XFLEX HYDRO

RECOMMENDATIONS TOWARDS INDUSTRIAL DEPLOYMENT OF HYDROPOWER FLEXIBILITY TECHNOLOGIES

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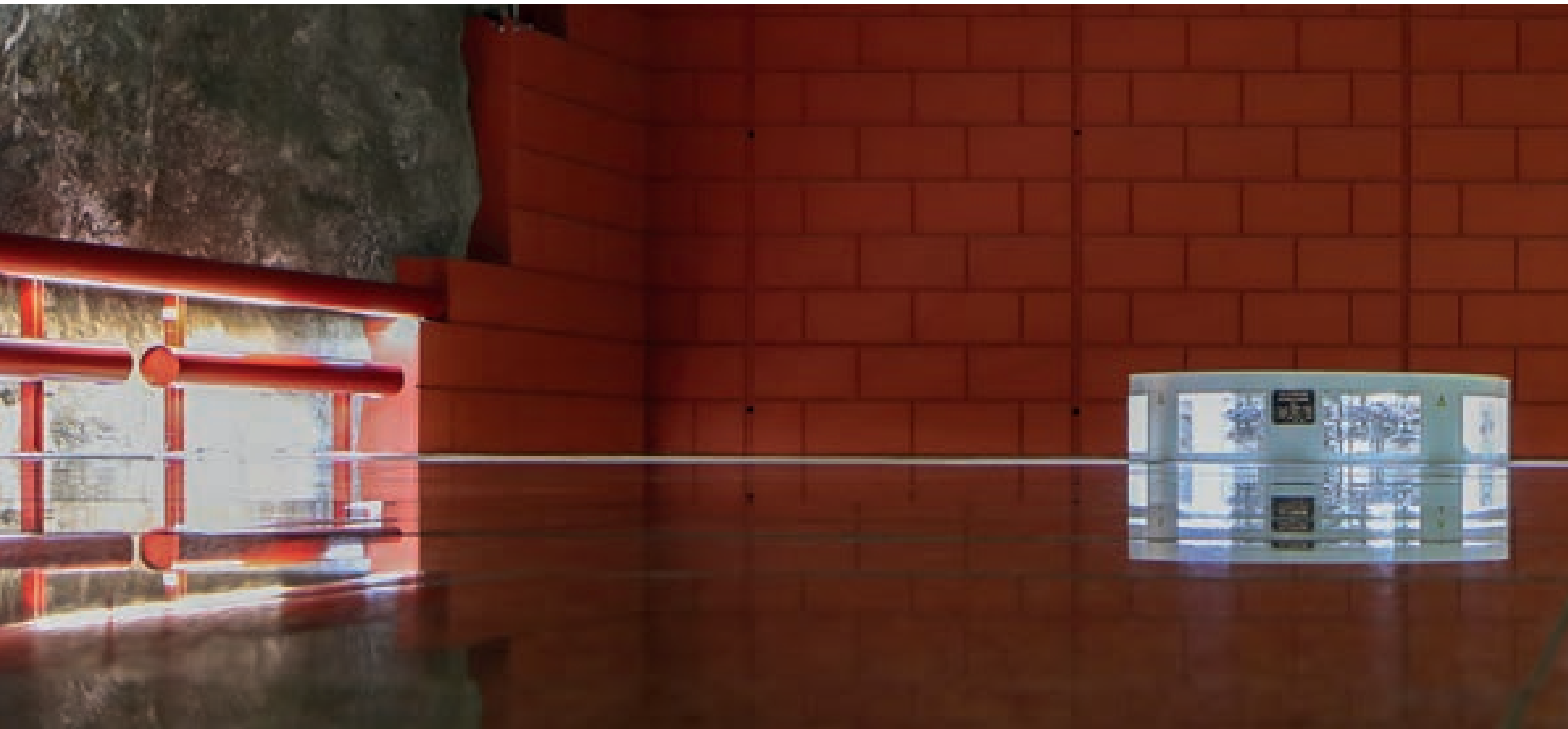
GLOSSARY

ACRONYM	DEFNITION
AC	Alternating Current
aFRR	Automatic Frequency Restoration Reserve
AJC	Advanced Joint Control
BESS	Battery Energy Storage System
BSP	Balancing Service Provider
CAPEX	Capital Expenditures
CE	Continental Europe
CfD	Contracts for Difference
CO2	carbon dioxide
DFIM	Doubly Fed Induction Machine
E&S	Environmental and Social
EC	European Commission
EPSs	Electric Power System(s)
EU	European Union
FCR	Frequency Containment Reserve
FFR	Fast Frequency Response
FSFC	Full-Size Frequency Converter
GHG	Greenhouse Gas
GW	Gigawatt, power unit
GWh	Gigawatt hour
h	Hour, time unit
HPP	Hydro Power Plant
HSC	Hydraulic Short Circuit
Hz	Hertz, frequency unit
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
JRC	Joint Research Centre
kgCO2	kilogram of carbon dioxide equivalent unit
km	Kilometre, length unit
KPI	Key Performance Indicator
LCOE	Levelised Cost of Electricity
m	Meter, length unit
MARI	Manually Activated Reserves Initiative
mFRR	Manual Frequency Restoration Reserve



ACRONYM	DEFNITION
MVA	Mega Volt Ampere, power unit
MW	Megawatt, power unit
OH&S	Occupational Health and Safety
OPEX	Operating Expenses
PICASSO	Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation
Pmax	Maximum power
Pmin	Minimum power
PPA	Power Purchase Agreement
PSP	Pumped Storage Plant
RoR	Run of River
RR	Replacement Reserve
RRIF	Replacement Reserve Implementation Framework
SHP	Reservoir Storage Hydropower
s	seconds
SCADA	Supervisory Control and Data Acquisition
SPPS	Smart Power Plant Supervisor
TERRE	Trans European Replacement Reserves Exchange
TSO	Transmission System Operator
TWh	Terawatt hours
UK	United Kingdom
Volt/var	United States
VRE	Voltage/Reactive Power Control
VS	Variable Renewables Energies
WP	Variable Speed
WP	Work Package

1

EXECUTIVE SUMMARY

The energy transition is a solid reality. In 2022, over 41 GW of photovoltaic capacity and circa 15 GW of onshore and offshore wind capacity were built in the EU [1], a deployment level which was respectively 60% and 45% higher than in 2021. At the same time, fossil fuel-based generation is progressively retiring and reducing its presence in the mix.

Whilst this moves us towards a renewable-based power mix, it also introduces additional issues for system operators in securing a stable and reliable electricity supply to consumers. Balancing a power grid when demand has doubled and the generation mix is dominated by non-dispatchable technologies will present new challenges, ones which have never been experienced before and are difficult to forecast in detail. What is undisputed is that demand for flexibility will increase rapidly over the next decade.

In this dynamic scenario, the existing hydropower fleet offers a renewable and indigenous solution with the potential to fill this flexibility gap. Hydropower plants can provide rapidly dispatchable and highly controllable power to the system, and store large amounts of energy for days and even seasons. The installed capacity of over 200GW in the EU is already supporting the integration of Variable Renewable Energies (VREs), avoiding flexibility solutions that require imported fuels, or technologies with supply chains primarily based outside European borders. Hydropower is a key strategic asset, necessary to achieve the long-term climate goals set by the EU.

XFLEX HYDRO is a European Union Horizon 2020 research and innovation project with the objective to show hydropower's technical and strategic role in demonstrating how renewable-based generation can be achieved in a secure and reliable manner. Thanks to this project, the sector has gained a better understanding of the flexibility that the existing EU hydropower fleet can provide to the electrical system, and demonstrated how, using a set of innovative technologies, this flexibility potential can be optimised and enhanced.

These innovative hydroelectric technological solutions are the following:

- Variable speed units;
- Hydraulic short circuit;
- Hybridisation with a battery energy storage system; and
- Smart Power Plant Supervisor (real-time optimisation methodology).

The project puts hydropower at the forefront of innovation, strengthening the industry's know-how, improving its technology export potential, and facilitating job creation.

This document is designed to speak to a wide range of stakeholders and its content is laid out in a manner so that the relevant information is clear, accessible, and actionable by the reader.

The technical part of this report provides the key takeaways from the project and enables plant owners and energy experts to identify opportunities to introduce some of the findings in their plants. This set of conclusions can be found in Section 4, where the four technologies relevant to the European hydropower fleet are discussed (presented individually, as well as in six possible upgrade strategies). To facilitate the identification of the relevant combination of technologies, these upgrade strategies are classified under the three categories of hydropower plants: reservoir storage plants (RSP), pumped storage plants (PSP) and run of river plants (RoR).

Despite the remarkable results achieved by the project and the technical benefits associated with the deployment of these innovative technologies, several barriers are currently limiting their wider adoption in the European context. The flexibility provision of the hydropower fleet will only be entirely optimised and utilised if dedicated energy policies are put in place, aimed at securing the availability of indigenous flexibility solutions over the next decades.

Through the dialogue carried out within the consortium's partners and external energy experts, seven key recommendations have emerged:

- **Recognise and Value Hydro Flexibility as an Essential Service to the Power System to Achieve a Successful Energy Transition.** As power systems are progressively losing the flexibility provided by non-renewable conventional energy sources, recognising, and valuing the growing necessity for flexibility services is crucial to ensure grid stability and security of supply over the next decades.
- **Remove Regulatory Barriers for Unrestricted Implementation and Operation of Hydro Flexibility Technologies.** To unlock the full potential of existing hydro assets and introduce new technologies, it is essential to eliminate regulatory barriers that limit the adoption of flexibility upgrades or that create discrepancy in the procurement process of flexibility services. For example, in certain countries operating in hydraulic short circuit mode is currently not allowed.
- **Provide Remuneration Mechanisms Enabling Investment in Flexibility.** Existing electricity and ancillary services markets (when available) excel in ensuring that the service required is provided at minimal cost to consumers, but their short-term nature does not provide the long-term revenue visibility required to justify new investment in flexibility technology upgrades.
- **Facilitate Cross-Border Collaboration for Efficient Exchange of Flexibility Services.** Encouraging international collaboration among European countries is essential for the efficient exchange of hydro flexibility services and expertise. By fostering cross-border connections, countries can share resources and expertise, optimising the utilisation of hydro flexibility on a broader scale.
- **Streamline Licensing Renewals for Optimised Hydropower Operations.** Simplifying the licensing process and accelerating permitting procedures are vital for the operational stability of hydropower projects. This not only reduces uncertainties linked to licence renewals and ownership transfers but also provides a clear and predictable framework in which power companies can operate.
- **Conduct System-Level Analysis to Anticipate and Address Future Flexibility Needs.** To effectively address future challenges and make sure that electric power systems can deliver a safe energy transition, system-level analyses are essential. These can provide the long-term vision needed to identify and prepare for future flexibility challenges in the most technically efficient, secure, and cost-effective way.
- **Promote Support Mechanisms for the Modernisation of Ageing Hydropower Infrastructure.** Financial or tax mechanisms that support the modernisation of ageing infrastructure are essential to secure and enhance the benefits currently provided to society by these plants. These mechanisms should be focused on rewarding modernisation projects that are introducing cutting edge technologies and leading in the adoption of cleaner and more flexible energy solutions.

These recommendations, together with an extensive review of the barriers, are presented in Section 5. In this section policy makers and regulators can see the priority issues that need to be addressed to enable the hydropower sector to deliver its full flexibility potential and underpin the energy transition.

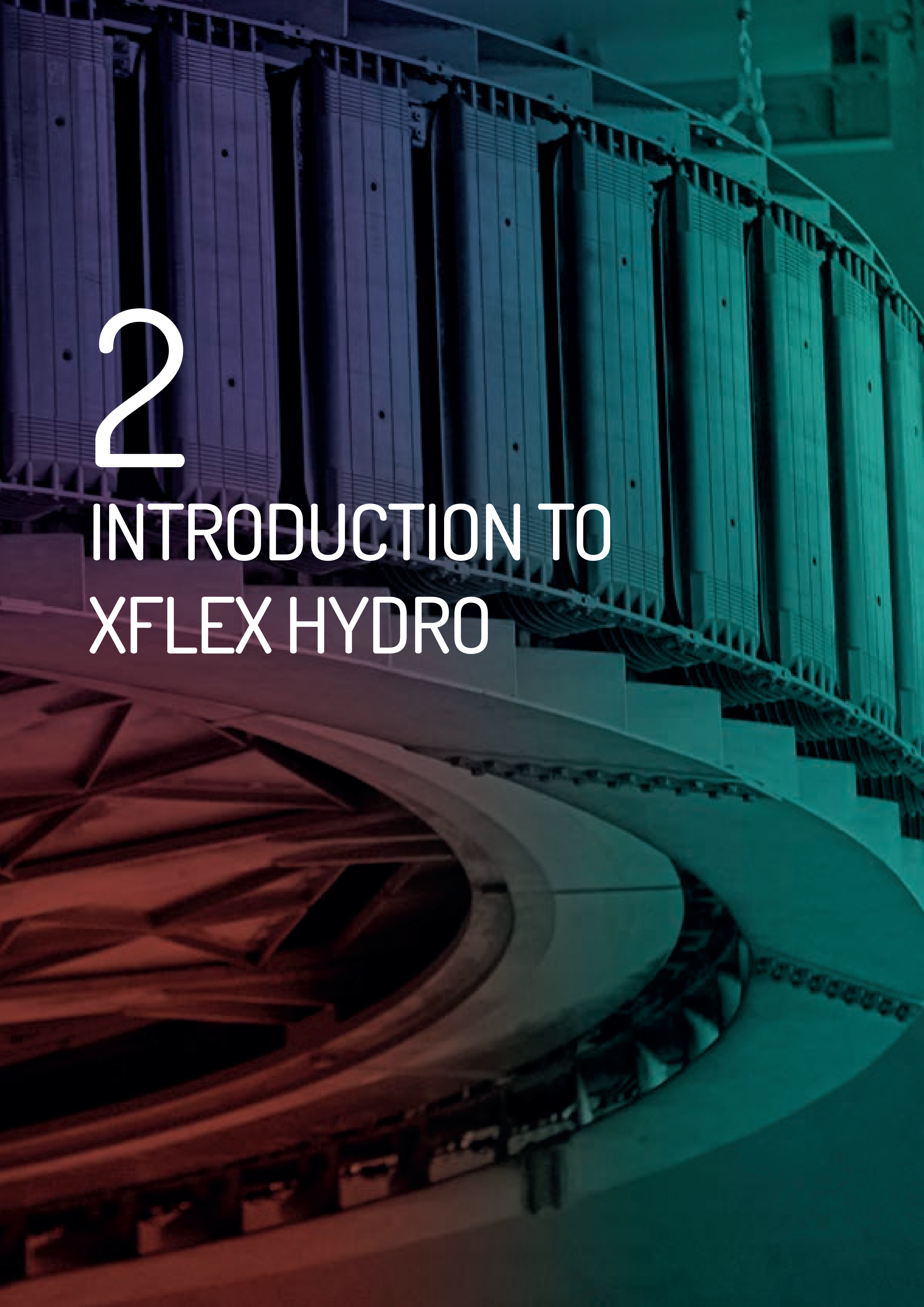
Section 6 reviews the current technological gaps and research needs that remain to secure and optimise the contribution of hydropower flexibility in future electric power systems. These have been divided into four macro categories: technologies and plant operations; flexibility potential and system-level planning; markets, revenue, and profitability; and environmental and social aspects.

Achieving a successful and just energy transition is a common challenge shared equally across society. Key actions which will need to be considered and implemented to make sure that European hydropower will be ready to provide the flexibility required over the next three decades are discussed and classified by stakeholder category in section 7.

This project has demonstrated how the role of hydropower can evolve and adapt in our rapidly changing energy landscape and that the range of services that hydropower can provide to society go above and beyond simple electricity generation. XFLEX Hydro should therefore be seen as a milestone project, showcasing how this technology is only scratching the surface of its full potential and setting out the value that it can, and will, provide to society on the road towards a carbon-neutral power system.

2

INTRODUCTION TO XFLEX HYDRO

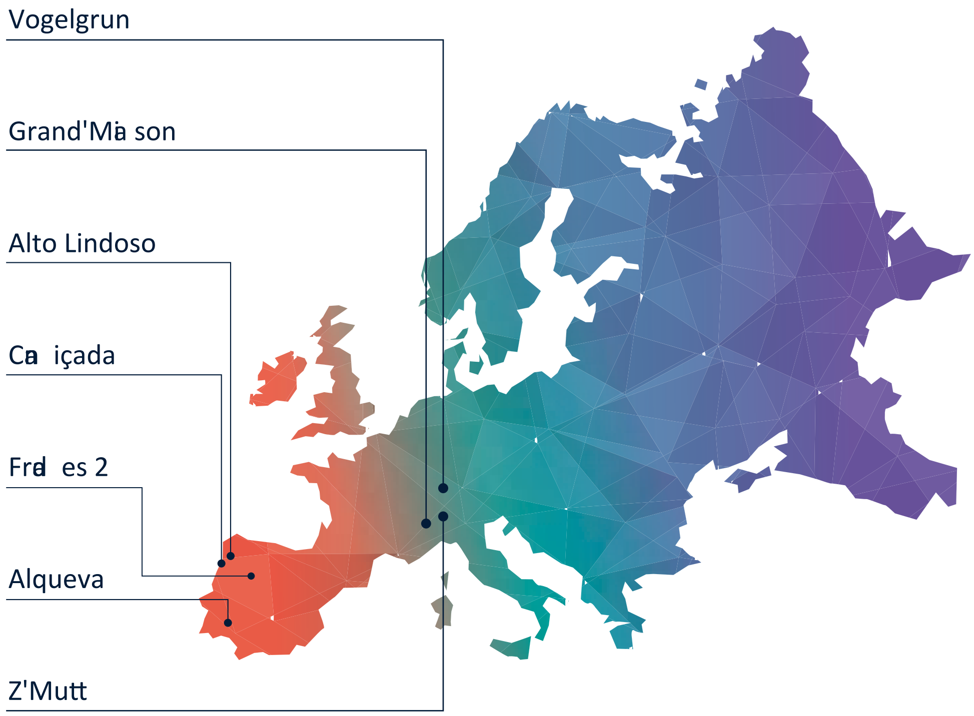


XFLEX HYDRO is a European Union Horizon 2020 research and innovation programme designed with the objective to increase hydropower potential in terms of plant efficiency, availability, and provision of flexibility services to the electric power systems (EPS).

XFLEX aims to demonstrate an innovative methodology for system integration of hydroelectric technology solutions and provide further enhanced flexibility services, assessed by a crosscutting analysis of their impact on both the technology and the market aspects.

Plant level demonstrations, Figure 1, are utilised to study and compare the improvements and benefits associated with the implementation of variable speed technology, hydraulic short circuit op-erations, hybridisation with chemical batteries, as well as digitalisation and real time monitoring tools. XFLEX HYDRO, therefore, draws a roadmap for the exploitation of these innovative solutions to use across the entire the European hydropower fleet.

Figure 1: Location of the XFLEX HYDRO project demonstrators



The XFLEX HYDRO Project duration is: 4.5 years from September 1, 2019, to February 29, 2024. (2019-2022)

The overall budget of the XFLEX HYDRO project (including non-EU funded) is 18 M€ of which the EU grant amount totals 15 M€, (83% of overall budget).

Figure 2: Project Consortium Partners.

ALPIQ
ANDRITZ
ARMINES
cea
EDF
edp
EPFL
GE
Hes-so
iha
INESCTEC
PSL
NEW
POWER VISION ENGINEERING
SuperGrid Institute
UPC
Universität Stuttgart
VOITH
zabala

The Project consortium is made by 19 partners, Figure 2, the consortium includes large European utilities, technology suppliers, research institutes, consulting firms and sector association.

3

NEED FOR FLEXIBILITY IN THE EUROPEAN LANDSCAPE AND THE FUTURE ROLE OF HYDROPOWER

3.1 AN EVOLVING ENERGY LANDSCAPE

The European Union has set the clear target to become climate neutral by 2050. If this long-term climate goal is to be achieved, according to projections by the IEA, VRE penetration in the European's energy mix is expected to grow from circa 20% today up to 68% by 2050, see Figure 3, [2]. This represents a dramatic shift for a system that historically was developed around coal, gas, nuclear and hydro and has always passively relied on the flexibilities associated with these energy sources.

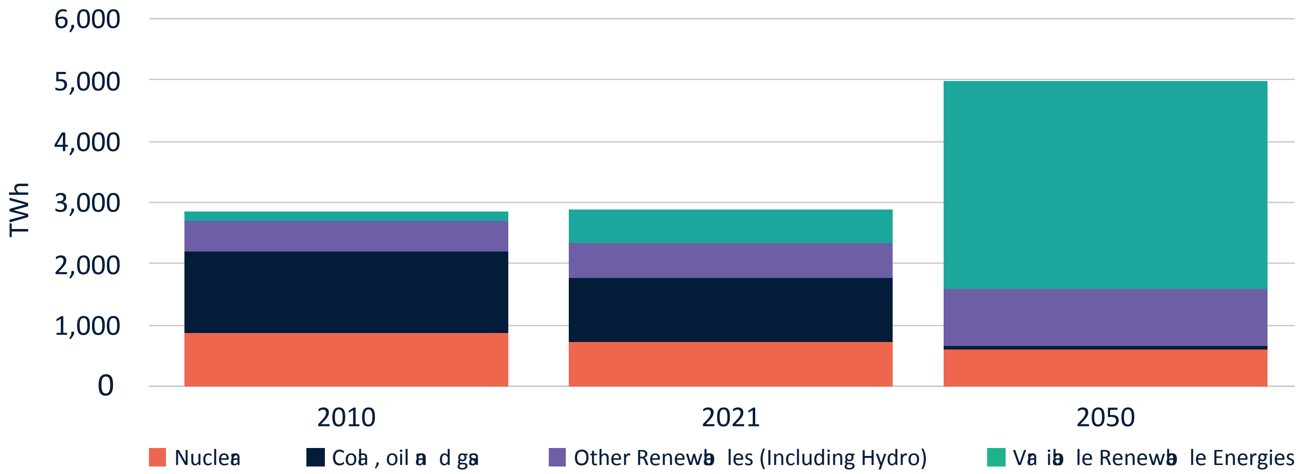
The effects of such a large deployment of VRE are multiple. From one side, the greenhouse gas (GHG) emission intensity of the European power system will greatly reduce, while electric power markets will experience an increased participation of zero-marginal-cost energy sources, enabling the supply of cheap indigenous electricity.

On the other side, the large amounts of wind and solar to be deployed will pose substantial challenges to grid operations, reducing the dispatchability and controllability of the power injected in the grid, which are crucial factors to ensure a reliable and secure electricity supply. At the same time, to reduce the carbon intensity of the European electricity mix, coal and gas plants will need to start retiring progressively, reducing their participation in the electricity mix at a rate of circa 35 TWh per year[1] (the equivalent of the annual electricity production in Denmark or Hungary) [2]. Consequently, the availability of regulating power and sources of system inertia will be noticeably lessened[2], posing an additional challenge to the reactivity and controllability of the grid operations.

It is therefore of utmost importance to provide reliable solutions to support the evolving electric power systems (EPSs) with sufficient flexibility (see section below). A recent study published by the EU Joint Research Centre (JRC) indicated that flexibility requirements will more than double by 2030 and be seven times as large by 2050, reaching a total of 2,189TWh across all timescales corresponding to almost 80% of today's power demand[3] [3]. There is therefore no doubt that the demand for the various flexibility services, existing, and new, will evolve and grow substantially over the next decades.

Today, renewable hydropower, in its forms of run-of-river and reservoir storage, and pumped storage are the largest clean sources of flexibility. Hydropower plays a fundamental role in the provision of both short-term ancillary services and long-term energy storage to balance electricity generation and demand on a daily, weekly, and

Figure 3: Expected Evolution of the European Electricity Mix (2010, 2021 and 2050 – Announced Pledges Scenario)



monthly basis. This role is bound to get even more important with the progressive retirement of coal and gas, as well as the partial retirement of the nuclear fleet. It can also be economically beneficial to rely on hydropower for these services: a report released by the International Renewable Energy Agency (IRENA) indicated that the global weighted average levelized cost of electricity (LCOE) of new utility-scale hydropower in 2021 was 11% lower than the cheapest new fossil fuel-fired power generation option.[4]

The extensive European hydropower fleet is a major strategic asset, being an abundant source of cost-competitive, renewable, dispatchable, and controllable power. It should therefore be a priority for all institutions to understand, preserve and enhance the benefits of hydropower. These benefits are the bedrock on which the challenging long-term European vision for a decarbonised economy will be achieved.

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1. Based on the projections prepared by the International Energy Agency for the European Union in the IEA World Energy Outlook 2022- Announced Pledges Scenario.
2. Inertia is an important component of electric power systems, greatly influencing its capability to absorb the impact of sudden incident. It is directly related to the mass and hence the kinetic energy stored in the rotating elements, such as synchronous generator-turbine unit and motors, connected to a grid. The lower the amount of inertia on the grid, the higher frequency will deviate from its nominal value following a grid disturbance.
3. This figure refers to the entire spectrum of flexibility (short term frequency services, balancing services, and long-term energy storage) that will be required by the grid to operate safely and efficiently.

3.2 A CLASSIFICATION OF FLEXIBILITY: FLEXIBLE POWER VS FLEXIBLE ENERGY

According to IRENA, electric power system flexibility represents 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"*. In other words, the term 'flexibility' should be used to describe the ability of a power system to manage the eventual mismatch between generation and consumption and keep the system in a status of performing its ultimate function in the most efficient and cost-effective way, constantly matching consumption with power generation.

Flexibility can be split into two the following main categories [5], [4]:

- **Power flexibility** is key to secure the short-term equilibrium between power supply and power demand. It is a system-wide type of flexibility, with the goal of controlling the stability of the system frequency (and voltage) which may be altered by unforeseen spikes or drops in consumption or sudden fluctuation of generation.
- **Energy flexibility**, on the other hand, is meant to balance the medium and long-term energy supply and respond to possible energy shortages and surpluses which may be caused by the hourly, daily or longer cycles associated with demand and VRE production profile, including the important task of storing surplus VRE in the system.

Most of the work done by XFLEX HYDRO focuses on enhancing power flexibility at existing hydropower stations, while noting that there are complementary benefits for energy flexibility.

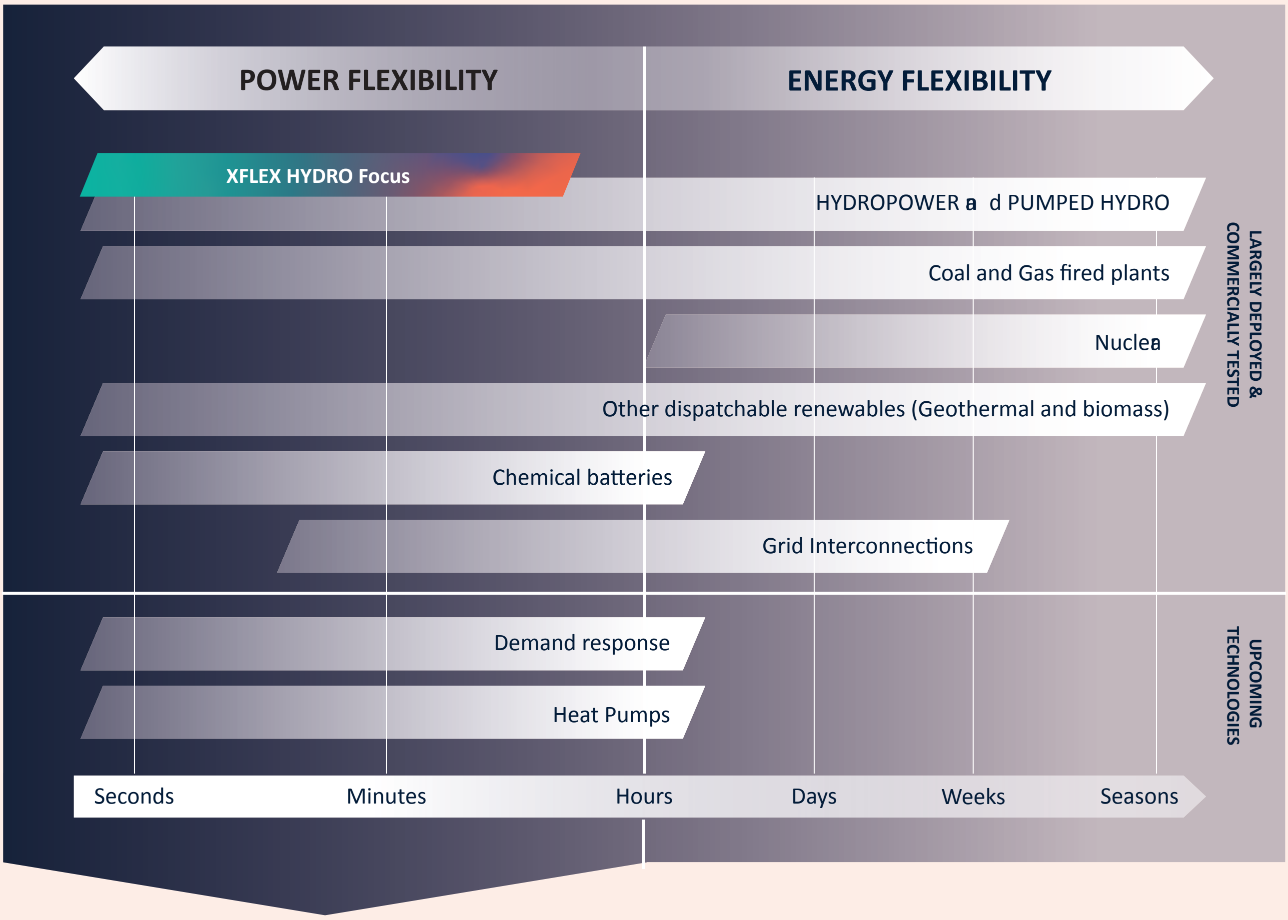
The capability of managing eventual imbalances is not only a matter of instantaneously responding and adjusting, but also to maintain this eventual correction over a certain period of time. Different technologies are usually capable of providing different types of flexibility, depending on how rapidly the power output can be corrected or activated and for how long the adjusted regime can be sustained.

A visual representation of the technical capabilities of the various sources of flexibility is provided in Figure 4.

The flexibility contributions that hydropower can provide are significant in scale and cover both power and energy. The advantages are numerous; hydropower generators can:

- quickly adjust the power produced (often in the range of seconds);
- start and stop their units (in the range of few minutes) with limited water waste;
- sustain production for long periods (typically for several hours or days); and
- efficiently store a large amount of surplus energy volumes produced by VRE (by reducing their own output and by absorbing and storing energy through pumped storage).

Figure 4: Flexibility categorisation and capabilities of the various sources



Power response is typically used to control short term (millisecond to minutes) imbalances which causes grid frequency deviations. Several ancillary services are responsible to harmonise the sequence of response to these imbalances. These are typically classified between primary, secondary and tertiary control.

This makes hydropower a perfect solution for grid control and VRE integration from a technical perspective. The XFLEX HYDRO project focused on the development of technical solutions, aimed at increasing the capability of existing hydropower plants to provide short-term power flexibility, and their capability to participate in associated ancillary electricity markets, (described further in section 3.3).

It is fundamental to make sure that our systems will be ready to support not only the demand for long term energy flexibility, but also capable of providing all the range power flexibility services need to keep the grid operational every second, minute and hour.

3.3 FLEXIBILITY KPI & ANCILLARY SERVICES

Because one of the goals of XFLEX HYDRO is to evaluate the economic benefits associated with the implementation of the technologies studied, an important part of the work focused on the identification of existing or prospective electricity markets where the flexibility services associated with the project technologies can be traded and converted into value. This task led to the identification of several ancillary services required by the grid. The characterisation of these ancillary services followed the strategies envisioned by the transmission system operators (TSOs) in Europe for the future operation of the EPS.

The impact that each of these technologies has on the power flexibility of the various types of hydropower plants was measured against two set of parameters:

- **The flexibility key performance indicators (KPIs)** which are a set of parameters, defined by the consortium partners and designed to measure the technical flexibility characteristics of a given power plant, its efficiency, and annual availability [6], [7]; and
- **The capability of participating in a range of existing and emerging ancillary service markets;** these markets were identified by the consortium partners and represent a group of power flexibility services where hydropower is (or could be) capable of providing a noticeable contribution. The specifications of these services were based on existing European grid codes. Some of these services are today associated with an existing market regulated at a national or international level; others, as of today, don't have a specific market yet but it is conceivable that the situation may change in the future [8].

A description of the key performance indicators and the ancillary services considered in this study are presented in Table 1 and Table 2.

Table 1: Flexibility KPIs definitions.

KPI	DESCRIPTION
OPERATING RANGE	It estimates the improvements in terms of operating range extension and operation in off-design conditions of the hydraulic machine. This range is determined as a percentage (%) with respect to the nominal power. Flexible technologies such as the variable speed, the hydraulic short circuit, and the Smart Power Plant Supervisor (SPPS) are expected to extend the operating range of the machine by allowing new off-design operating conditions.
FAST START AND STOP TIME KPI	This KPI estimates the time in seconds (s) to start the hydroelectric unit from standstill to nominal power and to stop the unit operation. This KPI is expected to highlight the benefits of hydroelectric technological solutions, such as variable speed and the SPPS for noticeably reducing the time of the transient operations of the hydraulic machine, especially during start-up.
FAST TURBINE-PUMP / PUMP-TURBINE MODE TRANSITIONS	This KPI evaluates the time in seconds of the transition from pumping mode at nominal condition to turbine mode at nominal condition (100% of the rate power), and vice versa in Pumped Storage Plants (PSPs). The time for changing modes is expected to be noticeably reduced thanks to flexible technology such as variable speed.
FAST RAMP-UP AND RAMP DOWN	This KPI provides an estimation of the rate for varying the power output in respect to the nominal condition, and it is expressed in percentage of rated power per second (%/s). This value is expected to be particularly improved by the hybridisation technology, thanks to the high ramping rate of BESS and the virtual inertia provided by the variable speed technology.
MAINTENANCE INTERVAL	The maintenance interval describes the hours (h) of operations between two similar and consecutive planned maintenance activities, based on a scheduled maintenance approach. It is considered a maintenance stop if it requires the unavailability of the hydroelectric unit. The hours of operation between maintenance intervals are foreseen to increase, which will also denote a reduction of the outage time, which is accumulated over a given period. This increase is achieved thanks to the investigations and developments performed within the XFLEX HYDRO project, providing higher awareness and confidence of the hydroelectric unit potential.
PLANT WEIGHTED EFFICIENCY KPI	This KPI is computed by considering the efficiency of the power unit in generating, pumping and hydraulic short circuit operation when relevant. This is computed by following the IEC 60193 Standards over the full range of operations. Therefore, it is given a range of efficiency for each operating mode from minimum to maximum efficiency.
DIGITALISATION	This KPI estimates the level of digitalisation of the Hydro Power Plant (HPP), by evaluating the measures adopted in the HPP for e-monitoring, advanced control systems and predictive maintenance. Two digitalisation indices will be estimated for operation and for maintenance. For each index, three levels are identified to yield. Operation Digitalisation Index: Level 1: Operation of the unit with individual unit control; Level 2: Offline evaluation of unit operation based on real time condition monitoring; Level 3: Real-time optimised set-point dispatch between units. Maintenance Digitalisation Index: Level 1: E-monitoring with Supervisory Control and Data Acquisition (SCADA) system and planned maintenance; Level 2: Real time condition monitoring with alerts on maintenance; Level 3: Optimised predictive maintenance.

Table 2: Ancillary services identified

CATEGORY		SERVICE	DESCRIPTION	MARKETS
FREQUENCY CONTROL	INERTIA	Synchronous Inertia	Proportional to the kinetic energy stored in the rotating unit connected to the grid. It plays a fundamental role in stabilising the frequency of the systems and reducing the rate at which the frequency deviates from its reference point in case of an accident.	Currently, there is no associated market in continental Europe but there are emerging frameworks in the United Kingdom (UK) and Ireland.
		Synthetic Inertia	Power electronic-interfaced energy sources can provide short-term frequency support with similar benefits to the synchronous inertia.	Currently, there is no associated market in continental Europe but there are emerging frameworks in the UK and Ireland.
	PRIMARY CONTROL	Fast Frequency Response (FFR)	FRR is designed to provide an active power response faster than existing operating reserves (FCR and aFRR). The time to fully activate this product is usually less than 2 seconds.	FFR is yet to be defined or rewarded as a service in Continental Europe (CE). FFR is currently being explored in other European markets such as in United Kingdom (previously tendered as Enhanced Frequency Response), the Irish and the Nordic markets.
		Frequency Containment Reserve (FCR)	FCR aims to contain system frequency after the occurrence of an active power imbalance. The time to fully activate this service is 30 seconds and should last for at least 15 to 30 minutes (depending on the specifics requested by the local TSO).	FCR has a dedicated EU platform (FCR Cooperation) designed to enable the exchange of this service among EU countries part of the same synchronous area. Nonetheless, only a limited number of countries are currently participating, while in other countries, the service is requested by the TSO but not compensated.
	SECONDARY CONTROL	Automatic Frequency Restoration Reserve (aFRR)	mFRR is a frequency restoration process, manually activated on TSO instruction, which has similar goals to aFRR. According to EU regulation, mFRR must be fully activated in 15 minutes and has a minimum delivery period of 5 minutes.	In accordance with the national frameworks, aFRR service is usually remunerated for both: the availability of spinning reserve (capacity) and the energy produced during the eventual activation. aFRR has a dedicated EU platform (PICASSO) designed to enable the exchange of this service among EU countries part of the same synchronous area.
	TERTIARY CONTROL	Manual Frequency Restoration Reserve (mFRR)	mFRR is a frequency restoration process, manually activated on TSO instruction, which has similar goals to aFRR. According to EU regulation, mFRR must be fully activated in 15 minutes and has a minimum delivery period of 5 minutes.	In accordance with the national frameworks, mFRR service is usually remunerated for both: the availability of the asset to provide to respond (capacity) and the energy produced during the eventual activation. mFRR has a dedicated EU platform (MARI) designed to enable the exchange of this service among EU countries that are part of the same synchronous area.
		Replacement Reserve (RR)	RR is used to progressively replace and/or support the frequency restoration control process. RR is usually activated through specific manual instruction of the TSO. According to EU regulation, the characteristic of RR requires full activation time of 30 minutes and a minimum delivery period of 15 minutes.	The service is regulated at a national level and compensates for the capacity and the energy produced during an eventual activation. RR has a dedicated EU platform (TERRE) designed to enable the exchange of this service among EU countries part of the same synchronous area.
OTHER SERVICE	VOLTAGE CONTROL	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.	Nowadays, this is typically a mandatory and not remunerated service. In some countries, there are bilateral contracts held between service providers and the TSO for the provision of extra Volt/var control.
	SYSTEMS RE-START	Black Start	This emergency process of restarting operation of a power plant during a grid blackout, from a completely non-energised operating state, without any power feed from the network.	The provision of this service is managed through a bilateral agreement between the TSOs and the power producers. Black Start is not expected to have its own market framework in the future.
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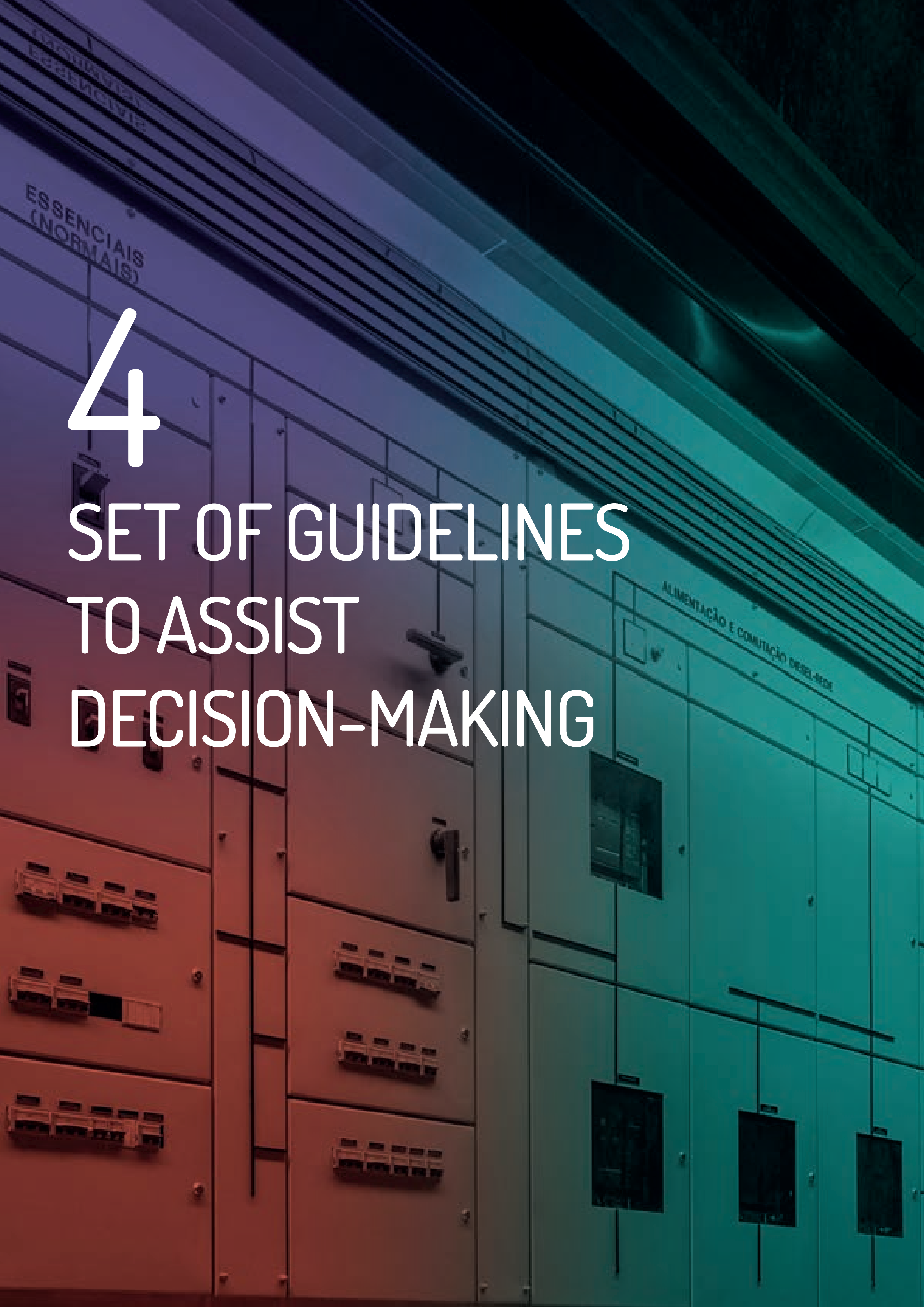


4

SET OF GUIDELINES TO ASSIST DECISION-MAKING

4.1 FLEXIBILITY, VALUE GENERATION AND DECISION-MAKING

The power systems are transitioning from a scenario where most of the flexibility and ancillary services were considered a by-product of the electricity generation, to a scenario where only a limited portion of the power fleet will be capable of holding reserves and dispatching power on demand, controlling its output, and participating in the grid balancing process.

Electricity markets and regulations are therefore evolving to secure constant and reliable provision of the full range of these services. There are several markets, available today in Europe, or that are in the process of being implemented in the foreseeable future, where the capabilities of hydropower plants to provide flexibility services to the grid can (or will) be traded and exploited to generate value for the operator.

It is difficult to forecast today which of these services will become prominent and, as a result, which flexibility markets will be more important over the course of the next 30 years; nonetheless, given the advanced age of the existing European hydropower fleet, there is a need to promptly develop the necessary internal know-how required to successfully implement and create value out of these innovative technologies. Operators are today facing urgent and critical decisions concerning the investments necessary in their hydropower fleet as well as the implementation of flexibility upgrades.

The purpose of the following section is therefore to provide a set of guidelines to decision makers, presenting the concept and benefits, in terms of flexibility provision, of each of the four technologies studied by the XFLEX HYDRO consortium, together with the key findings of the research carried out under the umbrella of the project.

4.2. SUMMARY OF THE TECHNOLOGIES INVOLVED IN XFLEX HYDRO

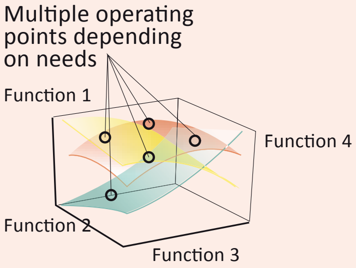
4.2.1 GENERAL

The work carried out under the XFLEX HYDRO project focused on the study and development of four technologies which share the following characteristics:

- They enhance the flexibility of hydropower plants and their ability to provide short-term power responses;
- They are applicable to existing hydropower plants and new green field projects;
- They can be implemented individually or in various combinations, depending on the plant’s type and the specific need.

4.2.2. SMART POWER PLANT SUPERVISOR (SPPS)

Figure 5: Smart Power Plant Supervisor (SPPS) – Applicability and Core benefits



APPLICABILITY:
ALL TYPE OF UNITS

CORE BENEFITS:

- Real time optimisation of power plants operations taking into consideration multiple factors: Efficiency, wear & tear, water consumption optimisation, unit start and stop...etc;
- Optimised integration of other technologies;
- Extended operating range;
- Extended components life.

Through the implementation of SPPS, power plant operations are not only based on turbine efficiency, as typically done. Instead, the operational choices concerning the turbine regulations, startup sequences and unit selections are optimised considering additional parameters as well as extensive knowledge of the hydraulic and mechanical components. This enables the plant owner to manage the risks and costs associated with a temporary off-design operation based on the potential benefits it offers. SPPS collects plant health information (monitoring of wear and tear of critical components) that will allow an asset management module to reduce the need of maintenance and maximise the productivity of the plant.

The extension of the operating range has been proven very successful, allowing for an almost continuous use of the operation of the unit, from 0 MW to maximum output power under certain conditions. This significantly increases the potential provision of ancillary services such as aFRR, mFRR vand RR.

It is also important to note that SPPS methodology plays an essential role in the integration of other flexibility technologies, ensuring that their potential contribution and benefits are maximised, according to the plant owners neds as well as market opportunities.

EXTENDING THE OPERATING RANGE OF AN EXISTING UNIT

Extending the operating range of an existing unit requires a deep understanding of the damages that the turbine will accumulate while operated outside the original design area. Among the various outcomes achieved by the XFLEX HYDRO project, there is a strong understanding of the process that can be followed to safely extend this range and map the damages caused by off-design operating conditions. The project has developed a process made up of the following four key steps that should be considered when undergoing this type of study.

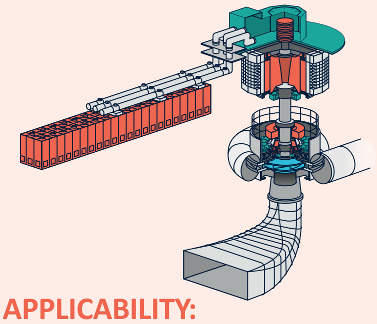
1- Numerical Simulation: Initial understanding of the behavior of the full components of the turbine at partial and deep-partial load.

2- Model & 3- Prototype Tests: Two parallel sets of tests are conducted, based on the installation of a set of sensors on the prototype and on a turbine model to further collect data on the most stressed areas of the runner and other non-rotating part of the unit.

4- Identification of the new operating range and continuous prototype monitoring: The results of these two tests are combined and compared to create the final damage model. Long-term monitoring system allows to check that no unexpected dynamic phenomena appear on the prototype. [10]

4.2.3. VARIABLE SPEED (VS)

Figure 6: Variable Speed (VS) - Applicability and Core benefits



APPLICABILITY:
ALL TYPE OF UNITS

CORE BENEFITS:

- Extended operating range and regulations in pump mode;
- Improved operations at partial load;
- Provision of frequency control services in pump mode;
- Faster regulation.

A typical hydraulic machine operates at a fixed speed which is dictated by two main factors, the frequency of the grid, measured in Hz and the design of the generator. The main constraint of fixed speed units is that if the HPP is featuring large head variations with respect to the nominal head, the operating point of the hydraulic machine deviates from the nominal head, leading to less efficient off-design operating conditions. This puts the system safety at risk, can cause damage to the hydraulic components, and can accelerate the aging process of the units. This is the main factor limiting the operating range of the hydraulic machine, imposing a minimum and maximum head (m), discharge (m3/s) and power (MW) at which the unit can be operated. [9]

Variable speed units can modify the rotational speed of the turbine and optimise their hydraulic performance on more extreme operating conditions, extending the exploitable operating range and providing improved weighted efficiency. This is particularly interesting since it enables the unit to operate at a reduced flow and head, lowering the threshold for the minimum power that can be produced by the unit. This also enables improved and faster start-up sequences.

When applied to PSP, which is the case predominantly, this technology not only extends the operating range, which for pumps is generally extremely limited, but also enables the provision of regulating power which can be traded on various flexibility markets, such as FCR or a/mFRR during pumping operations.

The speed variation is achieved by means of a power converter employing power electronics to decouple a motor/generator from the grid in terms of reactive power, voltage and frequency, which are set independently. Nowadays, the two main technologies available for variable speed HPP units are the Full-Size Frequency Converter (FSFC) and the Doubly Fed Induction Machine (DFIM), these were both investigated in the framework of the XFLEX HYDRO project.

DOUBLY FED INDUCTION MACHINE (DFIM) VS FULL-SIZE FREQUENCY CONVERTER (FSFC)

A FSFC is employed with a synchronous machine. The stator of the motor-generator is connected to the power network through a frequency converter which, rated at the same capacity, offers full flexibility for the rotating speed. However, FSFC are most suitable for relatively low power. For higher capacity, the cost of the frequency converter tends to be prohibitive. The world's largest FSFCs, featuring four 100 MVA synchronous units, were commissioned in 2013 at the Grimsel II PSP in Switzerland.

For DFIM, AC current is fed to the rotor of a non-conventional asynchronous motor-generator through a frequency converter, enabling a unit rotational speed variation of typically ± 10 %. Because the frequency converter rated power is only 10 % of the rated motor-generator power, it is typically the solution adopted for larger units.

4.2.4.HYDRAULIC SHORT CIRCUIT (HSC)

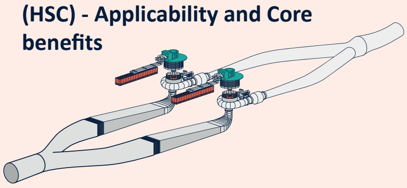


Figure 7: Hydraulic Short Circuit (HSC) - Applicability and Core benefits

APPLICABILITY: PSH

CORE BENEFITS:

- Extended operating range and regulations in pump mode;
- Provision of frequency control services in pump mode
- Faster switch from Pump mode to Turbine mode.

Traditional PSP are equipped with fixed speed pumps which are characterised by an extremely limited pumping range and therefore, no capability of regulating the power absorbed from the grid and the flow water pumped. [9]

Hydraulic Short Circuit (HSC) operation allows the simultaneous pumping and generating of different units of the same pumped-storage power plant. This operation extends the operating range of the plant, enabling to regulate the power absorbed when in pumping mode and to control the flow of water moved and stored in the upper reservoir, see Figure 7.

This additional flexibility can also be exploited for the provision of frequency control services during pumping operation, enabling participation in the ancillary service markets for frequency control, such as FCR, aFRR, mFRR and RR, while absorbing excess energy on the grid. Moreover, when introduced in a utility size generating fleet, HSC provides additional overall optimisation opportunities to fulfil generation and balancing power requests.

The hydraulic short circuit can be implemented in all types of pumped hydro stations, if they are equipped with at least one pumping unit, with a second unit that can be operated in turbine mode.

4.2.5. HYBRIDIZATION WITH BATTERY ENERGY STORAGE SYSTEM (BESS)

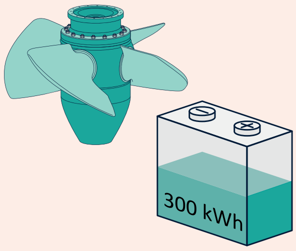


Figure 8: Battery Energy Storage System (BESS) Hybrid - Applicability and Core benefits

APPLICABILITY:
ALL TYPE OF UNITS (STUDIED ONLY ON ROR PLANTS)

CORE BENEFITS:

- Reduced wear & tear on hydraulic components;
- Fast provision of frequency control services;
- Enhanced regulating margin.

The hybridisation of a HPP consists of coupling a grid-connected Battery Energy Storage System (BESS) in parallel with an existing HPP, see Figure 8.

The applications of batteries in power systems are becoming of increasing interest thanks to their decreasing cost and high ramping duties compared to conventional generation units. BESSs consist of batteries, grid interfacing inverters as well as control and protection systems. Lithium-ion batteries are the most suitable and most used battery technology when high efficiency is desired.

Existing research demonstrated that BESS can be used to enable or improve hydropower units' participation in the FFR and FCR markets. It was also shown that slower dynamics of the hydropower unit enabled by the combined operation reduces turbine guide vane movements which are related to mechanical wear and tear. The slower dynamics of hydropower control systems lower the mileage and total number of guide vane movements.

4.3 THE ANCILLARY SERVICES MATRIX

The improvement in the provision of ancillary services associated with the implementation of these four flexibility technologies are summarised in Table 3. This is a simplified version of the Ancillary Services Matrix which is developed by the consortium. It focuses on transmitting two essential messages for each of the technologies studied:

- Clarify to what type of HPPs these technologies are applicable. Some can be applied to the entire fleet, but for instance, HSC is dedicated to PSPs.
- Indicate the benefits that each of these technologies will have on the provision of the ancillary services identified. The benefit can be of two types; it can **improve** the capability to provide a given service, or it can **enable** the provision of a service that was previously not possible. Finally, in the case of PSP, the provision of the specific service is also analysed for both turbine (◓) and pump mode (◒).

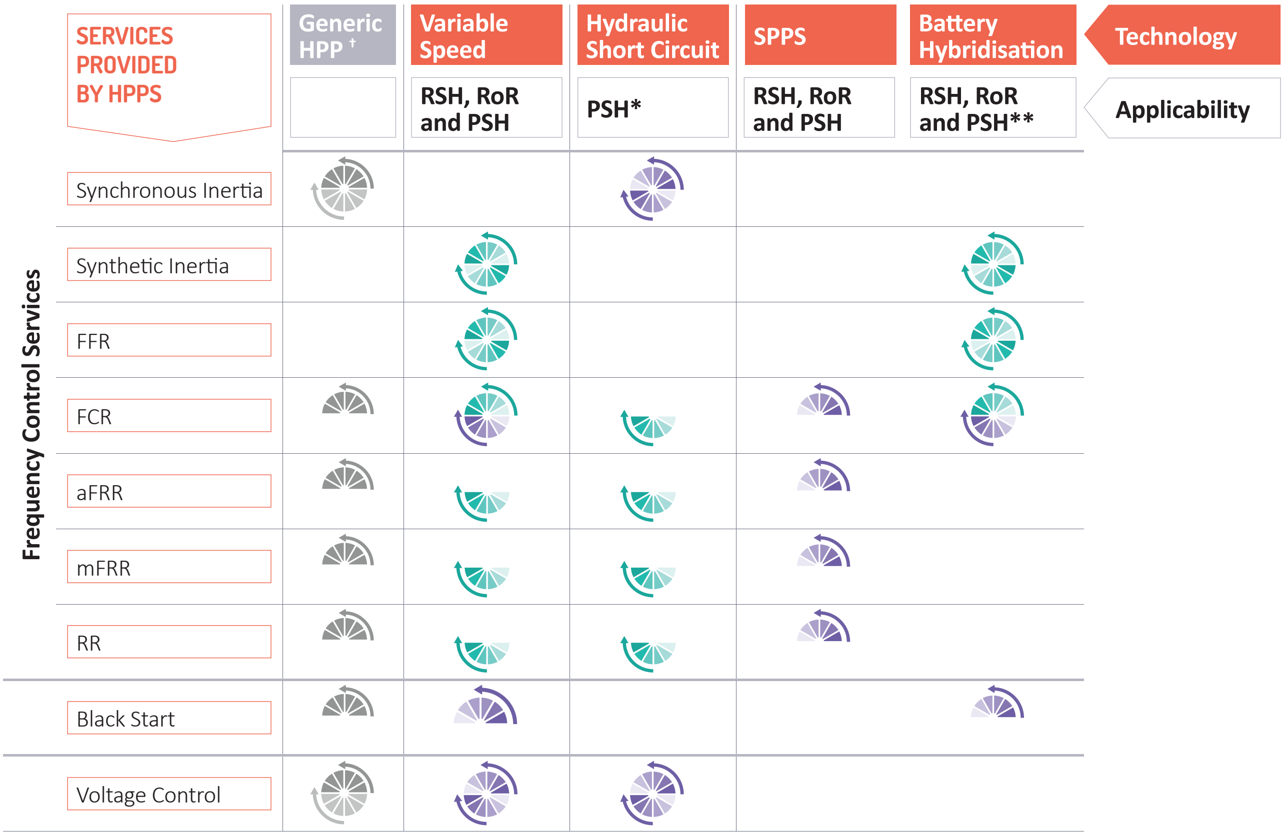
The first column on the left, in grey, indicates the capability of a baseline fixed speed hydropower unit, in terms of provision of ancillary services. This is based on the characteristics of the six plants used to test the technologies in the XFLEX HYDRO project.

SPPS offers the possibility to **improve** the existing capability of a hydropower plant to provide frequency control services through the extension of the operating range of the hydraulic units. In this case, the hydraulic unit can use the full power range, from 0 MW to maximum output power, instead of being limited to a minimum operating power point, as is typically the case. This extended operating range enables the owner to provide larger amounts of power reserve to the system, improving the provision of frequency control services and their participation in the existing power flexibility markets without changing any hydraulic or mechanical components of the unit.

Hydraulic Short Circuit is the only technology studied that can only be implemented in pumped storage plants. As presented in the matrix, it **enables** the provision of frequency control services when operating in pump mode. Additionally, because of the simultaneous operations of turbine and pumps, this operating mode also increases the system inertia.

Despite the low capital costs associated with SPPS and HSC, the benefits triggered by the

Table 3: The Ancillary Services Matrix



	SERVICES PROVIDED BY HPPS	Generic HPP †	Variable Speed	Hydraulic Short Circuit	SPPS	Battery Hybridisation	Technology
			RSH, RoR and PSH	PSH*	RSH, RoR and PSH	RSH, RoR and PSH**	Applicability
Frequency Control Services	Synchronous Inertia	◓◒ ⚪		◓◒ 🟣			
	Synthetic Inertia		◓◒ 🟢			◓◒ 🟢	
	FFR		◓◒ 🟢			◓◒ 🟢	
	FCR	◓ ⚪	◓ 🟢 ◒ 🟣	◒ 🟢	◓ 🟣	◓ 🟢 ◒ 🟣	
	aFRR	◓ ⚪	◒ 🟢	◒ 🟢	◓ 🟣		
	mFRR	◓ ⚪	◒ 🟢	◒ 🟢	◓ 🟣		
	RR	◓ ⚪	◒ 🟢	◒ 🟢	◓ 🟣		
	Black Start	◓ ⚪	◓ 🟣			◓ 🟣	
	Voltage Control	◓◒ ⚪	◓◒ 🟣	◓◒ 🟣			

Legend: Applicable mode

◓ Turbine

◒ Pump

Impact on provision of services

⚪ Generic capability of HPP 🟢 Enables provision 🟣 Improves provision

RSH – Reservoir storage hydropower;

RoR – Run of River;

PSH – Pump storage hydropower

*** Pump stations equipped with at least 2 separate units of which 1 capable of operating in pump mode**

**** Tested for run of river application only**

† Generic capability of fixed speed HPP. Not all fixed speed turbines are capable the services indicated in this table.

implementation of these technologies are notable. Indeed, if applied in conjunction, they could provide a complete improvement of the power flexibility that the power plant can provide, in turbine as well as in pump mode.

VS units excel in the provision of the entire range ancillary services studied by the consortium. The conversion of a fixed speed unit to VS **improves** the provision of fast frequency control service (such as FCR) in turbine mode and **enables** the provision of the entire range of services in pump mode. Additionally, it is the only technology that **enables** hydraulic units to provide FFR, both in turbine and pump mode.[4]

Because the generator rotor of a VS unit are decoupled, and the unit is connected to the grid through power electronics, VS units do not participate in the provision of synchronous inertia but can provide synthetic inertia (see box for further information).

It is also worth noticing that VS provides a noticeable **improvement** in the Black Start and Voltage control capability of existing plants.

Finally, the hybridisation of existing hydraulic turbines with Battery Energy Storage System does not directly change the unit's capability of providing ancillary services; rather, it adds to the existing ones, associated with the battery systems. The presence of the chemical battery **enables** the provision of very fast frequency control services such as FFR and can **improve** the FCR provision of the existing unit.

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[4] Hybridisation with Battery Energy Storage Systems also enables the provision of FFR, but this is provided directly from the chemical battery associated to the unit, rather than the hydraulic unit itself.

SYNCHRONOUS INERTIA VS SYNTHETIC INERTIA

Synchronous inertia is the instantaneous physical response provided by conventional generators which are electromagnetically coupled to the frequency of the systems. Their rotating mass acts as a stabiliser, limiting the magnitude of possible frequency fluctuations triggered by imbalances of supply and demand. This is proportional to the kinetic energy stored in the rotating unit (generator, shaft, and turbine) connected to the grid. It plays a fundamental role in stabilising the frequency of the systems and reducing the rate at which the frequency deviates from its reference point in case of an accident.

Variable Speed units do not rotate at the same frequency of the grid and are connected to the grid through a power electronic interface. This interface can read the frequency of the system and provide short-term but very fast active power injection (or reduction) to support the grid stability with similar benefits to the synchronous inertia.

According to the studies performed by the XFLEX HYDRO consortium, in scenarios with fast frequency deviation triggered by a major power loss, both the synchronous and synthetic inertia are an effective solution to improve frequency stability. Nonetheless, in low-inertia scenarios, such as the one with very high level of penetration of VRE, the performance of synchronous inertia proved to be 20% more effective at limiting the rate at which the frequency may deviate and 30% the maximum deviation. This is due to the time delays associated with the synthetic inertia control which needs to measure and process the system frequency before reacting. [18]

The profitability of these flexibility technologies has been studied as part of the activities carried out by the project. This analysis was carried out taking into account the trade-off between energy markets (represented by the Day Ahead market) and automatic reserve markets (FCR capacity market as well as aFRR capacity and energy markets).

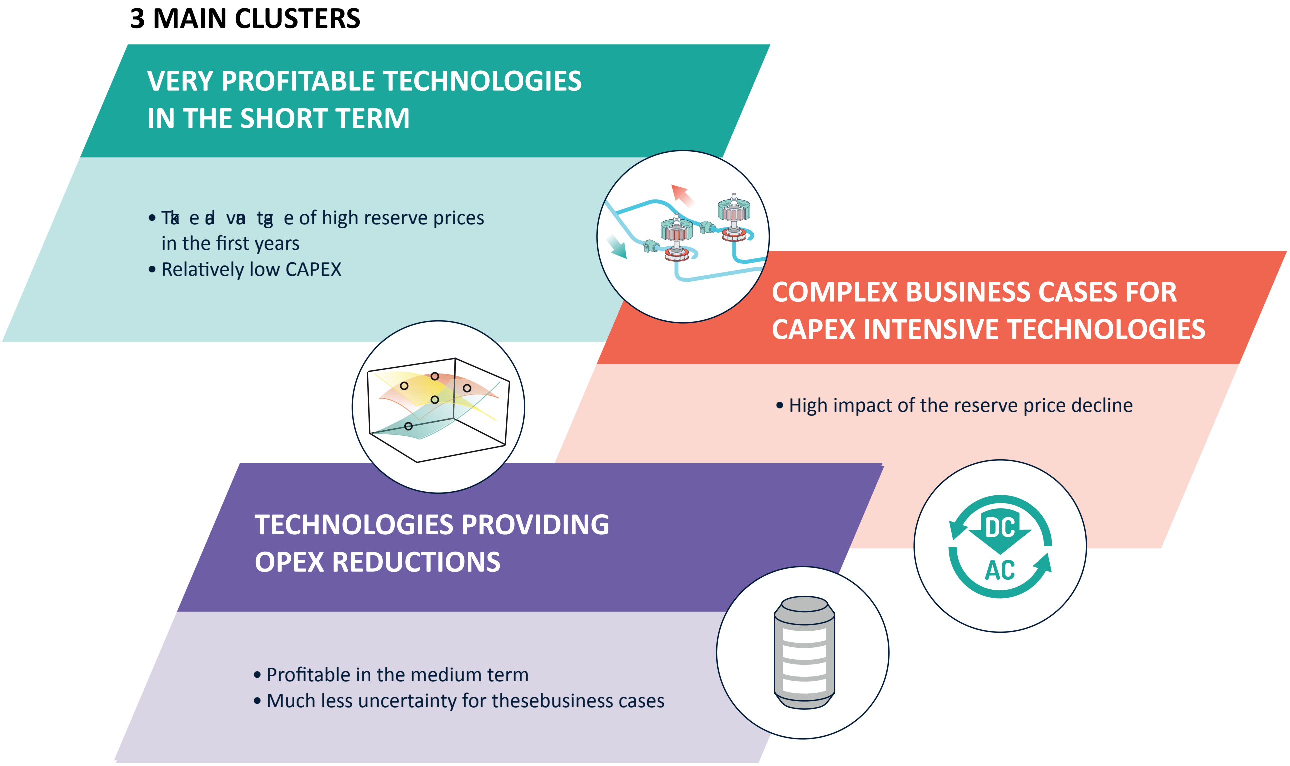
Price forecasts for the Day-Ahead, FCR and aFRR markets, based on the ENTSO-E scenario from TYNDP 2022 were generated up to 2050. The result of this analysis indicates that day-ahead electricity prices will be heavily impacted by the large deployment of zero marginal costs technologies such as wind and solar. There could be almost 400 hours of zero marginal price in 2030 and up to 2000 hours by 2040. The situation is even more extreme in the Iberian Peninsula where by 2030 there could be up to 1500 hours per year of zero marginal price and over 4000 hours (circa half of the year) in 2040. [33]

The revenue estimation was performed using a multi-market placement optimisation tool. It took into account the technical characteristics of the plant with and without flexible technology, the water availability and the different market prices over a full year. The tool determined the optimal hourly placement strategy on the day-ahead and automatic reserve markets (FCR and aFRR) for the hydropower plant and calculated the revenue for the two scenarios (with and without the XFLEX HYDRO technologies). [34]

The findings highlight that these technologies can be classified in three main clusters:[35]

Profitable technologies in the short term: Technologies such as HSC and SPPS, characterised by low capex requirements and shorter implementation time, can take advantage of the relatively high reserve prices identified in the first years (how many) and start generating surplus shortly after their implementation.

Figure 9: High level conclusion of the profitability analysis



Complex business cases: This category includes technologies such as VS with full size frequency converter and doubly fed induction machine. At the moment of writing this report, it is difficult to construct a business case for the implementation of these technologies solely focused on the additional revenues generated by the enhanced participation in existing ancillary service markets. Nonetheless several benefits, unlocked by the implementation of VS include an extended operating range, faster start-up and mode changing sequences, and more efficient exploitation of the water resources available which are not captured in the analysis performed.

Technologies providing OPEX reduction: Technologies such as BESS and SPPS which can provide substantial and quantifiable OPEX savings do not suffer from the uncertainty generated by volatile prices on ancillary services markets. These technologies can therefore be profitable in the short or medium term.

4.4 UPGRADE STRATEGIES STUDIED IN THE XFLEX HYDRO PROJECT

4.4.1 SCOPE

The following sections review in detail the various upgrade strategies, studied in the XFLEX HYDRO project, that are designed to enhance the provision of power flexibility of existing hydropower plants. These are presented under the three kinds of hydropower plant.

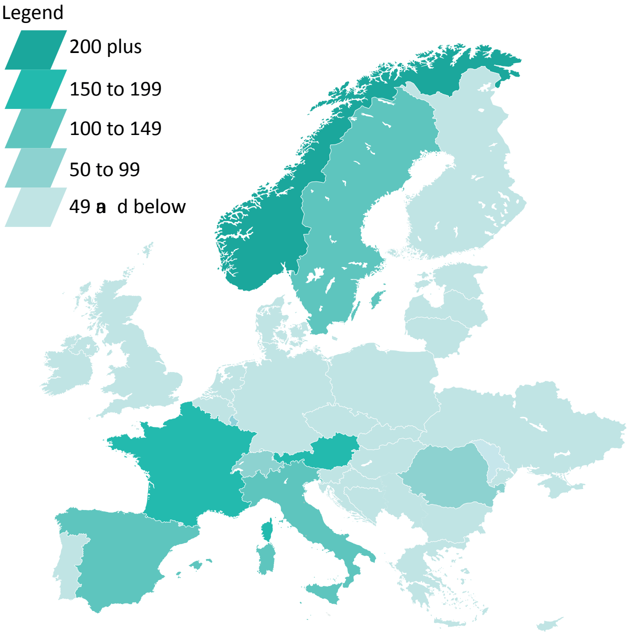
These are presented under three main categories, depending on the type of hydropower plant: reservoir storage, pumped storage, and run of river plants.

This section should be used a guide to understand:

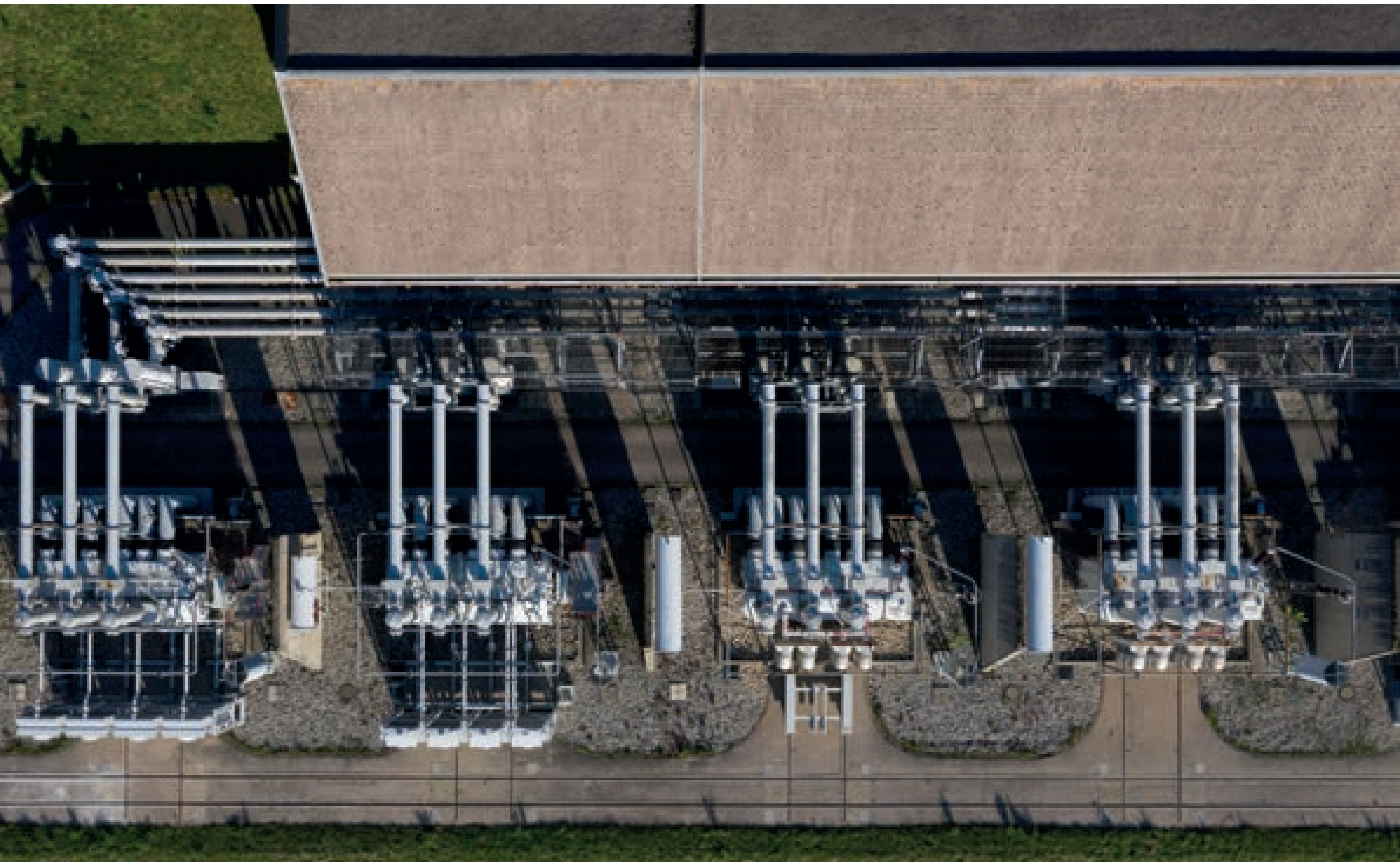
- the rationale behind the strategy identified by the Consortium;
- the type of technologies involved;
- and the possible results achievable through the implementation of each of these solutions.

4.4.2. STORAGE HYDROPOWER PLANTS

Figure 10: Number per country of storage hydropower plants in Europe.



- Indicative GW installed: 100 GW
- Indicative number of plants: ~ 1000



Role of reservoir storage plants

Storage Hydropower Plants (SHP) represent the highest capacity for the European hydropower asset. The key characteristic of these plants is to be connected to dammed reservoir capable of storing a large volume of water. The water released from the upper reservoir is forced into a penstock which is then used to feed one or multiple turbines. Reservoir plants are often used to accumulate water during periods of low demand, such as nighttime or summer, which is then consumed during peak hours of the day or winter season. This water storage capacity is key to reduce reliance on coal and gas plants. Furthermore, the relatively fast response of the hydraulic turbines combined with a high degree of control on the power generated enables the provision of a complete range of ancillary services, such as primary, secondary, and tertiary frequency control as well as Black Start and inertia.

Main characteristics of reservoir storage

The main characteristics of reservoir storage is to retain water at a higher elevation compared to the tailwater. The difference in elevation, usually to as 'head', is one of the most crucial parameters in the design of a hydroelectric power plant. Depending on the available head at site, this can vary from 10m up to over 2000 m, different types of turbine designs are used to optimise the energy production. Low head hydropower plants, typically between 20m and 50m, are often equipped with Kaplan double regulated turbines, while medium head installations, up to circa 500m, are usually fitted with Francis units. Finally, for high head configuration, Pelton units are preferable.

Kaplan and Francis turbines feature a reduced operating range when compared with Pelton units. Kaplan and Francis turbines operating range can vary between a minimum of 80% and 100% of the unit's rated power.

Pelton turbines offer an extremely large operating range, hence provide a larger margin for the operator to regulate the power generated by the plant. It is difficult to provide a single figure to describe the operating range of a Pelton unit, but this can be generally assumed to vary between a minimum of 15% and 100% of the rated power of the unit.

The regulating margin of an hydropower unit, used to provide grid frequency control, is specified by two parameters: the reactiveness of the units to adjust the power injected in the grid, either starting from idle or when in operation, and the operating range of the unit, which is characterised by the minimum power at which the units can be safely operated and the maximum power, or 'rated power', producible.

These minimum and maximum powers impose the operating range and the amount of power flexibility that the plant can provide to the grid for primary, secondary and tertiary frequency control. When a unit is operated at low power regime, unsteady hydraulic phenomena can occur. These phenomena negatively impact efficiency, can damage the turbine and other hydraulic components, and can substantially reduce the lifespan of critical components.

The XFLEX HYDRO project focuses its work on:

- Extending the operating range of existing Francis units to enable exploitation below minimum power and increase the regulating margin available for the provision of power flexibility to the grid;
- Optimising the unit operation, taking into consideration not only the unit efficiency but also other parameters such as: limiting the start and stop sequences and reducing the wear and tears of the components.

Enhanced flexibility technologies applicable

The strategy adopted in the XFLEX HYDRO project to increase SHP flexibility is to extend the:

- Operating range extension by using SPPS optimisation.

Upgrade Strategy 1:

EXTENDING OPERATING RANGE OF CONVENTIONAL FRANCIS UNITS

Alto Lindoso

Key objectives:

- Implement an innovative digital control tool based on SPPS methodology named *Advanced Joint Control (AJC)* to optimise the plant operations, taking into consideration multiple factors which contribute to the overall enhancement of plant operation and support the overall health of the machinery;
- Extend the operating range unlocking "off-design" operation areas of the units, targeting a continuous power output ranging from nearly zero to the rated power.

Applicable XFLEX HYDRO technologies:

SPPS

BENEFITS:

Table 4: Impact measured against Flexibility KPIs – Upgrade Strategy 1

Case	Operating Range	Maintenance interval
Base Case	Pmin=25%; Pmax=100%	2000 h
SPPS and operating range extension	Pmin=0%; Pmax=100%	> 2000 h

Table 5: Impact measured in terms of the provision of ancillary services - Upgrade Strategy 1

	Inertia		Primary Control		Secondary Control	Tertiary Control		Other Services	
	Synchronous Inertia	Synthetic Inertia	FFR	FCR	aFRR	mFRR	RR	Voltage Control	Black Start
Base Case (Pumping mode)	●			●	●	●	●	●	●
SPPS + HSC (Pumping mode)				🟣	🟣	🟣	🟣		

Legend: Applicable mode Impact on provision of services

Turbine ● Generic capability of HPP 🟢 Enables provision 🟣 Improves provision

Level of capital investment: The 0.500 kM€ ± 40% level of capital investment associated with the implementation of SPPS is relatively low, and mostly limited to the development costs of the optimisation algorithm, its implementation and the electronics required for the installation on site. All the existing components of the plants remain the same. The operating range extension requires a combination of simulations, model and prototype tests that can represent more notable costs.

Estimated impact on operating costs: This upgrade strategy resulted in lower maintenance costs, as it allows operators to optimise start and stoppage manoeuvres and reduce the amount of hours in operating points where the damage consequently, the wear and tear, are higher. The consequent extension of the maintenance intervals of the plant resulted in € 36k per year of reduced costs for both units.

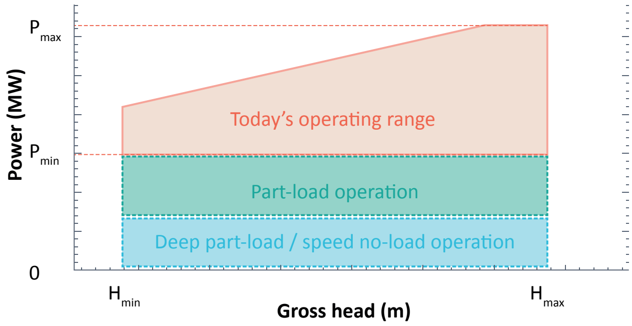
Demonstrator characteristics: The Alto Lindoso Hydroelectric Plant is in the far north of Portugal and owned by EDP. With a total installed capacity of 634 MW, it is one of the largest hydroelectric plants in the country. The infrastructure, commissioned in 1992, features 2 vertical Francis turbines with an outstanding gross head of between 227 m and 288 m and a rated power of 317 MW. It has an annual average production capability of 933.8 GWh.

Table 6: Alto Lindoso SHP characteristics

Type of units	Francis turbine
Number of units	2 units
Mechanical power	2 x 317 MW
Head	227m (min) – 275.6m (nom) – 288m (max)
Rotating speed	214.3 min^{-1}

Rationale: Conventional Francis units are usually designed to operate between a maximum power (P_{max}), often called “rated power”, and minimum power (P_{min}), typically corresponding to circa 50% of the rated power (orange area in Figure 11). However, units will need to be increasingly ramped up and down multiple times a day and over an extended operating range to provide power flexibility services, help balance the grid and improve their participation in the evolving electricity markets.

Figure 11: Illustration of operating range extension



Increasing the operating range of a unit means being able to operate below the designed minimum power of the turbine, at partial load and deep partial load/speed no-load (Indicated in green and blue in Figure 9). Traditionally, the units are not designed to operate in these areas because a wide range of unsteady hydrodynamic phenomena can be experienced which can impact the structural integrity and, therefore the overall lifetime of the hydraulic machine.

This upgrade strategy was designed to identify a low capex solution capable of extending the operating range of existing Francis turbines, below the minimum power set by the original design and, at the same time, optimise the overall operations of the plant.

The role of Smart Power Plant Supervisor: The SPPS methodology in Alto Lindoso, implemented by GE under the name of AJC, allows for the optimisation of the dispatching rules, taking into consideration criteria such as minimal water usage, optimisation of efficiency, the limitation of wear and tears as well as the avoidance of frequent start-up sequences with the units. It is a digital tool that results in a more efficient overall management of the powerplant operation. The optimisation criteria considered, as well as their prioritisation, can be easily adjusted depending on the plant operator needs.

The AJC has been designed as a plug-in that can be connected or disconnected without any change in the existing control system.

Results:

- The damage model developed for the runner of Alto Lindoso provided a better understanding of the existing Francis turbines' behaviour, both at partial and deep partial load.
- The units are now capable of a continuous operation between 0 MW and the rated power of 317 MW, providing a much larger regulating range (2x larger than the original design).
- The provision of aFRR by each unit is increased to 250 MW instead of 100 MW as in the original base case. The provision of FCR was also enhanced, even though this service is not currently remunerated in Portugal.

- The implementation of the AJC has been carried out successfully and the algorithm, based on the SPPS methodology, has demonstrated its performance over several months of operation
- Depending on the optimisation goal selected by the operator, the overall global efficiency of the plant can be increased by 0.58%, if the efficiency criteria is prioritised, or the accumulated damages by the runner reduced by almost 50%, in case of a prioritisation of the wear and tear reduction criteria.
- The methodology implemented allows for the operator to prioritise the criteria of the optimisation according to its requirement, with the possibility to combine efficiency increase and damage reduction benefits within the limits presented above.

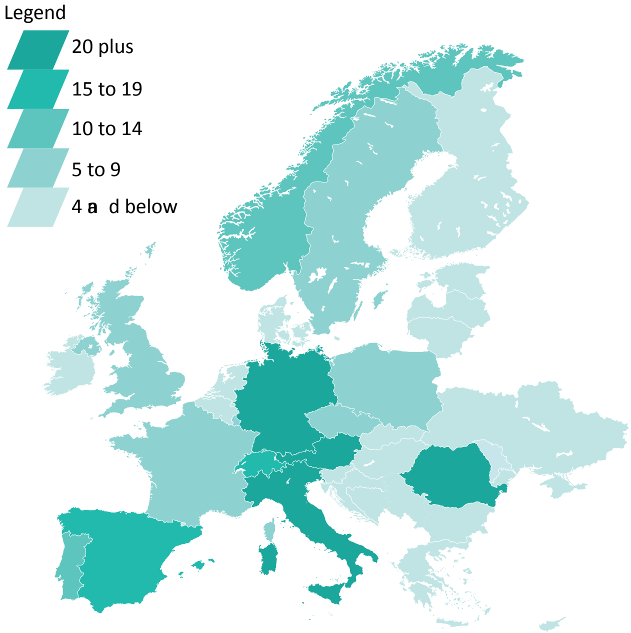
Further information can be found in the following relevant readings:

“Alto Lindoso final report of demonstrator”, EDP CNET [10]	“SPPS Methodology”, EPFL, [10]	“Final consolidated report implementation of the demos”, EPFL, [7]

4.4.2. PUMP STORAGE PLANTS

General statistics about the pump storage plants in Europe

Figure 12: Distribution of Pumped Storage Hydropower Plants



- Indicative GW installed: 60 GW
- Indicative number of plants: 200 +

Role of pump storage plants

PSPs can store large volumes of surplus electricity, especially from VRE output, which would have to be curtailed otherwise. The stored energy is then used to balance the grid, with short- and longer-term services to ensure adequate quantity and quality of supply in the system. Uniquely, PSPs absorb excess power on the grid by pumping water from a lower body and storing it in a higher reservoir. The water stored in the higher reservoir is then released and run through a turbine when the demand for electricity is high or production from other sources is low.

With generation (and demand) being increasingly dependent on weather conditions, storage technologies will play a major role in the energy transition. PSPs represent over 95% of installed storage capacity in Europe today and are the main large-scale solution available to avoid curtailment of VRE.

Main characteristics of pumped storage

The open-loop and closed-loop types of pumped storage plants are defined as follows:

- ***Open-loop:*** with either an upper or lower reservoir that is continuously connected to a river;
- ***Closed-loop:*** an "off-river" site that produces power from water pumped to an upper reservoir without a significant natural inflow connected to either the upper or the lower reservoir.

Compared with electro-chemical batteries, which are currently the main alternative storage technology available, PSPs feature a clear competitive advantage for the provision of long-term storage capacity, typically being capable of supplying/absorbing power to/from the grid for several consecutive hours and, in certain cases, days. PSPs also have a much longer lifespan, up to 100 years, with almost no limitation on the number of cycles.

Main limitations

When operated in generating mode, the limitations of pumped storage plants are comparable to the other hydropower plants, all of which are ‘dispatchable’ through the controlled release of water. The main constraints are predominantly determined by the amount of water storage, the head available, and the type of turbines installed.

One of the main limitations specific to PSP technology is that, when operated in pumping mode, a typical (fixed speed) machine is operating at constant power consumption. This lack of adjustability has two consequences:

- The head operating range is very limited;
- The operator has limited margin to decide how much power can be stored; and
- Pump storage plants, when operated in pump mode, cannot provide frequency control services.

The industry has developed various technologies to increase the flexibility of synchronous, fixed-speed PSP equipment in pumping mode; these include variable speed units, including either full-scale frequency converters (FSFC), or, more commonly, doubly fed induction machines (DFIM). Also, a form of operation combining simultaneous pumping and generation with two or more units at the same station has been identified; this mode is known as "Hydraulic Short-Circuiting" mode [6]. All three of these types of operation and equipment have the potential for enhanced flexibility and have been under the scope of the XFLEX HYDRO project.

Enhanced flexibility technologies applicable

To increase PSP power flexibility, three types of enhancements are investigated in the XFLEX HYDRO project:

- SPPS and Hydraulic Short Circuit (HSC) with the SPPS;
- SPPS and Variable Speed (FSCF or DFIM) with the SPPS;
- SPPS and Variable Speed (DFIM) and HSC with the SPPS;

Upgrade Strategy 2:

HYDRAULIC SHORT CIRCUIT WITH HIGH HEAD PELTON UNITS

Grand Maison

Key objectives:

- Enable the provision of ancillary primary and secondary control (FCR, aFRR and mFRR) while the plant is operated in pump mode with limited capital investment.
- Control and regulate the energy absorbed by the grid and the pumped flow when the unit is operated in pumping mode.

Technologies implemented::

SPPS + HSC

BENEFITS:

Table 7: Impact measured against Flexibility KPIs – Upgrade Strategy 2

Case	Operating Range	Ramp-up/Ramp-down	Turbine to pump / pump to turbine transition	Plant Efficiency
Base Case (Pumping Mode)	Turbine: from 15% to 100% Pump:- 100% (No regulating margin)	Turbine: 2.5%/s Pump: (No ramp-up capabilities)	T→P: 1800s P→T: 1500s	Turbine: Min=81% Max=88% Pump: Min=84% Max=87%
SPPS and operating range extension	Turbine: from 10% to 100% Pump: from-100% to -2%	Turbine: 2.5%/s Pump: 2.5%/s	T→P: 1800s P→T: 1500s P→HSC: 30s	Turbine: Min=81% Max=88% Pump: Min=84% Max=87% HSC: Min=66% Max=81%

Table 8: Impact measured against the ancillary services provision - Upgrade Strategy 2 (presented only in pump mode)

	Inertia		Primary Control		Secondary Control	Tertiary Control		Voltage Control	Systems re-start
	Synchronous Inertia	Synthetic Inertia	FFR	FCR	aFRR	mFRR	RR	Voltage Control	Black Start
Base Case (Pumping mode)	⚪							N/A	N/A
SPPS + HSC (Pumping mode)	🟣			🟢	🟢	🟢	🟢	🟣	N/A

Legend: Applicable mode

Turbine
Pump

Impact on provision of services

⚪ Generic capability of HPP 🟢 Enables provision 🟣 Improves provision

Level of capital investment: The 750 k€ ± 25% level of capital investment associated with all necessary hardware is already available in the plant to operate in hydraulic short circuit mode. Interventions are limited to the cost of mod-elling and testing, as well as the adaptation of the plant's control system.

Estimated additional operating costs: The < 500 k€ eEstimated additional operating costs, OPEX, are : (<0.5M€/year) The additional OPEX associated with the HSC operations relate and the to extra repairs and spending due to the additional hours of operations. The main cost elements affected are the following:

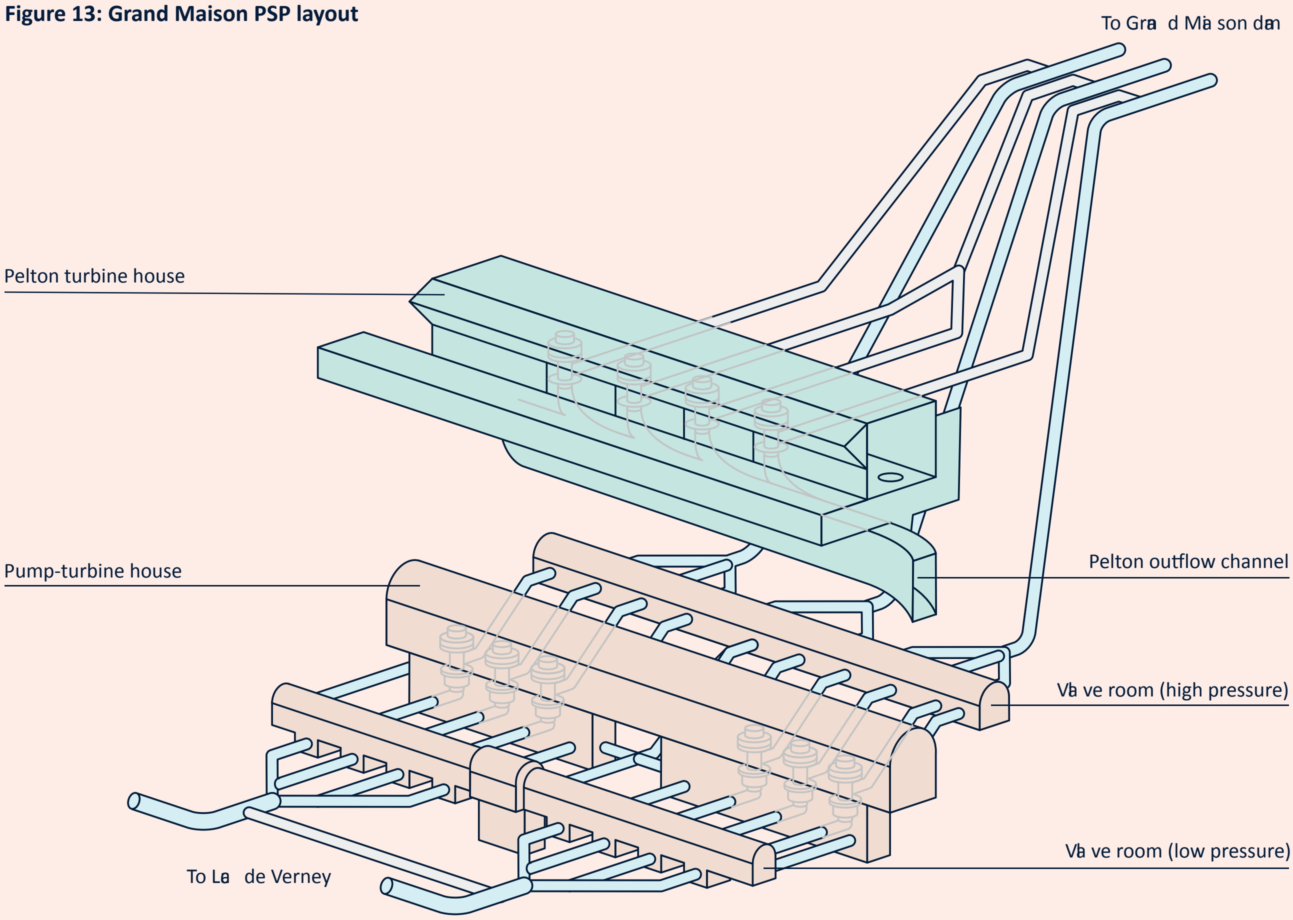
- Pelton injectors, additional wear;
- penstock, inner coating;
- generators and motor/generators, extra overhaul maintenance;
- generator circuit braker, extra overhaul maintenance; and
- and bearings, replacement of extra thrust bearings.

Demonstrator characteristics: The Grand-Maison PSP demonstrator is featuring 8 reversible multi-stage pump-turbines and 4 Pelton turbines, for a total installed capacity of 1800 MW, see figure 6. This makes it the largest PSP in Europe and one of the major PSP in the world. The waterway includes a headrace tunnel, a headrace surge tank, 3 parallel penstocks feeding the 12 units operated under a maximum gross head of 955 m, see table 9.

Table 9: Grand'Maison PSP characteristics.

Type of units	Pelton & Multistage pump-turbines
Number of units	Branch #1: 1 Pelton turbine and 3 pump-turbines Branch #2: 2 Pelton turbinesand 2 pump-turbines Branch #3: 1 Pelton turbine and 3 pump-turbines
Mechanical power	Pelton turbines: 170 MW x 4 Pump-turbines: 156 MW x 4
Head	820 m (min) – 918m (rated) – 955m (max)
Rotating speed	Pelton: 428 min^{-1} Pump-turbines: 600 min^{-1}

Figure 13: Grand Maison PSP layout

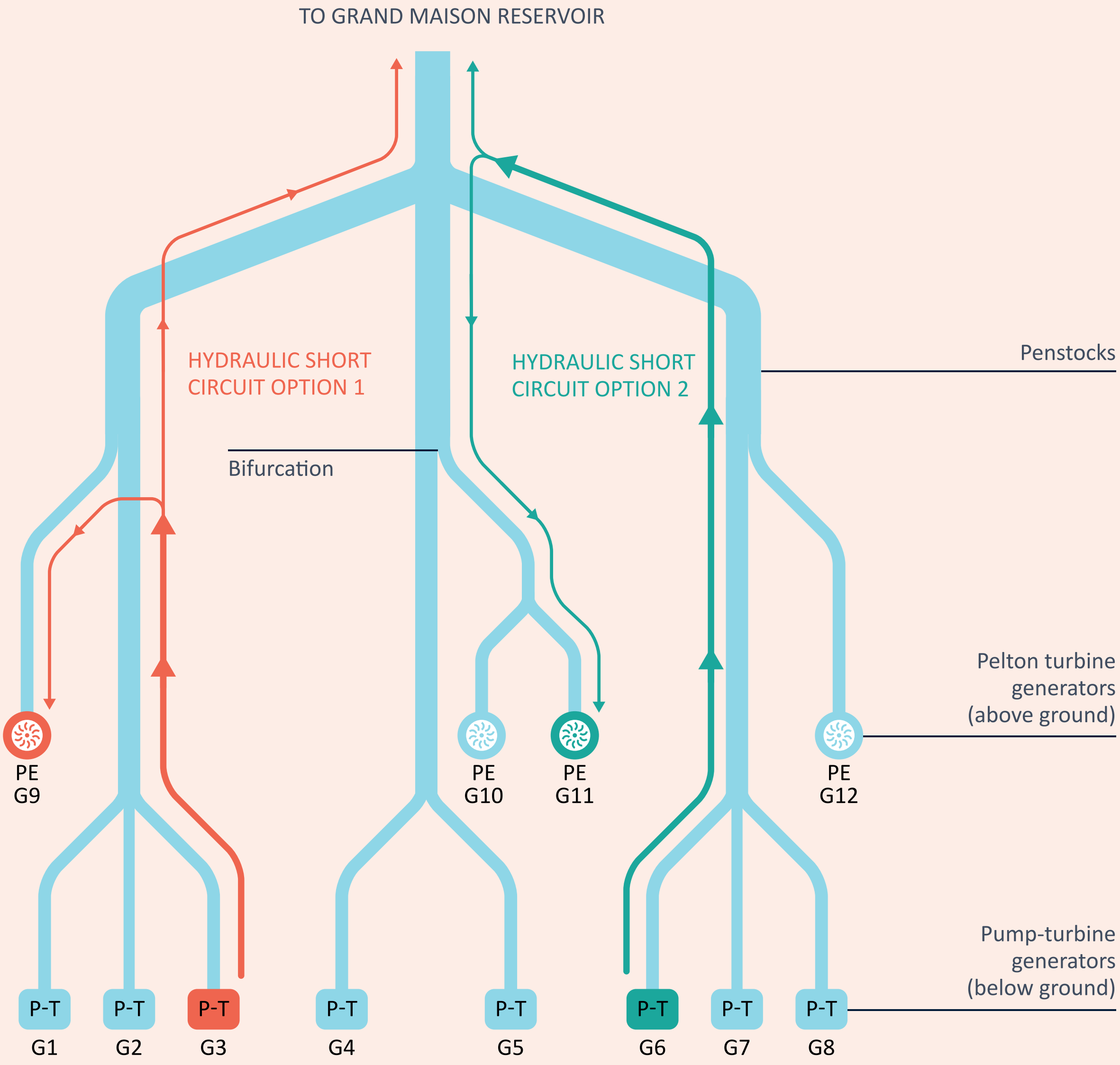


Rationale: The flexibility of a high head pumped storage hydropower plant, equipped with Pelton turbines, can greatly benefit from the introduction of hydraulic short circuit operations. The ultimate purpose of the Grand Maison demonstrator is to enable the provision of regulating power when the plant is operated in pumping mode during periods of low demand or generation surplus. Thanks to the operation in HSC, the plant will be simultaneously capable of storing excess electricity available on the grid and providing regulating power to the grid without using combustion power plants, i.e. gas and coal fired plants which would typically remain operative to provide the power flexibility to the grid.

Due to the complex layout of the Grand Maison power plant, two options illustrated in Figure 14 are selected to investigate the feasibility and the benefits of the hydraulic short circuit operations.

The role of Smart Power Plant Supervisor: Integrating hydraulic short circuit operation in a pumped storage plant is the equivalent of adding an additional operating mode on top of the existing pump and turbine modes. Some plants may have a very simple layout, with only one or two units available, therefore presenting a limited number of options for the operation in HSC mode. In other cases, such as Grand Maison, the plant may be equipped with several pumps and turbines units. The role of SPPS at this point becomes critical to ensure an optimal utilisation of the units, reduction of starts and stops and ultimately, limits the additional operating costs while reducing the adverse possible impact on the units.

Figure 14: Illustration of the hydraulic short circuit options



Results:

- Both simulations and on-site measurements demonstrated that the plant can be safely operated in hydraulic short circuit.
- Operations in HSC, in conjunction with SPPS, enable the provision of flexibility to the grid when the plant is operated in pumping mode.
- The Grand Maison plant is now capable of participating in the entire range of grid control services (FCR, aFRR, mFRR and RR), while storing excess energy from the grid.
- The plant is now equipped to provide up to 135 MW of reserve power (with possible scalability up to 500 MW), when operated in pump mode, which can be activated in less than 300s.
- The operation in HSC allows a more adjustable power consumption when the plant is operated in pump mode, enabling a superior control on the amount of energy stored.
- In its first year of operation, Grand Maison optimisation software has relied on HSC operation for 1,700h out of a total 3,100h spent in pump mode. Hence, HSC has been utilised for over 50% of the time spent in pump-mode.
- HSC was predominantly used for the provision of Secondary Control (aFRR) service which would have been otherwise provided by combustion plants. In the first 100 days of service, this has saved over 10,000 kgCO2 emissions per year.

Further information can be found in the following relevant readings:

“Grand Maison demonstrator in operation”, EDF, [12]	“Final consolidated report implementation of the demos”, EPFL, [7]	“Technical White Paper”, EPFL, [9]

Upgrade Strategy 3:

HYDRAULIC SHORT CIRCUIT AND RANGE EXTENSION WITH REVERSIBLE PUMP-TURBINE UNITS

Alqueva

Key objectives:

- Extend the operating range unlocking "off-design" operation areas of the units, targeting a continuous power output, ranging from nearly zero to the rated power.
- Enable the provision of ancillary primary and secondary control (FCR, aFRR and mFRR) while the plant is operated in pump mode with limited capital investment.
- Control and regulate the energy absorbed by the grid and the pumped flow when the unit is operated in pumping mode.
- Implement an innovative digital control tool based on SPPS methodology to optimise the plant operations, taking multiple factors into consideration, contributing to the overall enhancement of plant operation and supporting the overall health of the machinery.

Technologies implemented::

SPPS with operating range extension and Hydraulic Short Circuit (HSC)

BENEFITS:

Table 10: Impact measured against Flexibility KPIs – Upgrade Strategy 3

Case	Operating Range	Ramp-up / Ramp-down	Maintenance intervals
Base case (Fixed speed units)	Turbine mode: 25%- 100% Pump mode:-100 % (No regulating margin	Turbine: 1.95 %/s Pump: (No ramp-up capabilities)	14000
SPPS with range extension	Turbine mode: 0%- 100% Pump mode:-100 % (No regulating margin)	Turbine: 1.95 %/s Pump: (No ramp-up capabilities)	>14000
SPPS with range extension + HSC	Turbine mode: 0%- 100% Pump mode:-2%,-100%	Turbine mode: 1.95 %/s Pump mode: 1.95 %/s	>14000

Table 11: Impact measured in terms of the provision of ancillary services - Upgrade Strategy 3

	Inertia		Primary Control		Secondary Control	Tertiary Control		Voltage Control	Systems re-start
	Synchronous Inertia	Synthetic Inertia	FFR	FCR	aFRR	mFRR	RR	Voltage Control	Black Start
Base Case	◓⚪ ◒⚪				◓⚪	◓⚪	◓⚪	◓⚪	◓⚪
SPPS					◓🟣	◓🟣	◓🟣		
SPPS+HSC	◒🟣				◓🟢 ◒🟣	◓🟢 ◒🟣	◓🟢 ◒🟣	◒🟣	

Legend: Applicable mode

◓ Turbine
◒ Pump

Impact on provision of services

⚪ Generic capability of HPP
🟢 Enables provision
🟣 Improves provision

Level of capital investment:

SPPS - (€0.5mln ±40%) The capital investment associated with the implementation of SPPS is relatively low, and mostly limited to the development costs of the optimisation algorithm, its implementation and the electronic required for the installation on site. All the existing components of the plants remain the same.

HSC - (€750k ±25%) All necessary hardware is already available in the plant to operate in hydraulic short circuit mode. Capital costs are limited to the modelling and testing activities and the adaptation of the plant's control system.

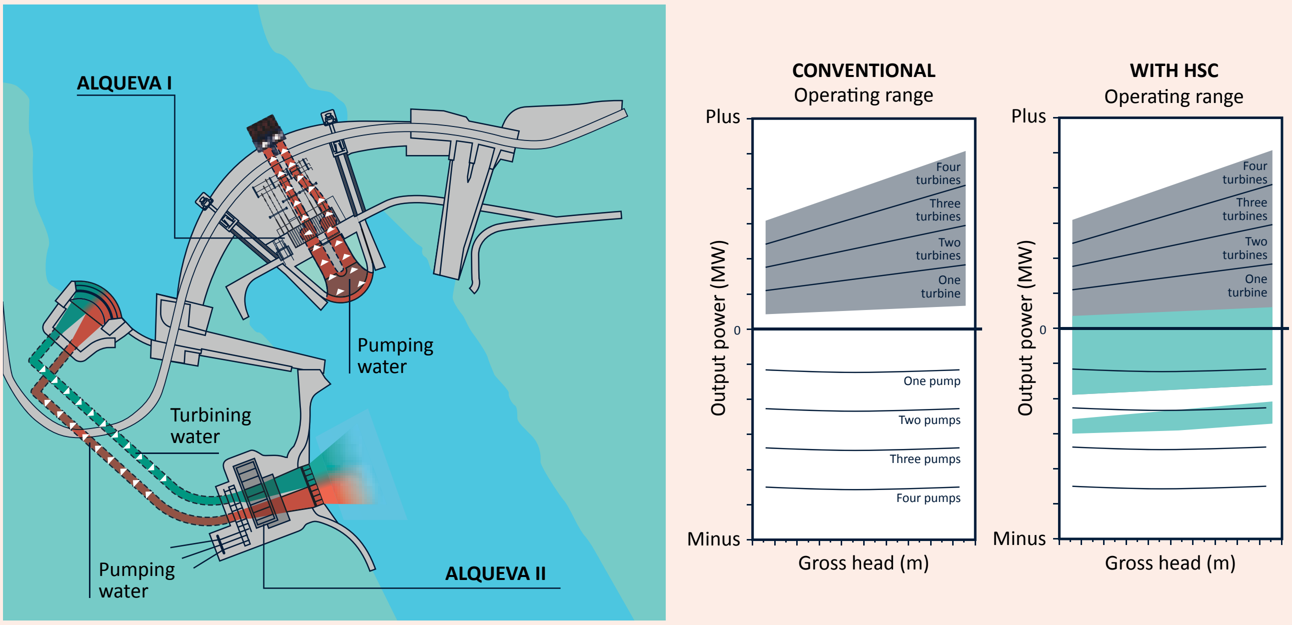
Demonstrator characteristics: Alqueva hydroelectric plant is a Pumped Storage Power plant located on the Guadiana River in the south of Portugal. The power plant includes two separate powerhouses, Alqueva I, commissioned in 2004 and Alqueva II, commissioned in 2017. Two fixed speed reversible pump-turbines with a total nominal power of 520 MW compose each powerhouse.

Table 11: Characteristics of Alqueva PSP

Type of units	Alqueva I: 2 Alqueva II: 2
Number of units	Alqueva I: 2 reversible pump-turbines Alqueva II: 2 reversible pump-turbines
Mechanical power	Alqueva I - 2 × 129.6 MW in turbine mode; - 2 × 106.9 MW in pump mode Alqueva II - 2 × 130 MW in turbine mode; - 2 × 110 MW in pump mode
Head	Alqueva I: 50.2 m (min) – 76 m (max) Alqueva II: 71 m (max)
Rotating speed	136.4 min^{-1}

Rationale: The objective of this Upgrade Strategy 3 is to increase the operating range and the margin available for power regulation of a pump storage plant equipped with reversible pump-turbines. In turbine mode, these reversible units, are designed to operate between a maximum power (Pmax), often called "rated power", and minimum power (Pmin). In the case of Alqueva, the minimum power in turbine mode is 25% of the rated power of the

Figure 15: Alqueva power plant configuration in HSC operating mode and regulating range improvement



unit, while, due to the fixed speed technology implemented, the plant has no regulating margin at all when operated in pump mode. When a turbine is operated below the minimum power, a wide range of unsteady hydrodynamic phenomena can be experienced negatively impacting the structural integrity of the hydraulic components, and therefore reducing their lifetime.

The simultaneous implementation of SPPS and HSC enables operators to optimise the operations of the power plant, extending the operating range in both turbine and in pump modes according to the following objectives::

- Turbine mode: Extend the operating range below 25% of the nominal power.
- Pump mode: Control the power consumed in pump mode and the associated pumped water flow. Enable the provision of balancing service while the plant is operated in pump mode.

The role of Smart Power Plant Supervisor:
The SPPS methodology applied in Alqueva, implemented by GE under the name AJC, can optimise the most efficient dispatch amongst the different units, following technical and economical boundaries. It is a digital tool that results in a more efficient overall management of the powerplant operation. The optimisation criteria considered, and their prioritisation, can be easily adjusted depending on the plant operator needs.

Results:

- The HSC operating mode was successfully implemented and no major obstacles for extended operations on a long period of time have been identified.
- The application of the SPPS methodology, through the Advance Joint Control, the Alqueva PSP enhanced the provision of Ancillary Services to the grid, namely aFRR, mFRR and RR in Turbine mode.
- The demonstration campaign showcased the ability of the Advanced Joint Control to increase the global efficiency of the plant, by up to 2.9%, and drastically mitigate the damage on the runner.
- Thanks to extensive numerical simulations, model tests, and site tests the operating range extension was enabled. This means a complete operation from 0% to 100% of nominal load is accessible in turbine mode, with only some restrictions at speed no load in terms of number of hours per year. This means 0 MW to 520 MW at the disposable of the asset owner.
- Thanks to the implementation of HSC, the Alqueva PSP is now able to provide ancillary services to the grid while in pump mode.

Further information can be found in the following relevant readings:

“Alqueva final report of the demonstration”, EDP CNET, [13]	“SPPS Methodology”, EPFL, [10]	“Final consolidated report implementation of the demos”, EPFL, [6]	“Technical White Paper”, EPFL, [9]

Upgrade Strategy 4:

RETROFITTING REVERSIBLE PUMP-TURBINE UNITS WITH VARIABLE SPEED FSFC

Z’Mutt

Key objectives:

- Enable the provision of ancillary primary and secondary control (FCR, aFRR and mFRR) while the plant is operated in pump mode.
- Control and regulate the energy absorbed by the grid and pumped flow when the unit is operated in pump mode.
- Improve start and stop sequences in both turbine and in pump modes as well as fast tran-sition modes.
- Extend lifetime of critical hydraulic components.

Technologies implemented::

SPPS and FSFC variable speed.

BENEFITS:

Table 13: Impact measured against Flexibility KPIs – Upgrade Strategy 4

Case	Operating Range	Startup time	Ramp-up / Ramp-down	Turbine to pump / Pump to turbine	Maintenance intervals	Plant efficiency
Base Case (Pumping Mode)	Turbine: from 50% to 100% Pump:-100 % (No regulating range)	Turbine: 90s Pump: 180s	Turbine: 3.5%/s Pump: No regulation	T→P: 1800s P→T: 1500s	5000 h	T: 82.1%-88.0%
VS (FSFC)	Turbine: from 50% to 100% Pump: from -50% to-100%	Turbine: 15s Pump: 35s	Turbine: 7 %/s Pump: 7 %/s	T→P: 50s P→P: 50s	> 5000 h	T: 84.8%- 86.3%
SPPS + VS (FSFC)	Turbine: from 50% to 100% Pump: from -50% to-100%	Turbine: 25s Pump: 35s	Turbine: 7 %/s Pump: 7 %/s	T→P: 60s P→P: 60s	>> 5000 h	T: 84.8%- 86.3%

Table 14: Impact measured in terms of the provision of ancillary services - Upgrade Strategy 4

	Inertia		**Primary Control**		**Secondary Control**	**Tertiary Control**		**Voltage Control**	**Systems re-start**
	Synchronous Inertia	Synthetic Inertia	FFR	FCR	aFRR	mFRR	RR	Voltage Control	Black Start
Base Case (Pumping mode)	● / ●							● / ●	● / –
SPPS + HSC (Pumping mode)		🟢 / 🟢	– / 🟢	🟢 / 🟣	– / 🟢	– / 🟢	– / 🟢	🟣 / 🟣	🟣 / –
SPPS* + VS (FSFC)		🟢 / 🟢	– / 🟢	🟢 / 🟣	🟢 / 🟣	🟢 / 🟣	🟢 / 🟣	🟣 / 🟣	🟣 / –

Legend: Applicable mode

◓ Turbine
◒ Pump

Impact on provision of services

● Generic capability of HPP
🟢 Enables provision
🟣 Improves provision

*Based on the assumption that SPPS would be implemented together with an operating range extension. This was not the case in the Z’Mutt demonstrator.

Level of capital expenditure: The implementation of variable speed technology, in the FSFC option, is a quite substantial cost for the power electronics needed to decouple the frequency of the unit from the frequency of the power system. The Z'Mutt demonstrator is not subject to economic analysis; rather, it focused predominantly on the implementation process of a FSCF in reversible pump-turbine and the as-sociated technical improvements.

Demonstrator characteristics: The Z'Mutt PSP demonstrator is part of the Grande Dixence hydroelectric scheme located in Canton Valais, in Switzerland. Z'Mutt PSP feature 5 storage pumps with two 30 MW units (U1, U2), two 14 MW units (U3, U4) and unit U5 used to regulate the flow from the Z'Mutt basin to the Bodmen basin, connected to the Schali-Bis glacier and the Grande Dixence reservoir, see Figure 16.

This unit U5 has been the object of the variable speed conversion. It is a 5MW Francis type variable speed pump-turbine. The unit has been equipped with an asynchronous motor-generator, driven by a full-size frequency converter, FSFC.

Table 15: Characteristics of the unit 5 of Z'Mutt PSP

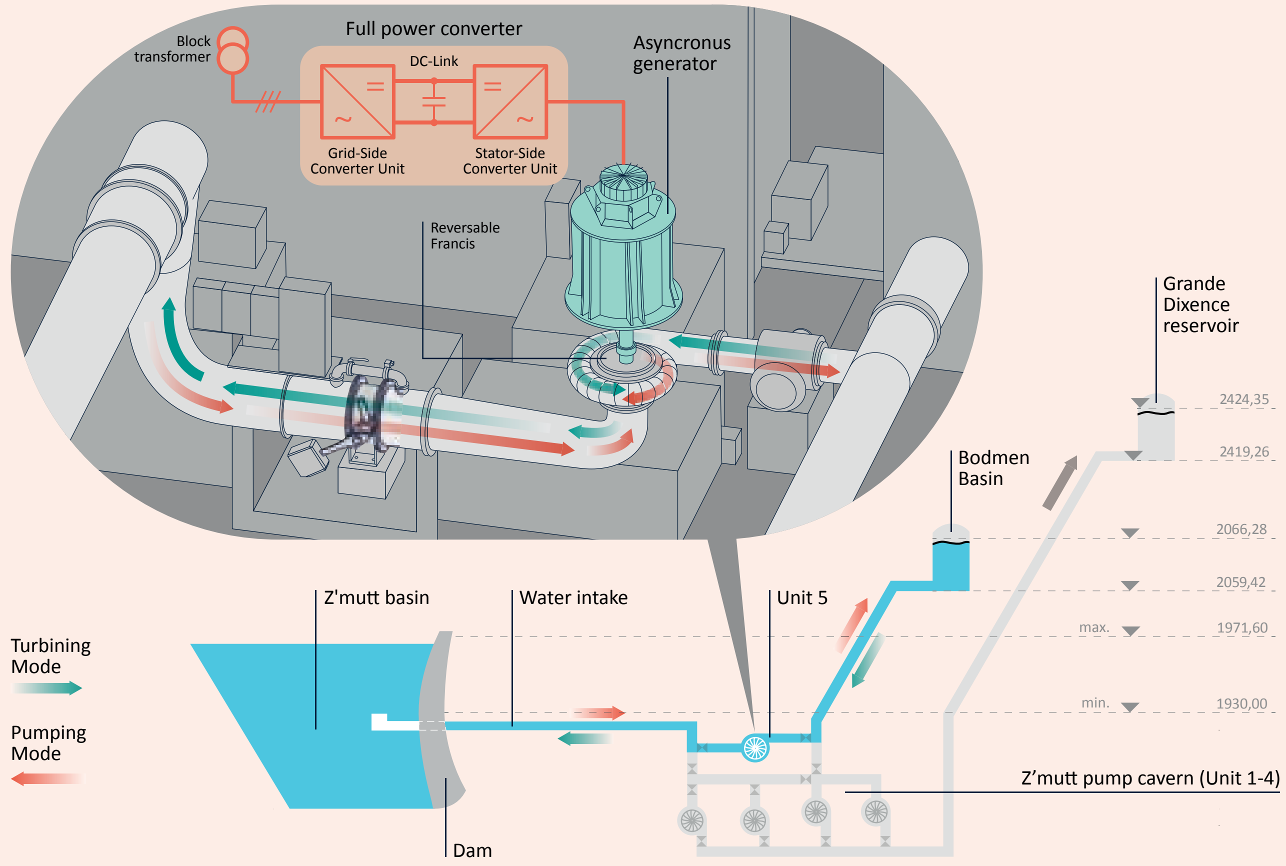
Type of units	Francis reversible pump-turbines with VS FSFC technology
Number of units	5 units, but these details refer only to U5.
Mechanical power	4.5 MW
Head	115 m

Rationale: The objective of the Upgrade Strategy 4 is to extend the operating range both in turbine and pump modes, the latter being particularly limited in the case of a fixed speed unit. The conversion from fixed speed to VS using a Full-Size Frequency Converter enable to extend the operating range as illustrated in Figure 17.

This enhanced regulation capability is particularly useful when the unit is pumping as it allows the operator to:

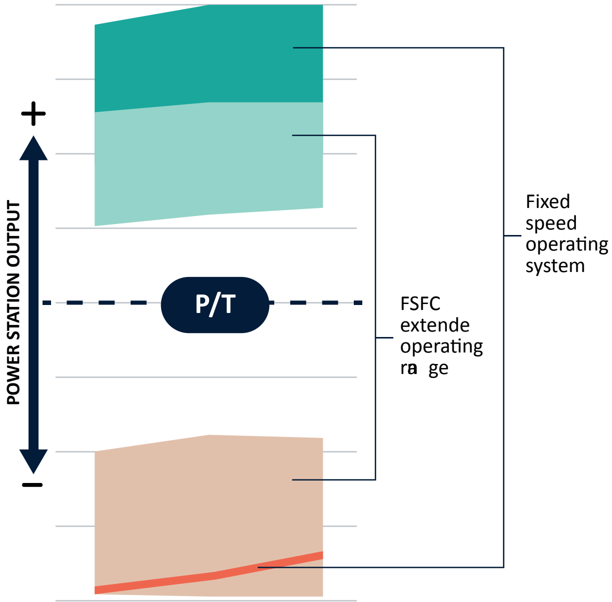
- control the power absorption from the grid and the flow of water pumped in the upper reservoir; and
- simultaneously provide ancillary services to the grid, potentially reducing the overall pumping costs.

Figure 16: Z'Mutt unit 5 - location and connections to reservoirs



Furthermore, the additional controllability of the unit unlocked by the FSCF technology allows for smoother operations of the unit and shortens the transition time between modes (from pump to turbine and turbine to pump), further increasing the responsiveness of the plant.

Figure 17: Pump turbine operating range extension; fixed speed vs full-sized frequency converter (FSFC)



The Role of Smart Power Plant Supervisor: The SPPS methodology applied in the Z'Mutt demonstrator through the development of a digital-twin based on Hydro-Clone. The digital-twin is based on real-time numerical simulation monitoring system, which enables continuous and detailed monitoring of unmeasured parameters, such as pressure throughout the water pipes, discharge, net head of the units, etc. The digitisation allows for efficient transient monitoring, offering valuable insights into the hydropower plant's performance. By providing a real-time comparison between simulated and measured quantities, the system significantly contrib-utes to the continuous assessment of the power plant's behaviour during commissioning and on-site demonstrations of the additional operational flexibility provided by the FSFC.

The digital-twin approach is key to enhance the system's diagnostic capabilities, allowing a more com-plete understanding of the plant's behaviour during commissioning.

Results:

- The provision of ancillary services for frequency control is now feasible in pump mode. In particular, the VS conversion using a FSFC enabled the provision of very fast frequency services such as FFR and FCR.
- The provision of FCR in turbine mode has also been improved. aFRR, mFRR and RR ancillary services have not increased by the use of the FSFC since the timeframe of the service is quite slow.
- FSFC enables soft start in pumping mode, avoiding severe mechanical and thermal loading of the unit, which drastically reduces maintenance and unplanned outage.
- The studies conducted indicated a damage reduction during the turbine start-up sequence of up to 9.9 times, thanks to variable speed operation with FSFC (meas-ured on the edge hub of the turbine which has been identified as a fatigue hot spot of the unit).
- Damage reduction is even more significant on the unit's penstock, where the ac-cumulated fatigue can be reduced by 50 times.
- Consequently, the number of start and stop cycles can be increased by up to one order to achieve enhanced grid regulation capacities without increasing impeller fatigue.
- Provision of Black Start service is significantly increased using the FSFC.
- The FSC enables a swift transition from turbine to pump mode, optimising opera-tional flexibility and responsiveness. A 70-second transition can be achieved with-out difficulty, and this could be further improved and optimise.

- The benefits of a variable speed technology with FSFC could be even greater but remain limited for the Z'Mutt demonstrator. Indeed, this demonstrator features a very low mechanical time constant which limits the provision capacity of ancillary services compared to units with higher mechanical time constant.
- Provision of Black Start service is significantly increased using the FSFC.
- The FSC enables a swift transition from turbine to pump mode, optimising operational flexibility and responsiveness. A 70-second transition can be achieved without difficulty, and this could be further improved and optimise.
- The benefits of a variable speed technology with FSFC could be even greater but remain limited for the Z'Mutt demonstrator. Indeed, this demonstrator features a very low mechanical time constant which limits the provision capacity of ancillary services compared to units with higher mechanical time constant.

Additional relevant readings:

"Z'Mutt final report of the demonstration", PVE, [14]	"Final consolidated report implementation of the demos", EPFL, [7]	"Technical White Paper", EPFL, [9]

Upgrade Strategy 5:

UPGRADE STRATEGY 5: IMPLEMENTING HYDRAULIC SHORT CIRCUIT IN A PUMPED-STORAGE PLANT EQUIPPED WITH VARIABLE SPEED DFIM

Frades 2

Key objectives:

- Extend power range through integration of hydraulic short circuit technology for variable speed machines and increase the potential of renewable dispatchable technologies.
- Enhance high-quality flexibility services of the electric power system by implementing syn-thetic inertia and frequency containment reserve.
- Improve the maintenance intervals and minimise outage times by optimising plant opera-tion, using smart controls and mode change procedures.
- Increase annual energy production by reducing auxiliary power load.

Applicable XFLEX HYDRO technologies:

SPPS, DFIM variable speed and HSC.

BENEFITS:

Table 16: Impact measured against Flexibility KPIs – Upgrade Strategy 4

Case	Operating Range	Startup time	Turbine to pump / pump to turbine transition	Maintenance intervals	Plant efficiency
Base case (Reversible pump-turbines + VS DFIM)	Turbine: from 47% to 100% Pump: from-100 % to –47%	Turbine: 60s Pump: 240s	T→P: 660s P→T: 180s	4000h	Turbine: Min=88%, Max=94% Pump: Min=93%, Max=94%
SPPS + VS (DFIM) + HSC	Turbine: from 0% to 25% & from 47% to 100% Pump: from-100 % to –77% & from-51% to 0%	Turbine: 45s Pump: 240s	T→P: 660s P→T: 60s	> 4000h	Turbine: Min=88%, Max=94% Pump: Min=93%, Max=94% HSC: Min=81%, Max=88%

Table 17: Impact measured in terms of the provision of ancillary services - Upgrade Strategy 4

	Inertia		**Primary Control**		**Secondary Control**	**Tertiary Control**		**Voltage Control**	**Systems re-start**
	Synchronous Inertia	Synthetic Inertia	FFR	FCR	aFRR	mFRR	RR	Voltage Control	Black Start
Base Case (VS DFIM)				⚪	⚪	⚪	⚪	⚪	⚪
SPPS + VS (DFIM) + HSC		🟣	🟣	🟣	🟣	🟣	🟣	🟣	🟣

Legend: Applicable mode   Impact on provision of services

Turbine   ⚪ Generic capability of HPP   🟢 Enables provision   🟣 Improves provision
Pump

*** The control system originally installed in Frades 2 is not predisposed for the provision of FFR and synthetic inertia.**

Level of capital investment:

SPPS: the 500 k€ ± 40% level of capital investment associated with the implementation of SPPS is relatively low, and mostly limited to the development costs of the optimisation algorithm, its implementation and the electronic required for the installation on site. All the existing components of the plants remain the same.

HSC: The 750 k€ ± 25% level of capital investment associated with necessary hardware is already available in the plant to operate in hydraulic short circuit mode. Capital costs are limited to the modelling and test-ing activities and the adaptation of the plant's control system.

Demonstrator characteristics: The Frades 2PSP demonstrator is a pumped storage power plant buil between 2010 and 2017 on the Rabagão river in the north of Portugal. The PSP features two high heads, variable speed units made of two reversible Francis pump-turbines, coupled with 420 MVA DFIM variable speed motor-generator which are currently the Europe's largest and most powerful machines. see Figure 18. The Frades 2 PSP characteristics are given in Table 18 .

Table 18: Frades 2 PSP Characteristics

Type of units	Francis type single stage reversible pump-turbines
Number of units	2 units
Mechanical power	Turbine mode: 190MW (min), 390MW (rated), 400MW (max) Pump mode:-300MW (min),-390 MW (max)
Head	Turbine: 413.6m (min); 426m (rated); 431.8m (max) Pump: 414m (rated)
Rotational speed	350 rpm (min); 381.2 rpm (max)

Rationale: The Frades 2 pump-storage plant, thanks to the reversible pump-turbine units equipped with variable speed technology, represents one of the most powerful, technologically advanced, and flexible plants in Europe.

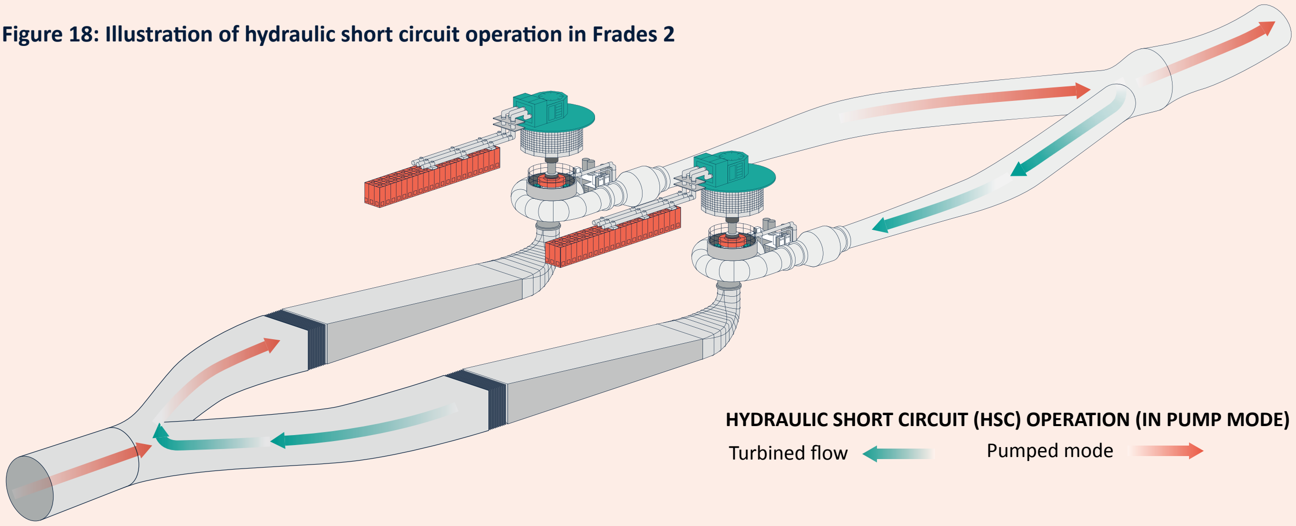
The DFIM technology enables the plant operators to optimise the pumping operations regulating the unit's speed according to the available head value, ensuring a highly efficient energy storage process. This also allows operators to control the power consumption during the pumping operating mode, therefore enabling the provision of an almost complete set of balancing services when the plant is storing electricity.

Nonetheless, a variable speed unit equipped with DFIM technology (see box in section 4.2.2 for additional information) has some limitations in terms of the range of regulation in pumping mode, which, in the case of Frades 2, is between -300 MW and-390 MW. A possible conversion to a FSCF variable speed would offer a significant improvement, further enhancing the regulating range available both in turbine and pump, but this would come at great cost and therefore, is not commercially viable.

The rationale behind this upgrade is to implement HSC operations to further expand the operating regime of the plant, particularly in pumping mode, beyond the current boundaries described above.

Furthermore, the overall operations of the plant can be further improved through the implementation of the SPPS methodology, allowing real time monitoring of the plant performances, reducing the maintenance intervals and minimising outage times, as illustrated in Figure 19.

Figure 18: Illustration of hydraulic short circuit operation in Frades 2



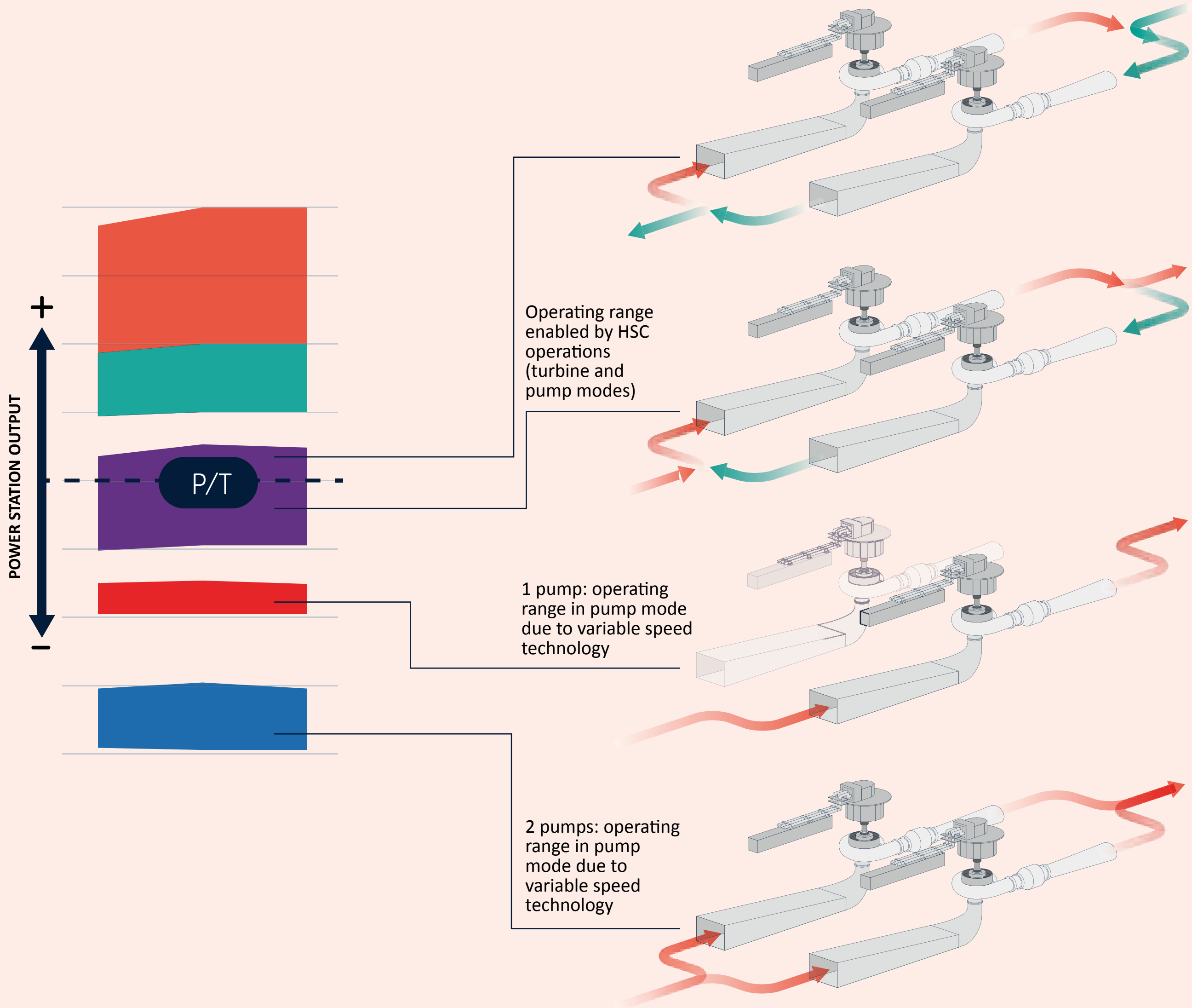
The role of Smart Power Plant Supervisor: The SPPS methodology applied to the Frades 2 PSP enables to compute and dispatch the plant active and reactive power set points between the two units, as well as the selection of the required operating mode of each unit.

For any given total plant output (or power take-up), the SPPS calculates the optimal active power set-points for the two power units in terms of efficiency and wear and tear and distributes these set points to the control system of each unit.

Furthermore, for any given plant reactive power, either capacitive or inductive operating point, the SPPS calculates the appropriate reactive power setpoints for the two power units in terms of the re-quired turbine or pump operation due to the active power requirements and the capability of the dou-ble fed induction machine (DFIM) and distributes these setpoints to the control system of each unit.

Before distributing the above setpoints, the SPPS triggers the necessary mode transition operations, i.e., stop, start turbine mode, start pump mode, start synchronous condenser mode, in the control system of each individual unit. The mode selection algorithm also contributes reducing wear and tear.

Figure 19: Illustration of the pumping mode operating range with units featur-ing DFIM variable speed with the range extension enabled by the HSC implementation.



Results:

- HSC has been successfully implemented in Frades 2.
- The study conducted by the consortium to highlight potential risks for civil and hydraulic components demonstrated that the power plant can be operated in HSC safely.
- The power range, both active and reactive, is extended by integrating hydraulic short circuit operation (HSC) for variable speed machines. This enhancement al-lows for greater adaptability to fluctuating grid conditions and demand variations. The additional active power range goes from-200 MW to 100 MW.
- Plant operation is improved with the introduction of Smart Power Plant Supervisor (SPPS). This technology maximizes efficiency and minimizes damage, leading to increased uptime and reduced maintenance requirements, ultimately resulting in longer outage intervals due to lower accumulated damage.
- Flexibility services to the power system are enhanced through the development and testing of Synthetic/Virtual Inertia (VI), Fast Frequency Response (FFR), and improved Frequency Containment Reserve (FCR). These advancements enable the plant to dynamically respond to grid fluctuations and optimize its contribution to grid stability.
- The overall plant efficiency is increased by reducing auxiliary power consumption. By optimizing energy usage and minimizing wastage, the plant achieves greater efficiency, thereby maximizing its economic and environmental performance.

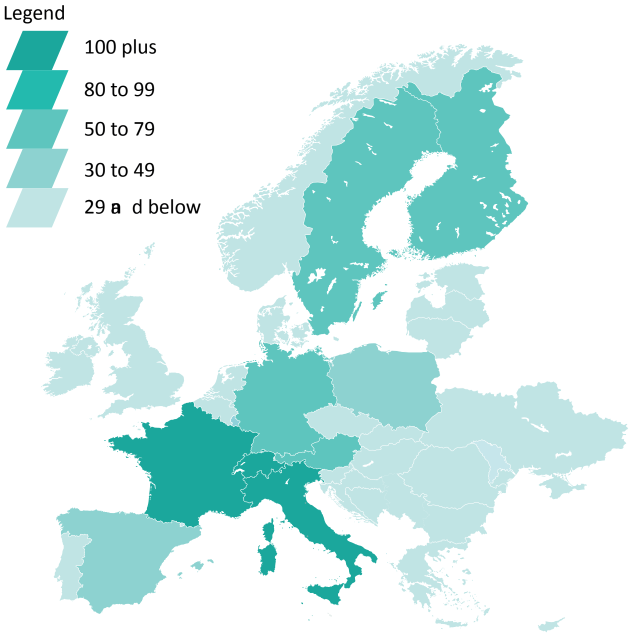
Further information can be found in the following relevant readings:

“Frade 2 final report of the demonstration”, EDP, [15]	“Final consolidated report implementation of the demos”, EPFL, [7]	“Technical White Paper”, EPFL, [9]

4.4.3. RUN OF RIVER PLANTS

Statistics about the run of river plants in Europe

Figure 20: Distribution of Run of River Hydropower Plants



- Indicative GW installed: 40 GW +
- Indicative number of plants: 700 +

Main characteristics of run of river plants

Run of river (RoR) hydropower plants are one of the most diffused assets in the European landscape. These are facilities built on, or in parallel to, a river, and channel the flowing water through a canal or penstock, which is then forced into a turbine. Typically, a RoR project has limited storage facility and has lower head than other types of hydropower plants, such as storage or pumped storage hydropower. On the other hand, they are often associated with a significant water flow and water level regulation.

Role of run of river plants

RoR plants are perfectly placed to provide a continuous supply of electricity (base load) injecting large amount of energy into the grid at a stable and controllable rate. On the other hand however, they are subject to the weather and water seasonality of the river to which they are connected. Because of this, RoR are in certain occasions regarded as intermittent sources of power, due to the limited water storage capacity. Furthermore, RoR are typically must-run-units, due to the limited water storage capacity. In terms of flexibility provision, RoR plants are great sources of system inertia and are also often used for the procurement of very fast power flexibility services, such as Frequency Containment Reserve (FCR, also known as primary frequency control) which require fast corrections to the power produced in a limited amount of time.

Main limitations

As previously mentioned, the utilisation of RoR plants can be relatively limited to the provision of short-term power flexibility services such as FCR (primary control), FFR (Fast frequency response). In the case of FCR, the provision of this type of ancillary service requires the plants to constantly adjust its operating point through a sequence of movements of some of the key mechanic and hydraulic components (such as guide vanes or runner blades in the case of Kaplan units). The mileage, i.e. the accumulated movements by these components and the repetitive change of direction of the movement, are some of the core issues reducing their expected life span, often forcing extra cycles of maintenance, increasing operating costs and reducing plant availability. These factors are not a limitation per se but represent a substantial economic burden for the plant owner, not to mention cost triggered by the provision of power flexibility to the grid.

Enhanced flexibility technologies applicable

The strategy adopted in the XFLEX HYDRO project to increase RoR power flexibility was:

- SPPS + Battery Energy Storage System (BESS)

Upgrade Strategy 6:

UPGRADE STRATEGY 6: ENHANCING FLEXIBILITY OF LOW HEAD KAPLAN UNITS WITH BATTERY HYBRIDISATION

Vogelgrün

Key objectives:

- Reduce wear and tear suffered by the turbines because of the provision of FCR.
- Improve the dynamic response of Kaplan units.

Applicable XFLEX HYDRO technologies:

SPPS + Battery Energy Storage System (BESS)

BENEFITS:

Table 19: Impact measured against flexibility KPIs – Upgrade Strategy 6

Case	Fast ramp-up and ramp down KPI	Maintenance
Base Case	300s	100,000h
VS (FSFC)	30 s*	+ 50% (for key mechanical components studied in the project) **

* With respect to the power response needed to provide FCR in accordance with the local definition.

**Specifically, this figure refers to the maintenance of the blade gasket, a critical component of the turbine heavily stressed by the continuous regulations.

Table 20: Impact measured in terms of the provision of ancillary services - Upgrade Strategy 6

	Inertia		Primary Control		Secondary Control	Tertiary Control		Other Services	
	Synchronous Inertia	Synthetic Inertia	FFR	FCR	aFRR	mFRR	RR	Voltage Control	Black Start
Base Case (RoR plant)	●			●				●	●
SPPS + BESS		🟢	🟢	🟣					

Legend: Applicable mode

Turbine

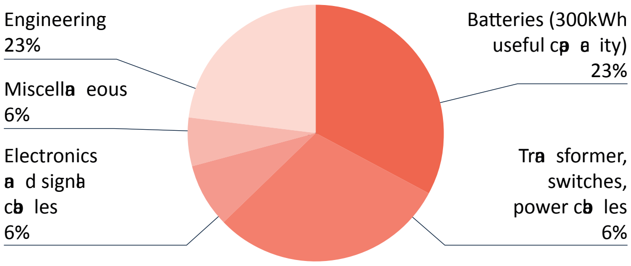
Pump

Impact on provision of services

● Generic capability of HPP 🟢 Enables provision 🟣 Improves provision

Level of capital investment: The 600 k€ ± 40% level of capital investment is associated with the implementation of the Vogelgrün SPPES and BESS hybridisation. The unit upgrade by this type of technology implementation does not require any modification to the hydraulic and mechanical components of the turbine or to the structure of the power plant. Most of the costs incurred are connected to the procurement and the installation of the battery storage system as well as the associated electrical and electronic equipment, such as transformers, switches, cabling, and the hybrid controller, see Figure 21.

Figure 21: Breakdown of capital investment required by the BESS hybridisation of Kaplan unit using the XFLEX HYDRO business model



*Miscellaneous includes items such as: fire protection, transportation, and lift crane.

Estimated additional operating costs: Operating costs' estimation is related to the objective. The point of the RoR battery hybridisation is to improve the provision of primary control services while reducing the wear and tear of key components of the turbine(s). The work carried out under the XFLEX HYDRO project demonstrated that the BESS hybridisation results in a positive effect on the maintenance cost. For in-stance, the life expectancy of the blade gasket, necessary component (for avoiding oil leakages in the river and often indicated as one of the main drivers for maintenance and down-time, estimated to be three times longer for a hybrid unit than in a similar non-hybrid unit; the risk of unexpected outages being substantially mitigated.

Economic analysis of the upgrade strategy: The project has demonstrated positive economic results over the life span of the BESS. The total costs savings and avoided losses achieved are well in excess of the initial capital investment.f revenue/ cost savings were identified.

The following four categories of revenue/cost savings are identified:

- the reduced maintenance costs, due to the unit reduced wear and tear;
- the additional energy production, due to reduced downtime for maintenance;
- the avoided potential losses due to improved turbine reliability; and
- the revenue generated by the BESS- hydraulic turbine hybrid unit providing primary control services.

In the case of Vogelgrün, the actualised sum of these four elements, in terms of Net Present Value, is estimated to be worth 3.3 M€ over a period of 12 years, corresponding to more than three times the Capex required by the BESS installation; the 12-year period being the expected life duration of the battery cells.

Demonstrator characteristics: The Vogelgrün RoR hydropower plant demonstrator is part of the Rhine River generating fleet owned by EDF. Commissioned in 1959, the infrastructure features 4 Kaplan units of 140 MW total capacity with an average annual 750 GWh generation. Furthermore, Vogelgrün RoR hydropower plant provides ancillary services to the grid as it contributes both inertia and FCR services.

Table 21: Characteristics of Vogelgrün RoR plant

Type of units	Kaplan turbine
Number of units	4 units
Mechanical power	4 x 35 MW
Head	9 m (min), 11.5 m (nom), 14 m (max)
Rotating speed	83 min^{-1}

Rationale and upgrade setup: The Vogelgrün RoR hydropower plant four identical Kaplan turbines, Kaplans are double regulated units with both guide vanes and movable runner blades. The provision of FCR requires the power generated by a turbine to be adjusted multiple times per minute. This is done by continuous repositioning of the guide vanes and runner blades which yields further wear and tear on components of both guide vanes and runner blades regulating mechanisms. Consequently, the useful life span is reduced, and extra cycles of maintenance are scheduled to replace worn out elements and to mitigate the mechanical failures' risk. The extra maintenance cycles are a noticeable cost for the operator over the life span of a unit.

Furthermore, the Rhine River is an important inland water navigation route. Therefore, any ancillary service provision must not introduce any water level perturbations.

The business case chosen to improve the situation is to introduce a BESS capable of supporting the Kaplan unit in the provision of FCR service, splitting the required power response between the BESS and the turbine. Small changes are shifted to the BESS, either charging or discharging, ensuring a smoother operation of the Kaplan turbine for most of the time. Hence, the motivation of the hybridisation is not to cover a specific share of the contracted FCR reserve in capacity (MW) terms, but to assist the unit in reducing the overall covered mileage and sign changes of the guide vanes and runner blades. The result of the upgrade is to lessen the wear and tear of the turbine mechanical components, to extend their life expectancy, reducing the unit downtime and maintenance cost and increasing the overall unit's availability and productivity.

Considering the need to serve additional reserve markets, e.g., automatic, or manual frequency restoration reserve, or enabling more flexible intraday energy market participation would have had resulted in a much larger BESS in terms of rating and storage capacity.

Inline with the upgrade Strategy 6, the objective is to minimise the size of the battery, a particularly expensive component, keeping untouched all the other elements of the existing unit. The parameters of the optimum battery size identified for the FCR provision with a hybrid unit are listed in Table 22.

Table 22: Summary of Vogelgrün unit's data and BESS

Unit power	35 MW
Battery power	0.65 MW
Battery capacity	0.3 MWh
Role	Support in the provision of FCR
Service characteristics	2.9 MW, in 30s for a grid frequency variation of 0.2Hz

The Role of Smart Power Plant Supervisor:

The SPPS methodology applied to the Vogelgrün RoR enables to control the interactions between the BESS and the turbine. The objective being to dampen the impact of abrupt changes in mechanical movements of the Kaplan unit key components, while ensuring the continued provision of the FCR service. This involved the development of algorithms, splitting the power set points between the BESS and the turbine and their evaluation compared to non-hybrid operation and the non-hybrid unit G3. In the initial phase, extensive studies are carried out to identify critical components, their current state of health and the relation between wear and FCR provision.

Results:

- Despite the small size of the BESS applied in Vogelgrün (1.9% of the turbine capacity), the amount of regulation carried out by the mechanical parts of the hybrid-unit on an annual level, associated with the provision of FCR, is re-duced by about 8 to 10 times.
- As a consequence, the turbine reliability was greatly increased and the expected time until end of life with critical components, such as the runner bearings, can be extended by of a factor of 3x, reducing the need for maintenance downtime and increasing the unit productivity.
- Great attention should be placed in the selection of the algorithm splitting the power set points to the BESS and the turbine, as this has a significant impact on the mileage reduction and life expectancy of the battery cells.
- Compared with the original configuration, the provision of FCR service of the hy-brid unit was not only made more efficient, but also improved in terms of dynam-ic response.
- Hybridisation of the Kaplan unit was proven more effective on older units rather than brand-new turbines and should be considered as an opportunity to extend the remaining life of aged units, especially after the first blade gasket overhaul.
- Even though FFR service is not currently regulated and remunerated in the Cen-tral European power system, the BESS hybrid has also enabled its provision.
- A larger BESS would also enable the provision of other types of balancing ser-vices, with longer duration, such asaFRRvand mFRR.

Additional relevant readings:

“Technical and economic benefits on hybridisation with battery storage”, ANDRITZ HYDRO, [16]

“Final consolidated report implementation of the demos”, EPFL, [7]

“Technical White Paper”, EPFL, [9]

4.5 ENVIRONMENTAL AND SOCIAL ASPECTS

4.5.1. GENERAL OBSERVATIONS

Retrofitting an existing hydropower station with new or additional equipment typically has lower environmental and social (E&S) impacts than a greenfield project. Also, enhancing flexibility can mean a change in the way an existing station is operated, rather than a major change in how it is equipped. In many cases, the changes may not be noticeable to external stakeholders. Some of the new equipment will be digital and compact, compared with the scale of electromechanical equipment, reflecting general trends in modern technologies.

Along with appropriate safety and impact assessment of equipment installation, some operator training will typically be required to ensure efficient and safe use of the new capabilities. Safety considerations need to include both occupational health and safety (OH&S), and public safety.

Additional flexibility is needed at different timescales and the investigation of E&S impact should take this into consideration. While the XFLEX HYDRO project focusses on very short duration services, flexibility requires balancing the grid level at all timescales:

- Seconds to minutes – the load and the supply of VREs fluctuate randomly; and there may be unplanned outages of other grid components.
- Hours to days – the load peaks at certain hours during the days and in the evenings; higher on weekdays than on weekends; the supply of VREs fluctuates (but more predictably than at shorter timescales); and grid component restoration after outages may take some time.
- Seasons – seasonal changes in load depend e.g. on cooling and heating demand; the supply of VREs fluctuates (quite predictably); grid components are taken off-line for scheduled maintenance.

For hydropower plants, flexibility requires adjusting the storage and generation to changing grid requirements. In turn, this implies changing water releases and changing levels (upstream and downstream). Hydropower operations thus affect the natural hydrology of rivers and other waterbodies. They may increase, decrease, or otherwise modify the underlying natural variability, which depends on the size and location of waterbodies, at the different timescales. Additional changes in the flow regime can affect several ecological, social and economic values which depend on water flows and levels.

Hydropower operations may increase variability (e.g. through daily peaking) or decrease variability (e.g. through seasonal storage). Changes can affect fisheries, erosion, public safety, navigation, recreation, irrigation, flood risks etc., either positively or negatively.

The XFLEX HYDRO project focusses on ancillary services provided by hydropower, such as primary frequency control (‘frequency containment’), secondary frequency control (‘spinning reserve’), tertiary frequency control (‘standing reserve’), voltage control and Black Start capability. The consequences for hydropower plants also include increased wear and fatigue of equipment, and efficiency losses during off-design operation. Generally, enhancing hydropower flexibility can be expected to modify short-term operations and, therefore, short-term effects on water levels and releases.

In general, rapid ramping up or down of generation would be expected to result in rapid short-term water fluctuations. However, the shorter these changes, the smaller are the water volumes involved. Very short-term changes will quickly dissipate, and levels of larger reservoirs are unlikely to be affected noticeably.

Depending on the scale and impact of technological changes at a hydropower station, it is conceivable that external stakeholders such as regulators, communities, grid operators or insurance companies may need to be informed or involved in the decision-making.

Because of the nature of the XFLEX HYDRO demonstration projects, no license modifications or major communication efforts were required. However, that may change if pilot technologies are scaled up and made permanent.

The following sections address each of the technologies being demonstrated by the XFLEX HYDRO project.

4.5.2 SMART POWER PLANT SUPERVISOR

The hardware for the SPPS systems is limited to digital equipment, sensors, processors, and monitors. Installation is not likely to present issues, but each specification will be unique in terms of the station. Operator training will be required to ensure efficient and safe use of the new capabilities.

The SPPS is expected to improve monitoring of machine conditions and scheduling of maintenance and operations, more agile performance (potentially pushing equipment closer to operational limits), fewer planned and unplanned shutdowns, as well as increased safety. With a better understanding of the health of key components in the station, it is possible that some environmental impacts might be avoided; for example, damage to seals may be foreseen and leakage of lubricant avoided.

4.5.3 VARIABLE-SPEED TECHNOLOGIES

In a variable-speed pump-turbine, magnetic fields are decoupled, and the unit is connected to the grid through power electronics. Variable speed allows a wider range of operations, quicker responses and transition times, higher efficiency, fewer starts and stops, and adjustable power consumption while pumping. No comment is made here in relation to the economic cost-benefit of this set of technologies.

Variable speed may have different effects on water levels and flows. On the one hand, there may be more (and more rapid) ramp-up/ramp-down changes, leading to more pronounced changes in flow. On the other hand, variable speed also allows more gradual operations, including soft start and soft stop options (reducing rates of change in flow).

Another effect of variable speed is that a higher efficiency can be reached even in the case of large head and discharge variations. Machines can be operated close to optimal efficiency, both in pumping and in generating mode. With higher efficiency, a reduced amount of energy can pump

the same amount of water, and the same amount of water can generate more energy: overall, less water needs to be extracted from rivers and reservoirs.

Two types of variable speed technology were involved in the XFLEX HYDRO project, ‘doubly fed induction machine (DFIM)’ and ‘full scale frequency converter’. Both may be preferable, from an E&S point of view to full start/stop operations that are required for fixed-speed pumps.

4.5.4 HYDRAULIC SHORT CIRCUIT

Hydraulic short circuit operations refer to one or several pump-turbines operated in pumping mode while one or more other units are in turbine mode. This can either be achieved though intermediate connections between waterways/penstocks (at least temporarily; water could be internally recycled and not actually reach the upper/lower reservoirs) or by a ‘long circuit’ version where independent waterways are used, so that water is withdrawn from and replenished into a reservoir at the same time.

In the ‘short circuit’ version, the most relevant E&S issues are related to the safe installation and operations of the plant, both in terms of OH&S as well as the possible hydraulic issues that could pose risks for equipment not designed for HSC operations. This needs to be studied and monitored closely, as was done in the case of the XFLEX HYDRO project.

In the ‘long circuit’ version, additionally there will be local impacts at water intakes and releases, in some cases including currents and turbulences. If HSC allows a plant to contribute more actively to grid stabilisation, there may be more start-stop cycles and more frequent flow and water level fluctuations. However, the advantage may be that there are fewer full drawdowns of the reservoir, i.e. fluctuations with a smaller range.

Because HSC allows more intermediate operating modes, the rate of water level changes may also be reduced, again with reduced environmental impacts.

4.5.5 BATTERY ENERGY STORAGE SYSTEM HYBRIDISATION

Depending on the battery capacity, a BESS system may only be able to provide the initial or fast frequency response and thus reduce the stress on the hydro turbine. Where a BESS is coupled with a hydroelectric power plant and takes over the fast frequency response, the initial rapid ramping up or down of the hydro turbine, and with it the rapid changes in water release, becomes unnecessary. However, the smaller the BESS, the shorter this effect. As described above, the water volumes involved may be so small to be hardly noticeable, particularly on larger waterbodies or where the regulated turbine makes up only a small part of the releases from a larger hydroelectric power plant. Even with a large design flow through a turbine, such as at Vogelgrün HPP where one turbine can release approximately 350 m^3/s, the effects of such a shortchange in releases, in the order of several seconds, would be hardly perceptible, neither upstream nor downstream. By reducing the number of start-stop cycles of a hydro turbine, a BESS may contribute to reducing some very localised impacts, such as turbulences and fish entrapment.

Larger battery systems can provide longer-duration storage and discharge. Large battery hybridised with hydro are already in operation in Sweden and Germany, but they feature a full transfer of frequency containment (FCR) to the BESS, where the Vogelgrün demo intends to show that a smart operation between hydro and BESS leads to smaller battery size (and investment and raw material), with avoided environmental impact.

4.5.6 CONCLUSIONS OF THE E&S ASSESSMENT

It is noted that the short-term nature of the ancillary services being enhanced by the XFLEX HYDRO technology will, intuitively, create a limiting factor on the extent of any socio-environmental impacts. However, impacts will be site-specific. For example, the size of the water bodies associated with the hydropower operations and the quantities of discharge associated with short-term services will combine to bring an impact, which may or may not be discernible.

In addition to water management aspects of the demonstration sites, installation and operational aspects were also considered, including OH&S

and public safety. No gaps in good practice were observed, especially noting that several of the interventions were either temporary or small in scale. Should the arrangements move towards being more long-term, larger in scale or permanent, additional training and communications measures would be needed, along with appropriate licencing/permitting.

Hydropower occupies a unique position from a flexibility supplier perspective as it can store primary energy (GWh) with high efficiency in 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 decentralised solutions, such as batteries, electric vehicles and demand response, are expected to provide short-term flexibility, but in a less predictable way.

Regarding climate mitigation, the carbon footprint associated with hydropower activities is related to any consumption it takes from the grid, plus that embedded in its construction materials and equipment, and that which is released through biogenic emissions following the creation of the water bodies. A study on one of the demonstrators, taking these three components into account, indicated a very low rate of carbon dioxide equivalent per unit of energy exchanged with the system. This is probably the lowest-carbon footprint that any technology is likely to achieve while delivering power and energy services to the system.

Given that emissions are effectively ‘spent’ prior to the provision of services, the higher the use of the asset, the more dilute the carbon footprint is. That is, the emissions have already been created within the electricity system prior to any consumption by the hydropower station, as well as embedded in the building of the powerplant and water bodies. Increasing the role of a hydropower station in delivering power and energy to the grid will further lower the rate of emissions per unit of service. Relevant avoided emissions include greenhouse gasses, acid gases and particulates.

Also, by improving the flexibility and range of services of existing assets will reduce the need for new solutions to be added to the system and consequently avoiding the socio-environmental impacts that these would bring.

Additional relevant readings:

“Summary report compiling results of the environmental and social impact assessments of the flexibility technologies at each demonstrator”, IHA, [16].

5

POLICY RECOMMENDATIONS TO ACHIEVE WIDER DEPLOYMENT

GENERAL

The XFLEX HYDRO Project demonstrates hydropower's potential to underpin the clean energy transition within Europe, driving the EU closer to its overarching goal of carbon neutrality. The set of enhanced flexibility technologies being demonstrated improves the capability of existing hydropower plants to deliver more flexibility services to the grid, enabling the maintenance of a stable and reliable power supply and reducing the need for fossil fuel-based backup.

Such flexibility improves grid stability as well as its restarting capability following a system fault – both pivotal elements to safely enable VRE integration in European power systems and ensure the security of electricity supply.

Balancing supply and demand fluctuations is at the core of electric power system (EPS) management. This challenge will be further amplified by the increasing share of VRE in the mix and the increasing electrification of energy services. The essential goals are to minimise disruptions in energy supply and enhance the overall resilience of power systems. Therefore, the integration of enhanced flexibility technologies in the existing hydropower fleet strategically aligns with the EU policy framework supporting its ambitious targets.

This section explores how these hydropower technologies fit into the current EU policy landscape and actively support long-term climate targets. Barriers and enablers to the implementation of these technologies are also reviewed and discussed. The section culminates in a set of policy recommendations, presenting some of the key priorities for future European policies and mechanisms to enable the hydropower sector to deliver its full flexibility potential, and thus underpin the energy transition.

5.1 EU POLICY LANDSCAPE

The introduction of enhanced flexibility technologies in HPPs is an important step towards maximising the flexibility potential of hydropower and offers a transformative opportunity to align with the ambitious targets set by the EU:

- Reduce greenhouse gas emissions by at least 55% by 2030 (compared with 1990 levels);
- Increase the share of renewable energy in total energy use to 42.5%, with the aspiration to reach 45%, by 2030; and
- Achieve a climate-neutral continent by 2050.

The modernisation-focused solutions demonstrated during the XFLEX HYDRO project lay a clear and crucial pathway towards realising these targets.

At the core of the EU's comprehensive energy policy landscape lies the **European Green Deal**. Established in 2019, the deal articulates the region's firm commitment to achieving climate neutrality by 2050 and the interim target of reducing greenhouse gas emissions by at least 55% by 2030. This framework not only underscores the urgency of addressing climate change but also maps out strategic pathways for action across various sectors, including energy. [17]

Aligned with the Green Deal's central objectives, several policies and initiatives have been set in motion, collectively propelling the EU towards a more sustainable energy future.

Following the exceptional rise in global energy prices since mid-2021, exacerbated by the conflict between Russia and Ukraine since February 2022, the energy crisis revealed some vulnerabilities in European electricity markets. These included: over-reliance on fossil fuel imported from Russia, combined with the dominant role that gas-fired power plants play in satisfying electricity demand, as well as their consequential price-setting nature in the electricity markets. This energy crisis brought the policy focus back to the security and affordability of electricity supply in the EU. In response to this, two new pieces of legislation were introduced: the **REPower EU plan** and the **Electricity Market Design reform**.

Launched in May 2022, the **REPower EU** plan emerged to further accelerate the deployment of renewables, reduce fossil fuel dependence, and tackle price volatility. Among the key actions introduced by this new policy was the mandating of dedicated 'go-to' areas for renewables, where there is a presumption in favour of development. Put in place by Member States, these areas should accelerate and simplify permitting processes for the deployment of new renewable energies in pre-identified locations with lower environmental risks. [20]

On the other hand, as part of the Clean Energy Package, the **Electricity Market Design** reform was prepared to reflect and respond to new market realities. The Electricity Market Design aims to integrate the increased share of renewable energy sources and new technologies in national electricity markets in a more flexible way, while not putting the security of supply and affordability at risk. A crucial aspect of the reform involves implementing measures to reduce market volatility and enhance long term price visibility for both consumers and producers. [21]

This initiative seeks to create a buffer between short-term markets and consumers' electricity bills by incentivising longer-term energy contracts. The reform recognises the role of the different market components and focused effort in the long-term instruments to complement the short-term market, namely by promoting the development of Power Purchase Agreements (PPAs), which are bilateral commercial agreements between industrial customers and generators, ensuring stable electricity supply and predictable pricing over an agreed-upon period.

Additionally, the reform promotes the use of two-way Contracts for Difference (CfDs), as an efficient mechanism to encourage investments in clean generation that the market alone is not able to deliver in such a short amount of time. This instrument does this by stabilising the market price seen by the generator while also reducing price volatility for the consumer.

National energy policies aimed at liberalising markets have also led energy trading to split

into forward, day-ahead, and intraday markets, which are differentiated to some extent in specific countries. These markets are based on time scales in relation to bidding processes, and the amount and duration of the energy provision.

The importance of these markets will be determined by the existing energy mix and the capacity of power generation within the market territory. A general trend is that day-ahead and intraday markets are becoming more important as technology drives towards real-time trading. Currently, the shortest intraday trading period within the European system is 15 minutes, although this is not the case throughout the region.

The growth of markets, from forward markets through to highly dynamic intraday trading, still leaves an important challenge for the balancing of the electricity system, as well as maintaining its stability. Various policies and associated regulations have sought to address these challenges. These build on national markets intended to stabilise the grid, particularly in the containment and restoration of grid frequency, but also on the principle of cross-border trading of such balancing services. At the European level, important regulations have determined the development of electricity balancing markets.

In 2009, **Regulation (EC) No 714/2009** set out rules for access to the network for cross-border exchanges in electricity and capacity allocation for interconnections and transmission systems affecting cross-border electricity flows. It notes the need for efficient balancing rules to provide incentives for market participants to contribute to solving system scarcities. [22]

In 2017, **Regulation (EU) 2017/1485** (2) set out harmonised rules on system operations applicable to transmission system operators ('TSOs'), regional security coordinators, distribution system operators ('DSOs') and significant grid users. It identifies different critical system states (normal, alert, emergency, blackout and restoration states). It also sets out requirements and principles to maintain operational security and aims to promote the coordination of these factors for load-frequency-control and reserves across the EU. [23]

This was followed by **Regulation (EU) 2017/2195** which established a guideline on electricity balancing. In summary, this establishes an EU-wide set of technical, operational and market rules to govern the functioning of electricity balancing markets. It sets out rules for the procurement of balancing capacity, the activation of balancing energy and the financial settlement of all parties responsible for maintaining this balance. It also requires the development of harmonised methodologies for the allocation of cross-zonal transmission capacity for balancing purposes. [24]

Such rules are intended to increase the liquidity of short-term markets by allowing for more cross-border trade and for a more efficient use of the existing grid for balancing energy. As balancing energy bids compete on EU-wide balancing platforms, this is intended to have positive effects on competition. At the same time, it commits that the development of the forward, day-ahead and intraday markets should not be compromised.

The regulation recognises the contributing role of demand response, including aggregation and energy storage facilities, as well as the need to facilitate the participation of new renewable energy sources. It seeks to apply the principle of "optimisation between the highest overall efficiency and lowest total costs for all parties involved, while ensuring that the procurement of balancing services is fair, objective, transparent and market-based, avoids undue barriers for new entrants, fosters the liquidity of balancing markets, while preventing undue distortions within the internal market in electricity".

The balancing platforms that are emerging include: [26]

- FCR Cooperation Platform for frequency containment reserve;
- PICASSO for automatic frequency restoration reserve (aFRR);
- MARI for manual frequency restoration reserve (mFRR); *and*
- TERRE for replacement reserve (RR)

FCR COOPERATION: The FCR Cooperation works currently with daily auctions with four-hour symmetric products. The auction takes place every day and applies for the next delivery day. The FCR Cooperation is organised under a TSO-TSO-model, where FCR is procured through a common merit order list, where all TSOs pool the offers they received. The interaction with Balancing Service Providers (BSPs) and the contracts between the TSOs and BSPs are handled on a national basis along with the responsibility of delivery.

PICASSO PLATFORM: The Platform for International Coordination of Automated Frequency Restoration and Stable System Operation (PICASSO) aims to: design, implement and operate an aFRR-Platform compliant with existing versions and regulations; enhancing economic and technical efficiency within the limits of system security as well as integrate the European aFRR markets while respecting the TSO-TSO model. The platform went live in 2022/23 with seven TSOs utilising it, and the majority of European TSOs committing to start in the near future.

MARI PLATFORM: The Manually Activated Reserves Initiative (MARI) is the project for the European platform for the exchange of balancing energy from frequency restoration reserves with manual activation (mFRR). Since 2023, six TSOs have been using the platform, and more TSOs are expected to access the platform in the course of 2024.

TERRE PLATFORM: The Trans European Replacement Reserves Exchange (TERRE) Platform enables the exchange and optimised activation of a standard product for balancing energy as defined in the Replacement Reserve Implementation Framework (RRIF), approved in 2019. This platform serves as the EU Target Model for the integration of the balancing markets. The TERRE Platform is based on the LIBRA IT system which supports the exchange of balancing energy by pooling the available balancing energy bids and providing an optimised allocation of the bids to meet TSOs' imbalance needs. It has been operational since January 2020. Since then, seven TSOs have been connected to the platform.

5.2 THE ROLE OF XFLEX HYDRO FLEXIBLE TECHNOLOGIES TO ACHIEVE THE EU LONG-TERM CLIMATE TARGETS

In the dynamic landscape of European energy policies aimed at delivering a carbon-neutral future, there is an urgent need for enhanced energy flexibility. The XFLEX HYDRO project is an example of innovation in this area. The initiative can play a pivotal role in shaping the future of the electricity market by highlighting the complementary relationship between hydro and other energy sources that overall secures a cleaner and more resilient energy ecosystem.

Other renewable sources, such as wind and solar, offer immense potential; however, their availability and output are fundamentally variable due to factors like weather conditions and daylight. This variability increases the risk of instability in the energy grid, which could lead to a mismatch of demand and supply, and consequent disruptions, such as blackout and load shedding.

In a system that may reach an extremely high level of penetration of VRE (see Figure 3 in Section 3), the power and energy flexibility of existing assets will need to be maximised soon to avoid disruption of supply which would come at great cost to society.

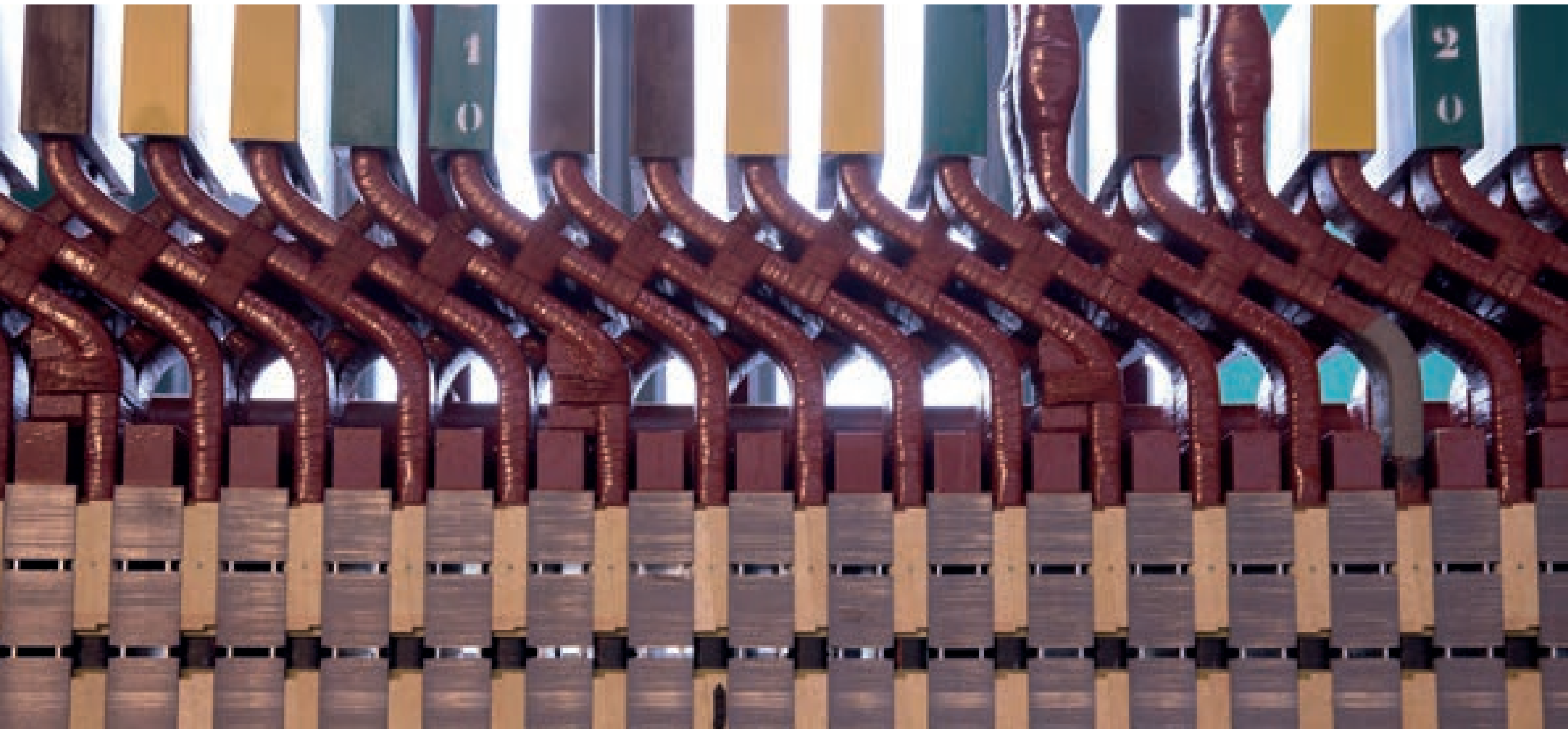
Hydropower is the only renewable technology providing flexible generation and storage on large scale. With its inherent ability to provide system inertia, hold reserve capacity, and rapidly adjust energy production, it provides a reliable means to respond to future flexibility demand, and should be seen as a strategic asset to enable a successful energy transition.

However, the provision of these services comes at a cost and takes a significant toll on the efficiency, operating costs and expected life span of some of the critical components of the plants. This is where the integration of enhanced flexibility technologies into hydropower plants becomes pivotal.

The XFLEX HYDRO project has demonstrated how this set of technologies is capable of both enhancing the capability of existing hydropower assets to provide grid stability services as well as to improve efficiency and reduce the damage caused by these operations.

This improved dynamic capability of existing hydropower plants provides multiple benefits to society and the whole European economy:

- It supports energy system stability and facilitates the integration of VRE into the mix. This reflects the European Union's commitment to modernise the energy grid.
- It strengthens the security of electricity supply, improving the stability of European power systems. This makes them more capable of overcoming accidents and reduces the risk of blackout and load shedding.



- It helps reduce the dependency on imported fossil fuels such as gas and coal, which are often kept operational for the provision of inertia and grid frequency control services.
- It provides the hydropower sector with the ability to navigate shifting market dynamics, positioning it as a resilient and cost-effective energy source and enhancing its competitive edge in the energy market.
- Through proactive participation across the various flexibility markets, it reduces the total grid management costs typically transferred to the final consumers, and the carbon footprint associated with the provision of these services.

This aligns perfectly with solving the energy trilemma, where the enhancement of flexible, affordable renewables and indigenous energy solutions contributes to a harmonious balance of affordability, security, and sustainability in the energy landscape. If the evolving energy policy framework is to support the transition effectively, precise objectives and strategies tailored to fostering flexible energy solutions must be included.

While hydropower will not be the only technology capable of providing power flexibility to the system, it represents a one stop solution covering the entire range of ancillary and storage services, which also provides the long-term energy flexibility needed to avoid the curtailment of wind and solar. This power flexibility contribution includes frequency control services but also physical inertia, voltage control and system Black Start which non-synchronous power sources, such as chemical batteries, are not in the position to supply.

Furthermore, the existing European fleet, which accounts for over 200 GW of installed capacity, represents an invaluable asset to support the evolving flexibility needs of electric power systems for several decades, without depending on non-renewable fuel sources or imported technologies with shorter lifetimes and supply chains primarily based outside of European borders.

The wide implementation of flexibility technologies within the European territory would also constitute a great opportunity to demonstrate the benefits associated with upgrading the capability of hydropower plants and strengthen the know-how of the local workforce. These are perfect ingredients to stimulate, export and reinforce the position of the European hydropower industry in the international markets.

5.3 BARRIERS AND ENABLERS

It is crucial to understand comprehensively the factors that could hinder or facilitate the enhancement of the flexibility provided by hydropower plants. Acting in a timely manner is essential to prepare the existing power fleet to respond to the flexibility demands of tomorrow.

This section presents a comprehensive analysis of nine critical barriers limiting the deployment of the flexibility technologies studied under the XFLEX HYDRO project.

Each barrier is defined and categorised under three macro categories:

- Market and Finance;
- Regulatory; and
- Technical.

To assess the magnitude of these barriers, a scale was employed to evaluate the impact of each barrier on the deployment of flexibility technologies. The analysis also extends to exploring enablers i.e., strategic factors supporting the mitigation or the elimination of these barriers.

The conclusions presented in this section are the results of a multifaceted methodology applied throughout the process, combining literature reviews, questionnaires, and interviews with industry specialists.

Figure 23 provides an overview of the impact levels of the barriers to the deployment of the four flexibility technologies studied within the XFLEX HYDRO project. The significance of these barriers varies across flexibility technologies, reflecting their diverse characteristics and distinct operational issues.

Variable Speed, being the most complex and capital-intensive, faces the most substantial overall obstacles. In contrast, the implementation of digital solutions, such as Smart Power Plant Supervisor, recognised for its relative simplicity, lower capital requirements and operating expense saving, is less impacted by the barriers identified.

One of the most significant barriers to the deployment of hydropower flexibility technologies is the uncertainty surrounding revenue streams. Existing electricity and ancillary services markets (whenever available), which are based on marginal pricing auctions, are designed to match real time demand with the cheapest available offer. Consequently, these markets excel in ensuring that the service required is provided at minimal short-term cost to consumers, but they are not capable of providing the long-term signals needed by plant owners and investors to justify investment in flexibility upgrades.

An additional challenge of the market-based approach is its compartmentalisation. This favours technologies that excel in the participation of one specific market but does not drive investment in technologies that can adequately provide the full range of flexibility that the system needs or may need in the future.

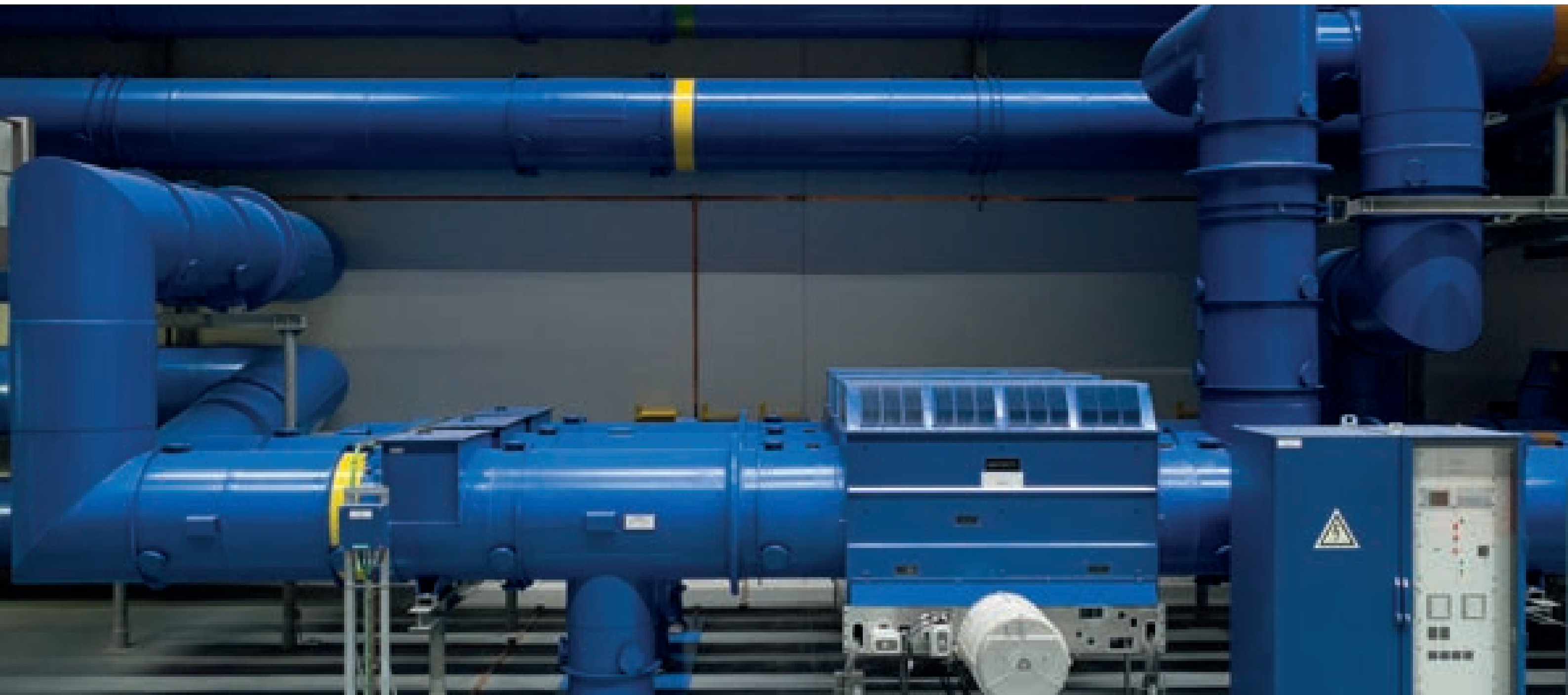
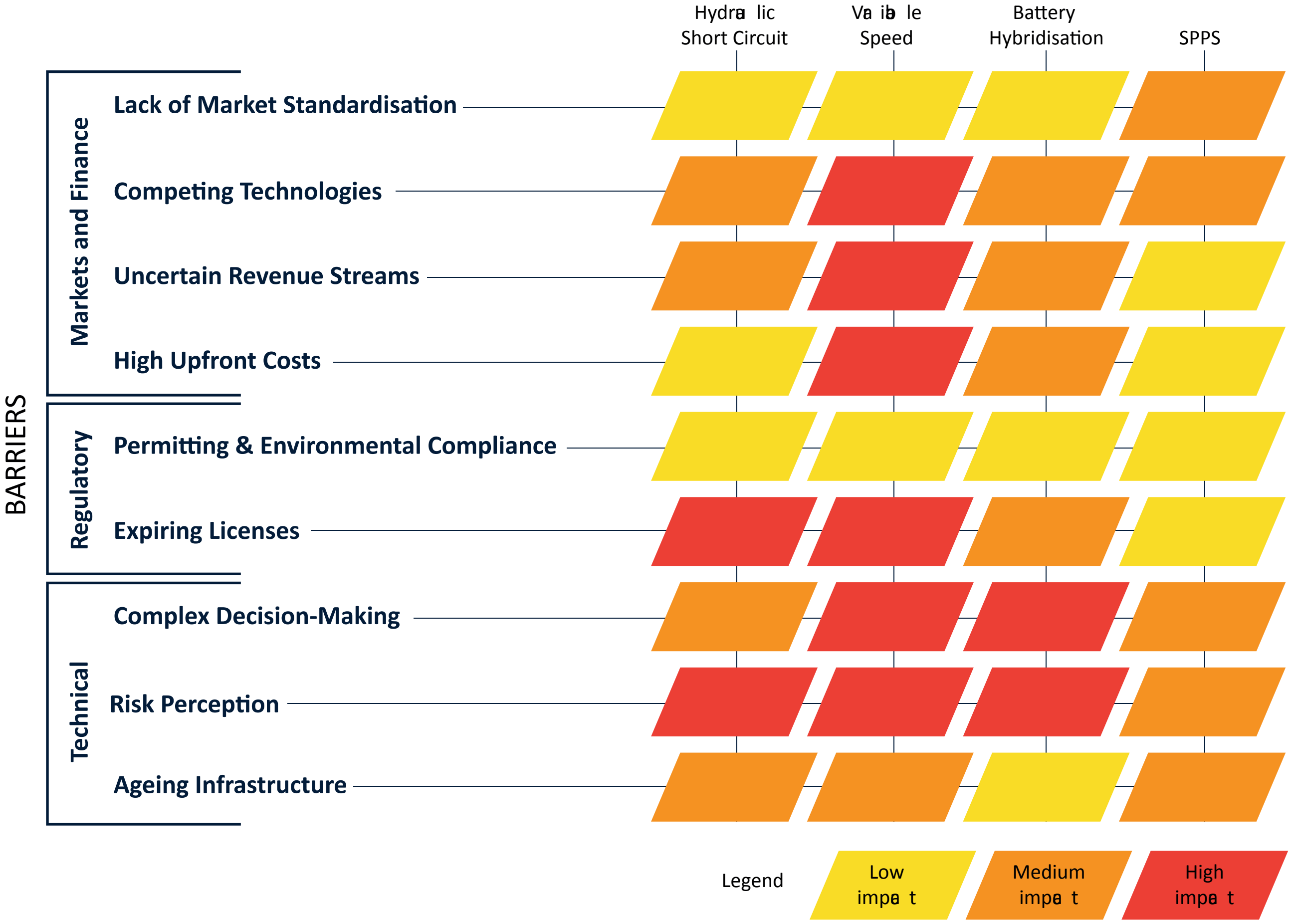


Table 22: Barriers to deployment of hydropower flexibility technologies

Markets and Finance	**Lack of Market Standardisation**	The energy landscape within the EU is characterised by non-homogenous market structures and regulatory frameworks among member countries. The absence of standardised practices and regulations across borders can complicate the implementation and the competitiveness of flexibility technologies. The increasing compartmentalisation of individual service markets may not foster the overall flexibility capabilities needed.
Markets and Finance	**Competing Technologies**	The emergence of alternative flexibility technologies, such as battery storage and demand-side response, not only creates competition but also introduces technological choices and considerations for investors and operators. While hydropower offers extended usage for the full spectrum of flexibility services, it faces challenges in terms of capital intensity, lengthy lead times, and environmental considerations.
Markets and Finance	**Uncertain Revenue Streams**	Uncertainty in market structure for flexibility services, high price volatility, and the lack of long-term pricing visibility, make it difficult for investors to predict returns on their hydropower flexibility investments, with the need to potentially extend the payback period. Owners and investors will be capable of justifying flexibility enhancing upgrades only if the markets where this flexibility will be traded exist, and if a minimum level of visibility of the associated revenue stream is ensured.
Markets and Finance	**High Upfront Costs**	The implementation of enhanced flexibility technologies may involve substantial upfront costs, encompassing preliminary studies, equipment procurement, infrastructure upgrades, and integration efforts.
Regulatory	**Permitting and Environmental Compliance**	The permitting process for retrofitting existing hydropower plants with flexibility technologies can be difficult and time-consuming, often requiring approvals from multiple authorities. Navigating environmental compliance for hydropower flexibility projects involves intricate considerations. This requires taking into account not only the immediate project site but also downstream and upstream effects.
Regulatory	**Expiring Licenses**	Hydropower projects often operate under licences granted for specific durations. These licences determine how long the plant can run and the conditions to meet. However, as licences approach their expiration dates, it introduces uncertainty regarding renewals and remuneration. These can impact operational plans and investments for modernisation as well as long-term strategies.
Technical	**Complex Decision-Making**	Hydropower plant operators must make complex decisions regarding which aspects of their facilities to enhance. This includes selecting the right flexibility technology and identifying the optimal market/s that the asset can profitably sell its services to.
Technical	**Risk Perception**	Hydropower plant operators may perceive the deployment of relatively new technologies as riskier compared to traditional operations. Deploying sophisticated flexibility solutions requires advanced skills, training, trust, and expertise. While the investment in these resources is valuable and can be compensated, there is a challenge in demonstrating this upfront.
Technical	**Aging Infrastructure**	Many existing hydropower plants have been operational for decades. Updating these facilities to incorporate modern flexibility technologies often requires upgrades of other key components of hydropower plants, which may be outdated or incapable of fully reaping the benefits of these new technologies.

Figure 23: Identified barriers and relative level of impact



BARRIERS		Hydraulic Short Circuit	Variable Speed	Battery Hybridisation	SPPS
Markets and Finance	Lack of Market Standardisation	🟨	🟨	🟨	🟧
	Competing Technologies	🟧	🟥	🟧	🟧
	Uncertain Revenue Streams	🟧	🟥	🟧	🟨
	High Upfront Costs	🟨	🟥	🟧	🟨
Regulatory	Permitting & Environmental Compliance	🟨	🟨	🟨	🟨
	Expiring Licenses	🟥	🟥	🟧	🟨
Technical	Complex Decision-Making	🟧	🟥	🟥	🟧
	Risk Perception	🟥	🟥	🟥	🟧
	Ageing Infrastructure	🟧	🟧	🟨	🟧

Legend: 🟨 Low impact 🟧 Medium impact 🟥 High impact

Furthermore, the challenge is often compounded by expiring licences, introducing regulatory uncertainty associated with renewals into assessments of long-term operational viability. This adds an element of risk as to whether (and under what conditions) the licences will be renewed, and the control of the asset retained. All of this, combined with the high upfront costs associated with some of the technologies, creates a seemingly high-risk environment for investors, reducing their confidence and willingness to allocate future funds to flexibility-enhancing upgrades for existing hydropower plants. As such, the need for careful and effective decision-making becomes paramount in navigating this complex landscape.

It is essential to explore strategic enablers that can mitigate these obstacles and foster a conducive environment for the successful deployment of flexibility technologies. The key enablers identified that can address these barriers and provide valuable insights for policy- and decision-makers are listed in Figure 24.

As further discussed in section 5.4, to address the market and finance barriers, a foundational step involves the establishment of a transparent and harmonised regulatory framework to strengthen long-term visibility and investor confidence. This should provide clear guidelines across diverse EU markets, fostering the seamless provision of flexibility services and removing limitations on portfolio optimisation and cross-border exchange of services.

In parallel, this should be complemented by the introduction of market mechanisms designed to recognise and secure the full range of power flexibility needed to navigate the energy transition. These market mechanisms should recognise the growing demand for flexibility and adequately value the provision of all services needed by the power system. Revenue visibility can be fostered using long-term capacity contracts focused on securing the provision of flexibility and stimulating the adoption of innovative technologies. These will be essential to create the necessary project bankability and make sure that the flexibility potential of existing and future assets will be maximised.

To effectively navigate the complex regulatory barriers, establishing well-defined contractual clauses and a structured concession award process is paramount to reinforcing investor confidence, offering a sense of security amid uncertainties tied to licence renewals and ownership transfers.

Simultaneously, the implementation of a streamlined permitting process for the modernisation of existing older plants has proven to be instrumental in providing solid business opportunities to exploit the flexibility potential of the existing European fleet and, at the same time, secure their contribution to the energy mix for the following decades.

To address technical barriers, the implementation of training programmes, knowledge-sharing platforms, and access to market-specific expertise should collectively equip stakeholders with the essential skills required to successfully deploy advanced flexibility solutions. This comprehensive approach aims to foster a knowledgeable and skilled workforce capable of not only embracing but also effectively navigating the complexities associated with rapid technological advancements.

To overcome all these obstacles, a holistic strategy is essential. Large-scale demonstration of these technologies becomes imperative, not only for studying flexibility improvements and for assessing the value they bring to the energy landscape, but also to lay the groundwork to help utility companies in making well-informed and timely investment decisions.

Figure 24: Identified barriers and enablers

Macro category	Barrier	Enabler
Markets and Finance	**Lack of Market Standardisation**	• Transparent and harmonised regulatory framework enabling flexibility portfolio optimisation • Facilitation of cross-border exchange of flexibility services • Flexibility market mechanisms capable of recognising the value of indigenous flexibility provision providing long-term revenue visibility • Development of in-depth comparative analysis of technologies across the full range of flexibility services • Holistic evaluation of flexibility technologies which goes beyond market factors • Support funds dedicated to enhancing power systems flexibility
	Competing Technologies	
	Uncertain Revenue Streams	
	High Upfront Costs	
Regulatory	**Permitting & Environmental Compliance**	• Lean licensing renewal process and contractual compensation clauses for non-renewal or ownership transfer • Concession extension award processes for asset modernisation • Streamlined permitting for retrofitting existing plant • Integration of environmental strategies into upgrade plans
	Expiring Licenses	
	Complex Decision-Making	
Technical	**Risk Perception**	• Platforms for skill enhancement and knowledge sharing • Training programmes for deployment risk analysis and mitigation • Accessible open-source data on flexibility technologies • Financial instruments incentivising plant modernisation • Consider mid-life renewals as opportunities for technology integration
	Ageing Infrastructure	

5.4 POLICY RECOMMENDATIONS

GENERAL

While XFLEX HYDRO has tested and put into practice these innovative technologies, it is essential to formulate robust policy recommendations. These policies play a pivotal role in fostering innovation, incentivising investments in hydropower flexibility and securing the availability of the power flexibility that is, and will be, needed to achieve a successful energy transition.

Policies that ensure the dynamic and harmonious evolution of the sector are required, steering the hydropower industry toward resilience and adaptability, and ensuring that the modern workforce remains well-prepared in the face of an evolving technological landscape.

The following recommendations lay out the key areas that governments and regulatory bodies should consider to support the full utilisation of the European hydropower flexibility potential.

1. RECOGNISE AND VALUE HYDRO FLEXIBILITY AS AN ESSENTIAL SERVICE TO THE POWER SYSTEM TO ACHIEVE A SUCCESSFUL ENERGY TRANSITION

As the provision of power flexibility becomes increasingly scarce due to the transition away from conventional energy sources, recognising and valuing the growing necessity for power flexibility services such as inertia, frequency control, voltage management, and black-start capability is crucial to ensure grid stability and security over the next decades. Hydropower is very important in that it has the potential to provide all the flexibility and storage services to meet the system needs.

As of today, the flexibility market landscape is heavily fragmented, with noticeable differences among European countries. Often, these services are poorly remunerated or not paid for at all and, in some cases, they also limit the aggregation of flexible resources, preventing portfolio optimisation.

The creation of larger and more integrated European electric power systems is helping in the provision of affordable options for the various types of flexibility required for the integration of VREs. Nonetheless, it is important to determine what are the balancing capabilities of existing infrastructure and their limitations. Long-term strategic planning designed to secure the timely provision of the flexibility needed over the next decades is essential.

Only the combination of efficient, clean sources and dispatch procedures with well-timed investments to enhance the existing infrastructure will ensure system cost minimisation and foster security of supply.

2. REMOVE REGULATORY BARRIERS FOR UNRESTRICTED IMPLEMENTATION AND OPERATION OF HYDRO FLEXIBILITY TECHNOLOGIES

To unlock the full potential of existing hydro assets and introduce new technologies, it is essential to eliminate regulatory barriers that hinder implementation and operation of flexibility upgrades or that create discrepancy in the procurement process of flexibility services. For instance, in certain European countries, operators are not allowed to implement HSC operations.

Defining, implementing, and enforcing standardised grid stability services among the various European TSOs will help plant owners and operators understand the services that are required. This will also help assess the necessary technical capabilities of the asset and facilitate the choice of the most applicable flexibility enhancing technologies for the case at hand.

3. Provide Remuneration Mechanisms Enabling Investment in Flexibility

Existing electricity and ancillary services markets (when available) are designed to match real time demand with the cheapest available offer, and they excel in ensuring that the service required is provided at minimal cost to consumers. These should cover the associated operational costs but are unlikely to provide the long-term revenue visibility required to justify new investment in flexibility technology upgrades.

Remuneration mechanisms capable of providing the required stability of revenue for provision of flexibility services to the grid are crucial, like capacity markets or long-term flexibility contracts. This will enable plant owners to proactively identify, economically justify and implement flexibility upgrade opportunities.

4. FACILITATE CROSS-BORDER COLLABORATION FOR EFFICIENT EXCHANGE OF FLEXIBILITY SERVICES

Encouraging international collaboration among European countries is essential for the efficient exchange of hydro flexibility services and expertise. By fostering cross-border connections, countries can share resources and expertise, optimising the utilisation of hydro flexibility on a broader scale. This collaboration enhances grid stability, reduces dependency on individual markets, and creates a more interconnected and resilient energy infrastructure. The development of existing platforms for the exchange of grid frequency services, such as PICASSO, MARI or FCR Cooperation, should be encouraged and accelerated.

5. STREAMLINE LICENSING RENEWALS FOR OPTIMISED HYDROPOWER OPERATIONS

Simplifying the licensing process, removing obstacles, and accelerating permitting procedures are vital for the operational stability of hydropower projects. This not only reduces uncertainties linked to licence renewals and ownership transfers but also provides a clear and predictable framework in which power companies can operate.

Operational longevity is consequently ensured, fostering an environment that encourages investment and innovation. Offering guarantees for

pay-back periods that go beyond the asset's current licencing period might enable the best investment decisions from the system perspective. Empowered operators can confidently strategies for upgrades, improvements, and future expansions, free from unnecessary administrative hurdles.

6. CONDUCT SYSTEM-LEVEL ANALYSIS TO ANTICIPATE AND ADDRESS FUTURE FLEXIBILITY NEEDS

To effectively address future challenges and make sure that EPS can deliver a safe energy transition, a system-level analysis is crucial. This can provide the long-term vision needed to identify and prepare for future flexibility challenges in the most technically efficient, secure and cost-effective way.

By understanding how flexibility requirements will evolve over time and which service(s) will be needed to support a successful energy transition, regulators and industry stakeholders can make better informed decisions today and ensure that the hydropower sector will remain adaptive and resilient in the face of the evolving energy landscape.

7. PROMOTE SUPPORT MECHANISMS FOR THE MODERNISATION OF AGEING HYDROPOWER INFRASTRUCTURE

Over 70% of the European hydropower fleet is at least 30 years old. This means that numerous hydropower plants are today running outdated technologies. Financial or tax mechanisms that support the modernisation of ageing infrastructure are essential to secure and enhance the benefits currently provided to society by these plants.

These mechanisms should be focused on rewarding modernisation projects that are introducing cutting edge technologies and leading in the adoption of cleaner and more flexible energy solutions. Operators should be incentivised to see this process as an opportunity to rethink the capability of existing assets to provide improved flexibility services to the grid. The flexibility key performance indicators (KPIs) defined by the XFLEX HYDRO project will provide important guidance in this respect (see section 3.3).

6

RESEARCH AND INNOVATION NEEDS

6.1 INTRODUCTION

To achieve a successful energy transition, it will be fundamental to fully assess and identify both the existing and the dormant flexibility potential of existing assets, study the eventual environmental and social consequences associated with the flexibility operations and identify the best business models and policies needed to see this potential exploited. XFLEX HYDRO has moved the sector forward on all these crucial aspects, generating a great wealth of knowledge which is now available to the entire sector.

For the first time, the flexibility of hydropower plants has been measured though a set of quantitative and qualitative KPIs which can be universally applied to any type of hydropower asset. These Flexibility KPIs should be regarded as a decisional tool to assess and compare the flexibility provision of different plants or describe the impacts on the flexibility enhancements of potential modernisation projects.

From a technological and operational perspective, the project has provided a great contribution in both understanding the flexibility capability of hydropower plants and identify the benefits associated with the implementation of innovative hydropower flexibility technologies. This included the creation of guidelines for the sector on how to compare these solutions, select the most appropriate, and safely and successfully implement them [9].

Through the insights gained from measurements and simulations, the project introduced optimised controlled methodologies and advanced the digital twin concept which enables a multi-functional and real-timed optimisation of power plant’s operations and improved water resources management. Additionally, the progress in the lifetime analysis of hydraulic components under various operating modes and conditions adds depth to the project's technological advancements, signalling the readiness of these flexibility-enhancing technologies for the wider deployment in service.

This comprehensive examination addressed not only the technical aspects but also the economic dimensions of integrating flexibility-enhancing technologies into hydropower operations. Indeed, also the revenues unlocked by several flexibility upgrade strategies and their associated costs were evaluated to fully understand the opportunities for supplying ancillary services to both existing and anticipated markets.

The environmental and social implications associated with flexibility operations were reviewed, demonstrating that these activities, including health and safety considerations, can be conducted with limited environmental and social effects.

By actively showcasing the adaptability of hydropower plants, the project challenged traditional perceptions of hydropower as a rigid baseload service, positioning it as a dynamic resource responsive to evolving energy needs. This paradigm shift not only enhances sector credibility but also fosters collaboration, advancing the role of hydropower today and highlighting its significance in shaping a flexible and sustainable energy future.

This section provides a list of suggestions on topics that should be further investigated in order to secure and optimise the contribution of hydropower flexibility in the future electric power systems. To facilitate their identification, these topics have been divided into four macro categories: technologies and plant operations; flexibility potential and system level planning; markets, revenue and profitability; and environmental and social aspects.

6.2 HYDROPOWER FLEXIBILITY TECHNOLOGIES AND PLANT OPERATIONS

1. LONG-TERM EFFECTS OF FLEXIBLE OPERATIONS ON KEY COMPONENTS OF THE UNITS:

The provision of frequency regulating services and participation in short-timed energy markets require plant operators to continuously correct the power produced by the units. This practice accelerates the wear and tear process experienced by the plant, shortening the lifespan of turbines, valves, penstock and electromechanical equipment. Transient and off-design operations should be further investigated both through numerical simulations, laboratory, and prototype level testing. Similarly, additional understanding and forecasting capabilities of the aging process of key components should be seen as a priority.

These, combined with advanced monitoring and detection solutions, will help owners and operators to achieve a better trade-off between damages accumulated and financial implications resulting from the participation in flexibility markets.

2. DEVELOPMENT OF TOOLS AND SOLUTIONS FOR THE OPTIMISATION OF PLANTS AND BASINS OPERATIONS:

Through the development of the SPPS methodology, the XFLEX HYDRO project has demonstrated how the integration of innovative flexibility technologies can be successfully combined with the optimisation of a plant's operations. Going further, the development of this optimisation process should also include additional parameters covering the entire chain; from the water availability to the electricity markets, including downstream modelling for discharge fluctuations.

Furthermore, the development of digital basin twins can improve the understanding and the visibility on key hydrological aspects such as water availability, impact of extreme events as well as sediment management and habitat protection. All these then can and should become criteria to be considered in the optimisation process of the plant operations.

3. IMPROVED KNOW-HOW ON HYDROPOWER PLANT MODELLING AND SIMULATION TOOLS:

The project has strengthened and validated existing plant modelling and numerical simulation tools which have been applied in conjunction with model and prototype testing. The continuous and progressing improvements of these tools will further reduce development costs and help increase the commercial development of flexibility technologies in the European hydropower fleet.

Research projects should therefore be focused not only on improving the final technologies, but also on the data acquisition, tools and the software used in the development process.

4. ADDITIONAL APPLICATIONS OF THE FLEXIBILITY TECHNOLOGIES STUDIED BY XFLEX HYDRO:

The consortium has demonstrated the applicability and the benefits deriving from the implementation of a range of flexibility technologies. These include: SPPS, hydraulic short circuit, variable speed, and chemical battery energy storage hybrid. Nonetheless, additional applications of these technologies and their associated business cases should be identified and investigated.

For instance, the study on BESS hybrid was only investigated on a RoR plant and could be expanded to other type of power plants, such as pumped storage or reservoir storage, to enhance dynamic response, improve the start and stop sequence, and possibly extend the operating life of the hydraulic units. Additionally, other types of hybrid storage technologies, such as hydrogen, should be considered and explored.

Studies on the extension of the operating range and the implementation of hydraulic short circuits should be conducted on additional types of machines and power plant configurations to assure their full scalability to the entire European fleet.

6.3 HYDROPOWER FLEXIBILITY POTENTIAL AND SYSTEM LEVEL PLANNING

1. QUANTIFICATION OF THE HYDROPOWER FLEXIBILITY POTENTIAL AT THE EUROPEAN SCALE:

Among the results obtained by the XFLEX HYDRO projects, there is a stronger understanding of the flexibility potential that various types of existing hydropower plants can provide to the grid, together with a structured approach on how this can be measured and quantified. Building on these findings, it is now crucial to extend the analysis at a system level, quantifying the overall power and energy flexibility that can be provided by the existing hydropower fleet.

Possible studies should also consider the opportunity associated with plant modernisation, pumped storage conversion, reservoir expansion and powering of existing non electrified dams. These will all contribute to strengthen the European power sector and support the upcoming energy transition.

2. DEVELOPMENT OF SYSTEM LEVEL ANALYSIS TO DETERMINE THE MOST EFFECTIVE FLEXIBILITY SOLUTIONS:

Securing the provision of flexibility on the long-term is a crucial step to strengthen the European security of supply and enable a successful electrification of the economies. System level studies should focus on comparing the most sustainable and cost-effective solution for the provision of flexibility over the next decades. This study should cover the entire supply chain of the various technologies available, comparing them under the lens of security of supply, affordability and sustainability.

6.4 MARKETS, REVENUE AND PROFITABILITY

1. ANALYSIS OF THE EVOLUTION OF THE FLEXIBILITY DEMAND:

The identification of the characteristics and the quantification of the flexibility that will be needed by the electric power systems over the next decades to achieve a net-zero economy is a fundamental step to secure a successful energy transition. This will enable regulators and policy makers to identify possible gaps in the capabilities of the existing fleet and the type of markets needed to source the provisions of the flexibility requested by system. This will also help technology providers and plant owners to develop and select the appropriate set of flexibility enhancing technologies.

The consortium has carried out extensive work on forecasting the evolution of the demand and the prices on several flexibility markets [REF]. Nonetheless, it is unproven whether the definitions and weights of these markets will remain relevant and unchanged over the next decades. For instance, additional new markets may be introduced, such as inertia or FFR, or some existing markets may lose interest over time.

For example, the progressive deployment of zero-marginal cost technologies, such as wind and solar, will further increase the amount of hours per day where spot market prices will be close to zero €/MWh and the progressive shift of spot markets toward shorter time frames (closer to 15 minutes). These will cause a possible overlapping and reduction of demand for some existing ancillary services, like for instance aFRR and mFRR.

The combination of all these factors should therefore be taken into consideration in dedicated system level studies, designed to not only identifying how decarbonised power systems should be structured, but also how they should be operated, managed, and controlled.

2. IDENTIFICATION OF CLEAR AND ACCESSIBLE FLEXIBILITY MARKET FRAMEWORKS:

This fast-evolving energy landscape and the complex regulatory landscapes poses substantial challenges to energy companies and finance institutions when it comes to identifying and forecasting the revenue streams associated with the provision of flexibility.

Research should not only focus on assessing the flexibility needed by the system over the next decades, but also on the identification and the design of appropriate market mechanisms, capable of securing the provision the full range of this flexibility in the long-term. Improved, more transparent market structures will incentivise the necessary flexibility investment and the deployment of innovative technologies in a timely manner.

3. EXPLORING THE REVENUE GENERATION POTENTIAL OF HYDROPOWER FLEXIBILITY TECHNOLOGIES UNDER DIFFERENT MARKETS:

The identification of bankable business cases for the deployment of hydropower flexibility technologies requires the identification of the most advantageous markets to monetise the enhanced potential.

The project has extensively reviewed the profitability of the technologies studied in several existing ancillary service markets. Additional studies should be conducted to explore opportunities to generate additional revenue. From the enhanced capabilities to operate in shorter energy markets such the 15-minute spot markets, to the provision of services that may not be regularly activated or yet compensated, such as Black Start or inertia, there is a wealth of potential to be opened and explored.

6.5 ENVIRONMENTAL AND SOCIAL ASPECTS

1. THE CARBON FOOTPRINT OF HYDROPOWER FLEXIBILITY:

XFLEX HYDRO has looked at the CO2 emissions associated with the provision of flexibility from hydropower plants through the study conducted on the Grand'Maison pumped storage plant. The carbon footprint associated with flexibility provision from existing hydropower plants and innovative flexibility technologies should be further investigated and compared against alternative storage and dispatchable technologies (such as chemical batteries, gas and coal) over their entire life cycle. This is needed to support a well-informed system level planning.

2. FLEXIBILITY OPERATIONS, WATER MANAGEMENT AND CLIMATE RESILIENCE:

The impact of flexibility operations on upstream and downstream water bodies and habitats should be further monitored and investigated with a particular focus on rapid change of operating regime and the associated water discharge. Enhanced data collection, monitoring and forecasting tools, focusing on the relationship between balancing services and water management, should be integrated in the optimisation process of hydropower plants' operations. These should also take into consideration all the aspects associated with sediment transportation, fish passage, habitat protection and other water uses.

Additionally, the impact of extreme events, such as flooding, draught or dunkelflaute[5], on the provision of flexibility from hydropower assets should be considered both at the plant and at system levels. The development and use of predictive tools for forecasting extreme hydrological events will help protect both the assets and the surrounding habitats, communities and infrastructures, while securing the provision of the balancing services required by the grid.

3. IMPACT OF FLEXIBILITY OPERATIONS ON THE MULTI-SERVICES PROVIDED BY POWER PLANTS AND SOCIAL COMMUNITIES:

Hydropower assets are often providers of a variety of services to the surrounding communities. These include water management for recreation activities, navigation, irrgation, and general consumption.

The consequences associated with the enhancement of flexibility provision from existing assets should be further studied and monitored, with strategies to engage with local stakeholders tested and standardised. This study should also identify equitable benefit-sharing mechanisms for communities affected by hydropower flexibility operations.

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5. Dunkelflauten is a period, often longer than one day, in which little or no energy can be generated with wind and solar power. In meteorology, this is known as anticyclonic gloom. In north of Europe this can happen from 2 to 10 dunkelflaute events per year. [27]

7

FINDING THE PATH FORWARD

7.1 THE OVERARCHING OBJECTIVE

An indication of what type of flexibility will be needed by the future EPS, depending on the level of deployment of VRE, can be obtained from the six phases of the framework developed by the IEA[26]. This framework looks at the type of challenges that the grid will be facing with the progressive introduction of VRE. These phases are described in Figure 25.

As of today, large European countries with a relatively high penetration of VRE in the power mix such as Italy, Germany Portugal and Spain, are in Phase 3. At this stage, local power systems start experiencing noticeable variations between supply and demand, which requires a systematic increase in dispatchable power to provide the flexibility needed. This is usually achieved through improved operations of existing plants, focusing their contribution on balancing the grid and carrying out retrofitting and modernisation projects [26].

Currently, only Ireland and Denmark are in Phase 4, due to their relatively small and isolated grids and the significant percentage of VRE integration. No country, as of today, has reached Phase 5 or 6.

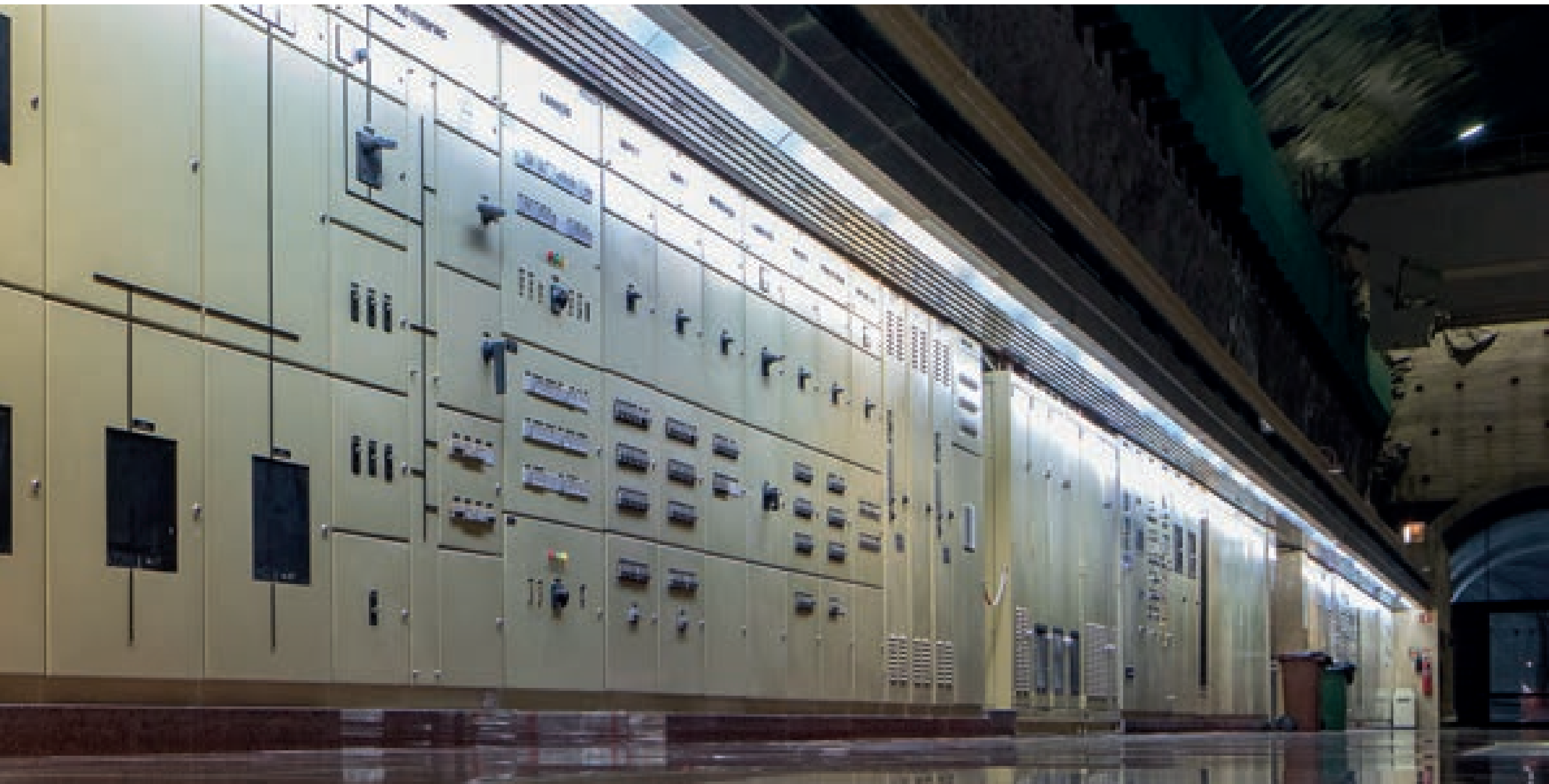
A fully decarbonised economy, with very high levels of VRE, such as the one envisaged by the EU Green Deal, will require several countries to navigate through phase 4 and achieve phases 5 and 6. At this point, VRE surpluses or shortages will become a normal feature of the power systems, which will occur for extended periods of time (months or, in certain cases, entire seasons).

The flexibility enabled by hydropower, thanks to its unique capabilities of providing both short-term power and long-term energy (for hours, days or seasons), means it is perfectly placed to play a key role and contribute to balancing the system in all six phases. The possible contribution that hydropower is capable of providing in order to solve the system's challenges identified by IEA is illustrated in Figure 2 (line: HPPs contribution).

The existing hydropower fleet and the accumulated know-how of more than a century's worth of powerplant development and operations are therefore unique assets that Europe needs to enable, exploit, and whenever possible enhance, to secure a successful transition.

Figure 25: Electric Power Systems Integration Phases, Challenges and Hydropower's contribution

	PHASE 1	PHASE 2	PHASE 3	PHASE 4	PHASE 5	PHASE 6
Phase Characteristics	No noticeable effect of VRE production.	VRE production has minor to moderate impact on system operation.	VRE generation determines the operation pattern of the system.	System experiences periods where VRE makes almost all of generation.	VRE production surplus for long periods of time (from days to seasons)	
System challenge	-	Random fluctuation in power demand.	Balance demand before and after sunrise, and power supply robustness during peak VRE production hours.	Manages large disturbance due to loss of a large power plant, establishing and securing sufficient system inertia.	Availability of energy during day and night, wet and dry seasons and extreme meteorological events.	
HPPs contribution	-	Moderate provision of short-term power flexibility during period of VRE production.	Increase ramp-up/down operations, plus fast switching between production and storing.	Provision of inertia, power, and long-term energy flexibility. Role of hydro moves into providing the power and the energy when needed.	Ultimate provider of utility scale, low-carbon power, and energy flexibility on the entire time scale (from second to seasons).	



7.2 THE ROADMAP: A PATH TOWARDS HYDROPOWER FLEXIBILITY

OBJECTIVES:

The following sections present a series of key actions which will need to be considered and implemented to make sure that European hydropower fleet will be available and equipped to provide the flexibility required to support power systems' evolution up to phase 5 & 6. These are divided by category of stakeholders explaining what these parties are accountable for, the key actions that they need to deliver and the associated outcomes.

The roadmap is designed to achieve the following three overarching objectives on three different scales:

1. **SYSTEM LEVEL: Provide the flexibility needed to achieve a secure, cost-effective, and sustainable energy transition;**
2. **SECTOR LEVEL: Secure hydropower's role as the recognised champion of flexibility in a carbon neutral economy;**
3. **TECHNOLOGY LEVEL: Ensure the opportunities behind the XFLEX HYDRO's flexibility technologies are understood and recognised.**

The roadmap is structured to enable the appropriate stakeholders to engage, both on an individual and collective basis, towards the objectives laid out above. Each stakeholder has specific responsibilities to attend to, as well as direct key actions to follow up on to ensure they are actively playing their part in achieving a decarbonised economy.

Some of these responsibilities/actions are shared across parties, and some speak directly to the different entities coming together for the collective good to drive this movement forward. This roadmap sets the stage for the direction, accountability, and collaboration the sectors and its stakeholders want and need to see as this challenge is embraced together.

7.2.1 KEY ACTIONS AND RESPONSIBILITIES FOR GOVERNMENTS AND PUBLIC INSTITUTIONS AND REGULATORS AND SYSTEM OPERATORS

Table 23: Key actions and responsibilities for Governments & Public Insitutions and Regulators & System Operators

	Responsibilities	Actions
GOVERNMENTS AND PUBLIC INSTITUTIONS	• Identify and enforce the long-term decarbonisation strategy. • Deliver a secure, affordable, and equitable energy transition. • Support the development of the European hydropower industry and its competitiveness on the international stage. • Raise consumers' awareness about the challenges associated with the energy transition and the benefits associated with renewable dispatchable power systems.	• Prioritise system flexibility and consider it a crucial element of the European security of supply. All EU Member States should develop clear national objectives for energy system flexibility. • Create a level playing field for technologies to be compared, selected, and implemented based on long-term benefits to society. • Create a consistent and transparent framework to provide flexibility to the system. • Design financial mechanisms capable of rewarding the value provided to society and supporting long term investment in flexibility. • Facilitate and incentivise the modernisation process of existing assets.
← Shared →		• Identify solutions to implement the long-term energy strategy at the European and national level. • Conduct system level analysis to identify future flexibility needs and support an informed decision-making process.
REGULATORS AND SYSTEM OPERATORS	• Secure the provision of electricity to society and support the development of local economies. • Ensure equitable and fair participation in all the electricity markets. • Protect consumers.	• Continuously monitor and study the evolution of EPS to actively pre-empt the flexibility requirements. • Create and implement transparent market structures. • Continuously develop the European energy infrastructure and increase cross-border connectivity. • Accelerate the implementation of pan-European platforms for the exchange of the grid services.

7.2.2. KEY ACTIONS AND RESPONSIBILITIES FOR PLANT OWNERS AND OPERATORS AND OEM AND RESEARCH INSTITUTES

Table 23: Key actions and responsibilities for Plant Owners & Operators and OEM & Research Institutes

	Responsibilities	Actions
PLANT OWNERS AND OPERATOS	• Safely and ethically operate hydropower assets. • Ensure a cost-effective energy and flexibility supply to the system. • Generate return for investors.	• Constantly optimise capabilities and operations of existing plants. • Continuously monitor the environmental and social footprint of plants operations. • Prioritise flexibility and sustainability criteria during modernisation project.
← Shared →	• Support the development and adoption of innovation. • Ensure the long-term profitability of hydropower assets. • Communicate the entire range of benefits provided to society by hydropower plants.	• Identify hidden hydropower flexibility potential to bring to market. • Identify business models that enable the effective implementation of flexibility technologies. • Share insight and best practices among the hydropower community. • Encourage and nurture a diverse and thriving culture in the sector to attract and retain skilled labour. • Become public advocates of hydropower best practices and communicate the importance of flexibility.
OEM AND RESEARCH INSTITUTES	• Ensure the long-term competitiveness of hydropower technologies. • Provide plant owners with best-in-class technologies. • Provide transparent and scientific analysis of power systems evolutions and support the identification of innovative solutions.	• Continuously monitor the system evolution and anticipate shifts in flexibility needed. • Continuously challenge the status quo and identify solutions to innovate, reduce costs and implementation time. • Conduct system level analysis to support an informed decision-making process.

7.2.3. KEY ACTIONS AND RESPONSIBILITIES FOR FINANCIAL INSTITUTIONS

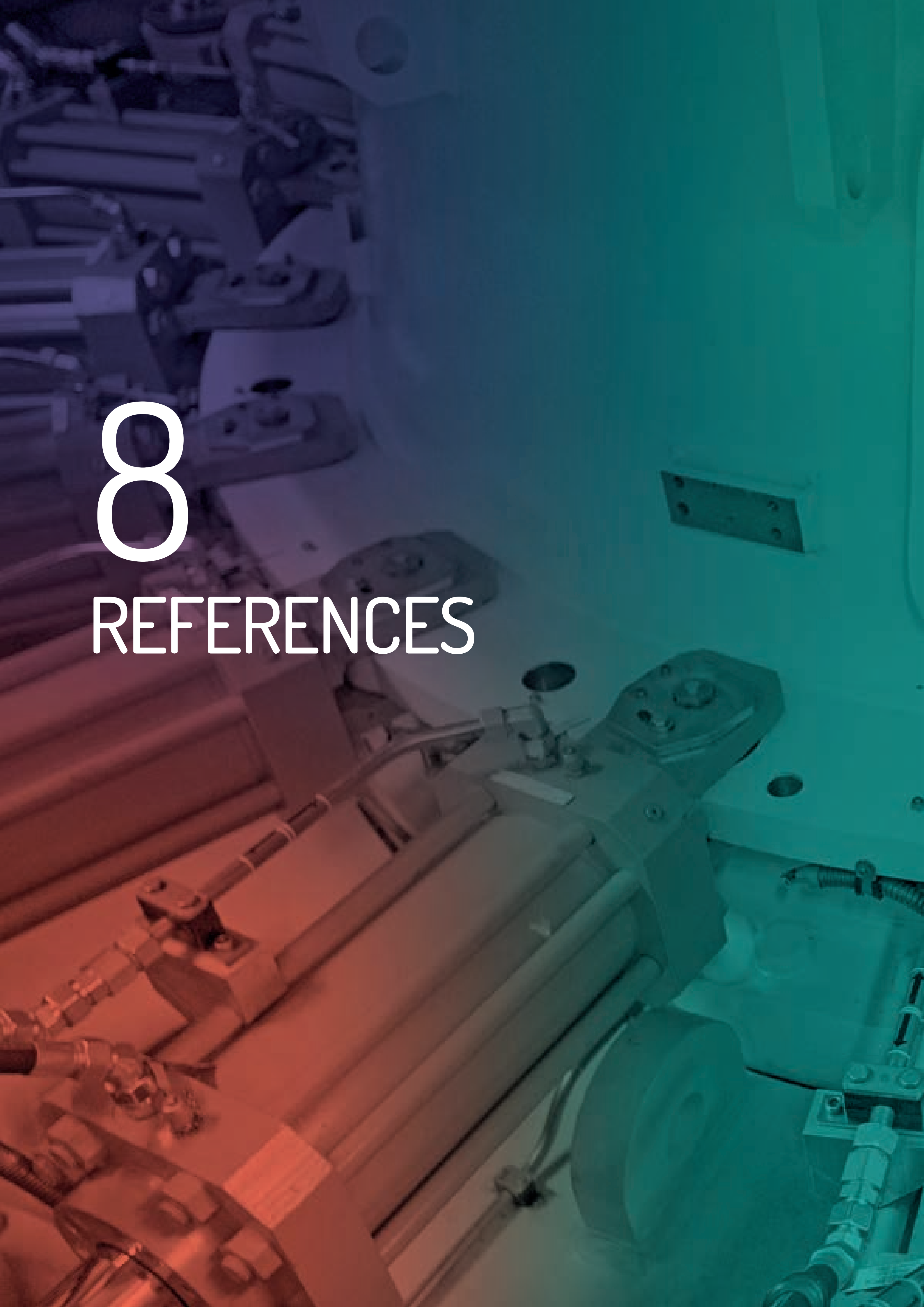
Table 24: Key actions and responsibilities for Financial Institutions

	Responsibilities	Actions
FINANCIAL INSTITUTIONS	• Provide the capital required to finance the development needed to enable the energy transition. • Encourage the decarbonisation process by aligning investment and landing decisions E&S risk.	• Design bespoke financial products to fund long term hydropower projects. • Introduce sustainability criteria into project selection processes. • Actively understand the potential of flexibility and identify the associated revenue streams.

7.2.4. KEY ACTIONS AND RESPONSIBILITIES FOR CONSUMERS & SOCIETY

Table 25: Key actions and responsibilities for Consumers & Society

	Responsibilities	Actions
CONSUMERS AND SOCIETY	• Understand the challenges that the energy transition is trying to address, and the challenges faced by the evolving energy systems. • Understand the role that energy consumers and society as whole have in achieving a decarbonised power system.	• Support the implementation of policies that promote the development of a decarbonised energy system. • Prize flexible sources for the additional value that they provide to society. • Recognise the value provided by hydropower beyond electricity production.



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