2025, 2030 and 2040. Scenario data for the year 2050 is not available in the open platforms. This data is available: on the TYNDP 2020 Scenarios Visualization Platform (online) [72] and in an excel data file that can be downloaded together with the main scenario report that is publicly available [20].

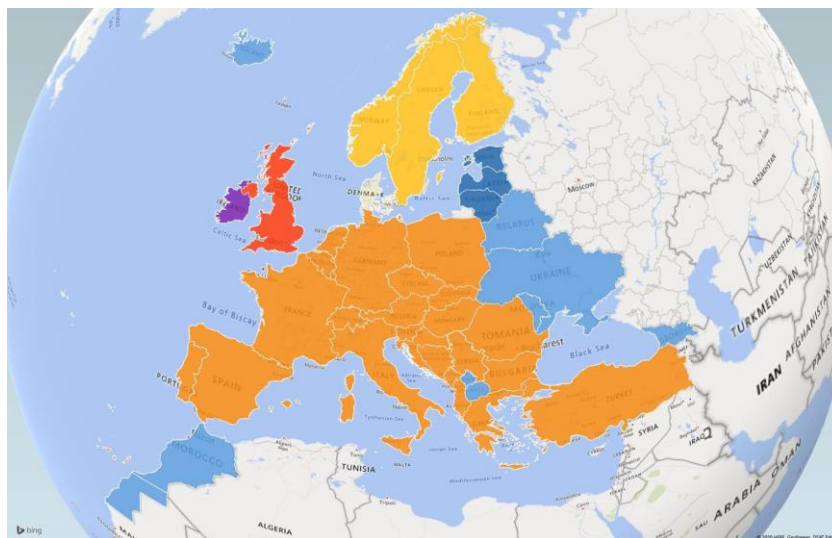


Figure 53 Map of Europe showing five grid SAs (excluding light blue)

In terms of geography, ENTSO-E 2020 scenario data also goes beyond just the EU-28 and covers more than 35 countries in Europe, see Figure 53. This could be useful for system-scale modelling because non-EU countries are synchronized to the CE grid, and/or may be participating in the emerging power markets (e.g. MARI, PICASSO, TERRE). Countries in neighbouring synchronous grids including the Nordics, Baltics and UK are interconnected to the CE grid via high voltage interconnectors allowing power trades. They are also considered in ENTSO-E regional cross-border network development plans, which include new proposed pumped storage projects and new interconnectors approved under EU Projects of Common Interest [73].

8.2. Future generation mix

The ENTSO-E future scenarios in terms of annual generation (TWh) totalling over all 33 countries in Europe (EU + non-EU), and which aim to participate in emerging markets for flexibility are presented in Figure 54. The actual data for 2019 have been added for comparison.

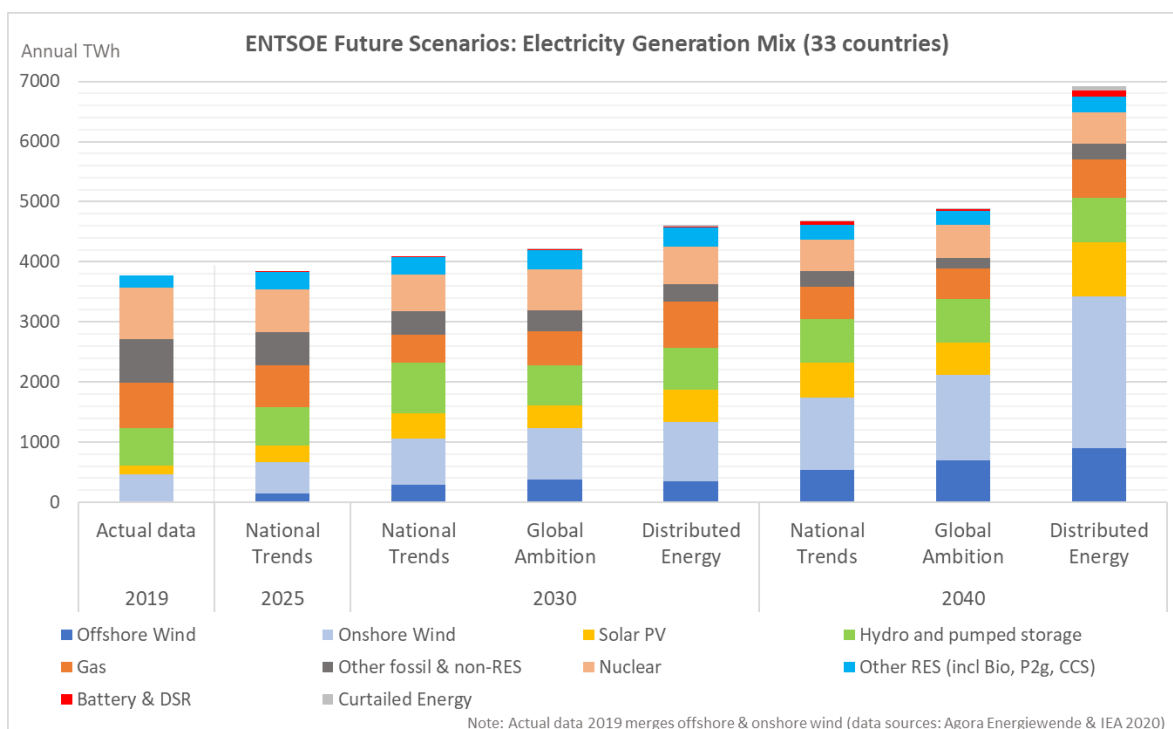


Figure 54 Graph showing the electricity generation mix under future ENTSO-E scenarios for Europe

Compared to the 2019 baseline, the future scenarios exhibit the following trends:

- Increasing total supply given increasing electricity demand to 2040.
- Significant growth in VREs across all scenarios including onshore and offshore wind and solar PV. Together the VREs account for 16% of total generation in 2019, which under National Trends scenario grows to 36% by 2030 and 50% by 2040.
- Nuclear reduces from 22% in 2019 down to 11% in 2040 under National Trends.
- There is a sharper decline in thermal generation, especially in other fossil fuels including coal, and natural gas reduces from a 20% baseline in 2019 to a 12% share of the mix in 2040 in National Trends.
- Hydropower including PSP is 16% of the generation mix in 2019 and under National Trends increases to 20% share in 2030 as capacity growth is assumed, but then stays broadly stable contributing a 15% share of total generation in 2040. This means that hydroelectric generation grows in absolute terms in-line with the increasing total supply/ demand, from 623 TWh in 2019 to 716 TWh in 2040 National Trends, but noting year-on-year variation typically seen due to seasonal hydrology and climate variability.
- The ENTSO-E Scenario 2020 report describes that gas will continue to provide peak power flexibility to balance increasing variable renewables on the grid, alongside other technologies that can provide flexibility. In the longer term under Global Ambition and Distributed Energy,

use of renewable and decarbonized gases is used to keep large gas-fired power plants as a viable option.

- In the case of Distributed Energy scenario in 2040, there is larger growth in solar PV and increased use of small-scale generation and innovative methods for flexibility provision. For example, batteries and demand side response (DSR) contribute 99 TWh (1.4% share) in 2040 in Distributed Energy, and power-to-gas is also used.

The scenario data for the years 2025, 2030 and 2040 under National Trends, and splits out 5 different geographies most relevant to XFLEX HYDRO are presented Table 47.

Table 47. Annual generation (TWh) by energy source in 2025, 2030 and 2040 in National Trends

National Trends	Generation Source	Europe area: 33 countries	Continental synchronous grid area: 25 countries	Portugal (PT)	France (FR)	Switzerland (CH)
2025	Wind offshore	143	84	0.3	9.8	-
	Wind onshore	525	343	13.7	53.6	0.3
	Solar PV	275	213	6.9	28.1	3.9
	Hydro (w/ PSP)	633	365	16.2	64.2	35.9
	Natural gas	705	536	13.1	17.7	3.4
	Other fossil & non-RES	551	541	-	9.4	-
	Nuclear	704	523	-	410.4	16.9
	Other RES	298	179	5.1	10.5	3.7
	Battery & DSR	1	1	-	-	-
	Curtailed Energy	-	-	-	-	-
	Total Supply	3,836	2,784	55.3	603.8	64.2
2030	Wind offshore	296	178	0.8	19.3	-
	Wind onshore	769	510	26.3	90.9	0.5
	Solar PV	422	332	15.2	45.8	5.4
	Hydro (w/ PSP)	833	493	22.7	73.1	46.1
	Natural gas	466	367	4.0	6.9	3.6

National Trends	Generation Source	Europe area: 33 countries	Continental synchronous grid area: 25 countries	Portugal (PT)	France (FR)	Switzerland (CH)
2040	Other fossil & non-RES	394	390	-	4.2	-
	Nuclear	609	478	-	322.9	8.3
	Other RES	296	187	6.0	10.6	4.9
	Battery & DSR	12	8	-	-	-
	Curtailed Energy	-	-	-	-	-
	Total Supply	4,096	2,943	74.9	573.6	68.8
	Wind offshore	538	352	1.5	33.5	-
	Wind onshore	1,203	803	39.0	180.9	1.1
	Solar PV	587	439	22.6	68.4	8.4
	Hydro (w/ PSP)	716	421	22.9	68.1	40.5
	Natural gas	543	470	4.2	10.0	3.6
	Other fossil & non-RES	254	241	-	5.1	-
	Nuclear	533	437	0	221.0	0
	Other RES	243	154	6.5	10.6	4.9
	Battery & DSR	51	31	2.2	4.6	1.1
	Curtailed Energy	12	4	3.3	0.0	-
	Total Supply	4680	3353	102.3	602.3	59.6

The key driver in the power sector is the dramatic increase in VREs including wind and solar supply. In [5], IEA Hydro describes that increased phasing of variable renewables into a grid system brings also investment need into flexibility provision.

When totalling across Europe, in the 2019 baseline the ratio of conventional hydropower and pumped storage to conventional thermal generation considering all fossil fuels is 0.4, meaning fossil-fuel generation is more than double of hydro. In the ENTSO-E future scenarios, this ratio of hydro to fossil generation increases to almost 1 in 2030 and 0.9 in 2040 under National Trends, as contribution from conventional thermal generation declines in the energy mix. This suggests hydropower will have to play

a leading role in the coming decades, as in parallel to massive rise in VREs it will be the major source of conventional and flexible generation feeding the system as well as storage. While batteries and DSR are also assumed to play a role in generation for adequacy and flexibility, their contributions are relatively minor in the scenarios when compared to hydropower.

In summary, the future scenarios for the European area are presented in the following matrix (Figure 55) arranged by VRE levels assumed.

0-20% VRE	Actual 2019		
20-30% VRE	National Trends 2025		
30-50% VRE	National Trends 2030	Global Ambition 2030	Distributed Energy 2030
50%+ VRE	National Trends 2040	Global Ambition 2040	Distributed Energy 2040

Figure 55 Matrix of ENTSO-E future scenarios for all Europe (EU + non-EU) by VRE share

8.3. Future capacity mix

The ENTSO-E scenarios also project installed power capacity (GW) for each energy source, with totals shown in Figure 56 covering the European region (EU + non-EU).

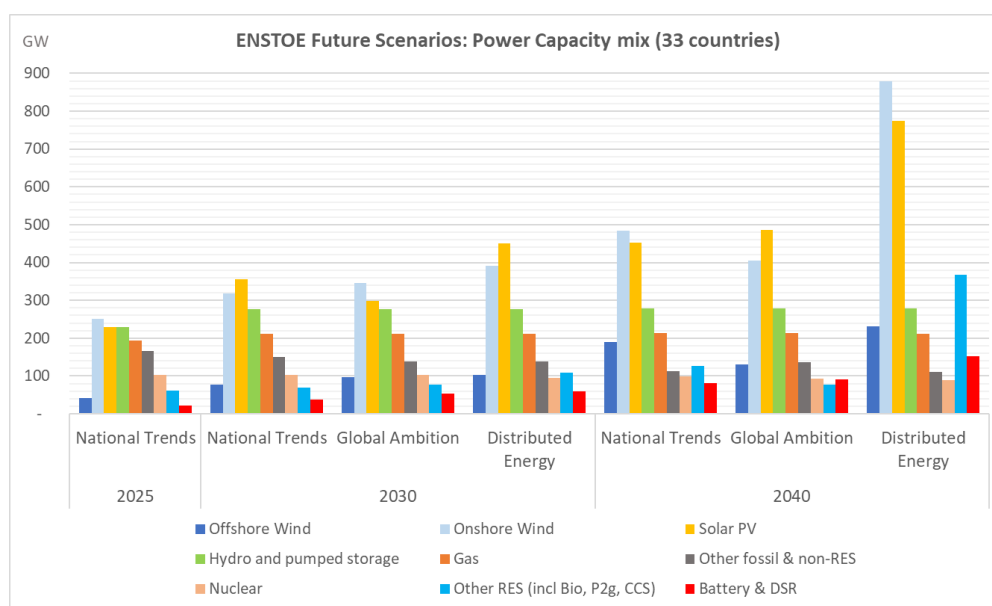


Figure 56 Graph showing the power capacity mix under future ENTSO-E scenarios for Europe

The key observations from the chart are the following:

- Significant growth in installed wind offshore, wind onshore and solar PV capacity across all scenarios following EU and national climate policies. Totalling for all VREs, capacity grows from around 522 GW in National Trends 2025 to more than 1000 GW across all scenarios in 2040.
- Solar PV rises to almost 500 GW in 2040, or in the case of Distributed Energy to over 700 GW.
- Hydropower including pumped storage rises from 230 GW in 2025 to 276 GW in 2030 and 279 GW in 2040 under National Trends, suggesting an increase of approximately 50 GW capacity assumed in the scenarios.
- Natural gas remains at around 200 GW installed across the scenarios, reflecting assumptions that it remains as a key flexibility and peaking service provider. Similarly, other fossil-fuel capacity reduces, though stays above 100 GW in 2040.
- The capacity of batteries and DSR technology increases towards 100 GW in National trends and higher in Distributed Energy.

The ENTSO-E capacity scenarios for the years 2025, 2030 and 2040 under National Trends for the 5 different geographies are presented Table 48.

Table 48. Total installed capacity (GW) by energy source in 2025, 2030 and 2040 in National Trends for 5 different geographic regions

National Trends	Capacity source	Europe area: 33 countries	Continental synchronous grid area: 25 countries	Portugal (PT)	France (FR)	Switzerland (CH)
2025	Wind offshore	42	23	0.1	2.9	0.0
	Wind onshore	251	166	5.6	26.5	0.2
	Solar PV	229	188	3.7	23.9	4.0
	Hydro (w/ PSP)	230	155	8.6	25.3	16.3
	Natural gas	194	132	3.8	7.4	0.0
	Other fossil & non-RES	166	143	2.5	6.7	0.8
	Nuclear	103	77	0.0	61.8	2.2
	Other RES	60	34	1.0	2.6	0.9
	Battery & DSR	21	8	0.0	3.4	0.0
	Total Capacity	1,297	926	25.4	160.5	24.4
2030	Wind offshore	78	45	0.3	4.9	0.0

National Trends	Capacity source	Europe area: 33 countries	Continental synchronous grid area: 25 countries	Portugal (PT)	France (FR)	Switzerland (CH)
2040	Wind onshore	318	213	8.9	36.1	0.3
	Solar PV	355	294	8.8	39.0	5.5
	Hydro (w/ PSP)	276	187	9.2	25.5	16.3
	Natural gas	211	140	2.8	7.4	0.0
	Other fossil & non-RES	150	134	0.8	6.7	0.9
	Nuclear	103	80	0.0	58.2	1.2
	Other RES	70	38	1.4	2.6	1.2
	Battery & DSR	38	19	0.0	3.4	0.0
	Total Capacity	1,598	1,150	32.2	183.8	25.3
	Wind offshore	189	84	0.5	8.4	0.0
	Wind onshore	484	276	12.9	60.0	0.5
	Solar PV	452	386	14.2	58.4	8.5
	Hydro (w/ PSP)	279	189	9.2	25.5	16.3
	Natural gas	213	144	2.8	7.2	0.0
	Other fossil & non-RES	112	116	0.8	6.5	0.9
	Nuclear	98	75	0.0	43.1	0.0
	Other RES	128	42	6.6	2.6	1.2
	Battery & DSR	82	52	1.6	9.4	1.8
	Total Capacity	2037	1364	48.6	221.2	29.1

Hydropower capacity

Existing hydropower capacity at country-level for Europe sourced from IHA 2020 Hydropower Status Report [24] are presented in Table 49 and Table 50. The publication is based on national and international published statistics as well as updates to IHA hydropower station database, which covers over 90% of hydro capacity installed globally.

Table 49. Existing hydropower capacity for European countries at end of 2019, (pre-existing before 2019) [24]

Country	Conventional SHP & RoR (GW)	PSP Pumped Storage ¹⁸⁾ (GW)	Total (GW)
Norway	31.23	1.44	32.67
Turkey	28.50	0.00	28.50
France	19.72	5.84	25.56
Italy	14.91	7.69	22.59
Spain	14.30	6.12	20.41
Switzerland	13.83	3.03	16.86
Sweden	16.38	0.10	16.48
Austria	8.95	5.60	14.54
Germany	4.66	6.36	11.02
Portugal	4.37	2.82	7.19
Romania	6.22	0.09	6.31
United Kingdom	1.88	2.83	4.71
Greece	2.70	0.70	3.40
Finland	3.26	0.00	3.26
Bulgaria	1.73	1.40	3.13
Serbia	2.46	0.64	3.10
Slovakia	1.51	1.02	2.52
Bosnia and Herzegovina	2.09	0.42	2.51
Poland	0.61	1.78	2.39
Czech Republic	1.10	1.17	2.27
Albania	2.19	0.00	2.19
Croatia	1.85	0.29	2.14
Latvia	1.58	0.00	1.58

¹⁸⁾ PSP country totals include sites with mixed generating configurations (e.g. pumping and conventional)

Country	Conventional SHP & RoR (GW)	PSP Pumped Storage ¹⁸⁾ (GW)	Total (GW)
Slovenia	1.34	0.18	1.52
Belgium	0.12	1.31	1.43
Luxembourg	0.03	1.30	1.33
Lithuania	0.12	0.90	1.02
Montenegro	0.66	0.00	0.66
Ireland	0.24	0.29	0.53
Hungary	0.06	0.00	0.06
Netherlands	0.04	0.00	0.04
Denmark	0.01	0.00	0.01
Estonia	0.01	0.00	0.01
Total	188.6	53.3	241.9

The hydropower capacity for European countries at end of 2019 with added countries/ states in the region is presented in Table 50.

Table 50. Existing hydropower capacity for European countries at end of 2019, sourced from IHA 2020 (Added countries/ states in the region) [24]

Country	Conventional SHP & RoR (GW)	PSP Pumped Storage ¹⁸⁾ (GW)	Total (GW)
Ukraine	4.67	1.56	6.23
Iceland	2.09	0.00	2.09
Macedonia	0.67	0.00	0.67
Belarus	0.10	0.00	0.10
Kosovo	0.09	0.00	0.09
Greenland	0.09	0.00	0.09
Moldova	0.08	0.00	0.08
Andorra	0.05	0.00	0.05
Faroe Islands	0.04	0.00	0.04
Liechtenstein	0.04	0.00	0.04
Cyprus	0.00	0.00	0.00
Gibraltar	0.00	0.00	0.00
Malta	0.00	0.00	0.00

Country	Conventional SHP & RoR (GW)	PSP Pumped Storage ¹⁸⁾ (GW)	Total (GW)
Monaco	0.00	0.00	0.00
San Marino	0.00	0.00	0.00

The total capacity for the 33 countries is 242 GW, which is close though a little higher (5%) than ENTSO-E expected capacity in 2025 under National Trends (230 GW). This could be because some additional capacity is captured in IHA existing database compared to ENTSO-E figures.

From this baseline, ENTSO-E National Trends scenario suggests that capacity will grow by around 20% to 280 GW by 2030 when totalling across the same countries. According to IHA historical figures, over the last few years annual growth of total hydropower capacity in Europe has been between 0.3% and 1.8%, averaging at around 1% per year. A simple extrapolation of this growth rate per annum reaches 270 GW by 2030 reflecting an increase of 28 GW (12%) over the next decade. It should be noted that growth could be higher or lower, depending on how large-scale projects under construction or planned may progress. Future growth in hydropower capacity will strongly depend on enabling policies and market frameworks implemented at the national and EU level, which support investment into strategic and particularly flexible generating assets for the power grid.

Age profile of existing hydropower

The XFLEX HYDRO technologies will be applicable to improve flexibility of existing hydropower stations through modernization and retrofit projects, not only in new-build capacity. The age profile of existing hydropower capacity in Europe, showing historically the amount of capacity added by decade is presented in Figure 57.

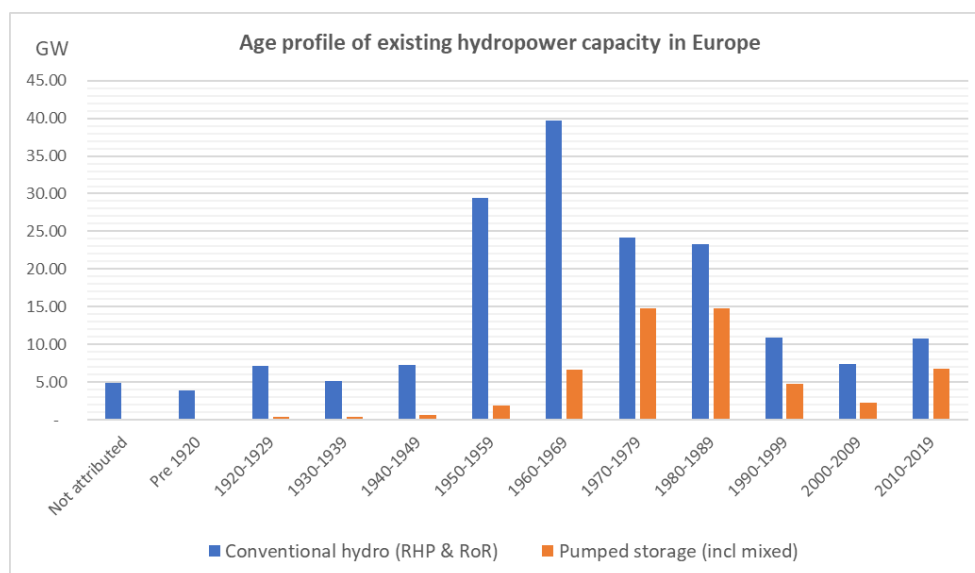


Figure 57 Existing hydropower capacity in Europe (33 countries) by year of commissioning, from IHA station database

The graph shows much of Europe existing hydropower capacity was commissioned before 1980, totalling 117 GW for conventional hydro and 25 GW for pumped storage (including mixed) sites. Many of the hydropower stations in this category being 40 years old or more will, if not already refurbished or modernized, be candidates for upgrade with flexibility technologies. Over the next decade to 2030, the

capacity installed in 1980-1989 (an added 23 GW conventional and 15 GW PSP) will also fall into this category. This starts to scale the market for XFLEX HYDRO flexibility solutions, and in later WPs (e.g. WP11) the existing capacity data can be further interrogated at country and station-level to understand the potential for future deployment.

9 Final remarks

The overarching objective of the XFLEX HYDRO project is centred on the demonstration of an innovative methodology for system integration of hydroelectric technology solutions aiming to contribute for the increasing flexibility requirements of future electric power system as one of the key enablers for a transition to a decarbonized economy. To properly characterize existing and prospective flexibility services within European Electric Power Systems (EPS), an extensive review is performed ranging from currently services being demanded by the TSOs to which Hydro Power Plants (HPP) being considered within the context of this project are connected, to EU-wide initiatives mastered under the Electricity Balancing Guideline (EBGL) as well as the existing grid codes. In particular, the framework emerging from the EBGL initiative is enabling the implementation of transnational markets within EU in which countries/TSOs are expected to share their resources aiming to efficiently assure the fundamental principle for a stable operation of EPS: making generation matching the demand at all times. Such an initiative opens avenues for HPP owners to access wider markets in contrast to the traditional principle of services provision to the TSOs to which a generation unit is connected.

Under the different dimensions for flexibility requirements for future EPS, the emphasis is on the generation-side flexibility services as the ones that potentially HPP operators can provide. These flexibility services cover:

- Ancillary services - services required for the operation of the transmission system, including balancing and non-frequency ancillary services but not including congestion management. Within this scope, the Fast Frequency Response (FFR), Frequency Containment Reserve (FCR), automatic Frequency Restoration Reserve (aFRR), manual Frequency Restoration Reserve (mFRR) and Replacement Reserve (RR) services are identified.
- Non-frequency ancillary services - services used by a transmission system operator (TSO) for steady state voltage control, fast reactive current injections, inertia for local grid stability, short-circuit current, black start capability and island operation capability. In this case, relevant services within the scope of HPP is selected, namely the inertia-based services (synchronous and synthetic), voltage/reactive power control and black start capability.

By combining the most recent flexibility products, the associated flexibility markets, the hydropower technologies and advanced solutions for complying with flexibility and the level of adequacy of each technology to the flexibility products and markets, an ancillary services matrix is created. It is expected this matrix will be of upmost importance for the hydropower stakeholders, since it will provide a synthetic mapping of the hydro technology regarding the provision of different services and the capability of participating in new power markets.

From this characterization of services, as well as from the initial characterization of the different demonstrators involved in the project, the work documented in this report lays important contributions regarding future activities to be developed in the project. At Work Package 2 (WP2) level, this document is relevant to:

- Develop Business Use Cases (BUC) aiming to characterize the opportunities for each technology for participating in new markets (Task 2.2). BUCs are expected to describe the functional specifications for the demonstration of the identified services, which will be undertaken at the project demonstrators covering the envisioned hydroelectric technologies, while relying on the outputs of Task 2.1, in particular the ancillary services matrix, in order to properly map the flexibility services, market framework and technologies in each demo.
- The evaluation of each technology/solution on complying with flexibility services (Task 2.3) will be made by the detailed modelling of the identified HPP followed by numerical simulation to define flexibility boundaries (Task 2.3). In order to characterize the adequacy of the envisioned

HPP solutions with respect to the identified services, extended modelling of each hydroelectric technology that will be adopted in the demonstrators, using the SIMSEN software. Simulations will then be carried out to evaluate the dynamic performance of each technology against the set of flexibility products while enabling the flexibility envelope of each technology/solution to be identified. This assessment will also enable the ancillary service matrix to be progressively populated, by properly scoring the compliance level of each hydro solution and variable speed option against the different flexibility services.

- Finally, by exploiting the flexibility envelope of each technology/solution, prospective scenarios for the future integration of the envisioned solutions will be defined, encompassing the knowledge and future plans of the players in the hydropower sector involved in the project, together with European Commission targets and the inputs from the advisory board members. In this task, dynamic simulations will be carried out across a simplified European grid model, aiming to assess the behaviour of the European interconnected system under the deployment extended hydropower flexibility solutions proposed in the project (Task 2.5). This requires also setting up macro scenarios regarding EU-wide generations fleet development, in particular regarding the share of variable renewable energy sources integration and the progressive decommissioning of fossil-fuelled based power plants. System studies without the consideration of the extended hydropower flexibility under a business as usual scenario will be also targeted in order to assess specific improvements coming from the progressive integration of the HPP flexibility solutions envisioned in the project.

By defining the ancillary services matrix and the technical requirements of each service to which HPP can contribute to, this document defines the master guidelines to be considered within the scope of defining specific demonstration activities (WP 4 to 9). Moreover, by defining the services requirements, it provides direct contribution for the cost-benefits analysis regarding the innovative hydroelectric technology solutions in terms of and participation to modern power market needs (WP 11) as well as for the definition of best practices for its future implementation/replication (WP10). In this sense, a structured link is promoted alongside project development, supported also on global Key Performance Indicators (KPI) that are identified and are aimed to highlight potential improvements beyond currently existing services requirements that HPP are prone to provide. These KPI are expected to be quantified during the project development, constituting a summary of the main achievements in terms of HPP flexibilities.

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