

## Research and Innovation Agenda



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## GLOSSARY OF TERMS

AAR	Alkali-Aggregate-Reaction
ADAS	Automatic Data Acquisition System
AI	Artificial intelligence
CAPEX	Capital expenditure
CEP	Consultation Expert Panel
CMD	Cemented Material Dams
CP	Consultation Platform
CSP	Concentrated Solar Power
C&I	Control & Instrumentation
DFIM	Doubly Fed Induction Machines
EC	European Commission
EIA	Environmental Impact Assessment
ESS	Energy Storage System
EURELECTRIC	Sector association of electricity industry at pan-European level
E&S	Environmental & Societal
FRCM	Fibre Reinforced Cementitious Matrices
FRU	Functional River Unit
FSFC	Full-Size Frequency Converter
GHG	Greenhouse gas
GIS	Geographic Information System
GLOF	Glacial Lake Outburst Flood
HMI	Hydropower Modernisation Initiative
HP	Hydropower
HPE	Hydropower Europe project
HPP	Hydro Power Plant
ICOLD	International Commission on Large Dams
IEA	International Energy Agency
IEEE	Institute of Electrical and Electronics Engineers
IHA	International Hydropower Association
IIoT	Industrial Internet of Things
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
LCOE	Levelised Cost of Energy
NDC	Nationally Determined Contribution
NREL	National Renewable Energy Laboratory
OEM	Original Equipment Manufacturer
OPEX	Operating expense
O&M	Operation & Maintenance
PAT	Pump as Turbine



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PP	Power Plant
PSH	Pumped Storage Hydropower
PV	Photovoltaics
RED III	Renewable Energy Directive III
REN	Renewable Energy Network
RES	Renewable Energy Sources
RIA	Research and Innovation Agenda
RO	Reverse Osmosis
R&I	Research & Innovation
SCADA	Supervisory Control and Data Acquisition
SIR	Strategic Industry Roadmap
SSH	Social Sciences and Humanities
SWRO	Sea Water Reverse Osmosis
TRL	Technology Readiness Level
UKPS	Underwater Kite Power Systems
UN	the United Nations
VPP	Virtual Power Plant
VRG	Variable Renewable Generation
WFD	Water Framework Directive
WFPS	Whooshh Fish Passage System
WSC	Wider Stakeholder Consultation
WWF	World Wildlife Fund

## SUMMARY

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This document presents the final version (2021) of the HYDROPOWER EUROPE Research & Innovation Agenda (RIA). The goal is to provide recommendations on R&I priorities for hydropower to EU institutions and national authorities, to contribute to shaping public spending for R&I, such as the upcoming calls in the Horizon Europe Funding Programme. The document also provides a useful reference to the entire hydropower community. Starting from the current status of hydropower technologies, the RIA identifies the main challenges for further hydropower development, optimised maintenance, environmental and economic performance of existing assets and the related R&I gaps. As a result, R&I needs for hydropower are listed and clarified, specifying the type of challenge, expected results, R&I activities needed, the relevant stakeholders, indicative timeframe and an assessment of the funding required. The RIA is not limited to technological issues, such as equipment and infrastructure improvement and extension or advanced operation managing systems, but also includes environmental, social and economic issues in view of sustainable development to understand how community and the wider public react to hydropower projects and how social awareness can be enhanced. However, the RIA looks at these issues exclusively through a research and development perspective. The R&I needs have been prioritised according to criteria defined with the support of the HYDROPOWER EUROPE Consultation Expert Panel (CEP) (e.g. consistency with EU policy objectives, the maturity of the technology, expected benefits, etc.).

The research themes identified are grouped according to the challenges which hydropower in Europe must address, namely:

- Increasing flexibility
- Optimisation of operations and maintenance
- Resilience of electromechanical equipment
- Resilience of infrastructures and operations
- Developing new emerging concepts
- Environmental-compatible solutions
- Mitigation of the impact of global warming

In total, 18 research themes including multiple research topics under each of them have been formulated based upon a wide consultation process. After several workshops with the Consultation Expert Panel the priorities, the suggested time horizon when the call should be initiated as well as the recommended funding scheme for all research themes, could be defined as summarized in Figure S-1 below. For the more detailed research topics listed under each research theme the Technical Readiness Level (TRL) was also defined.

As can be expected from hydropower as a renewable energy, all research themes are addressing most of the European Green Deal goals. The research themes identified hereunder are also more advanced compared to the previous attempt to formulate R&I priorities for the hydropower sector (i.e., in the 2015 Global Technology Roadmap of the Hydro Equipment

Association). The 18 research themes are well aligned with new renewable energy and climate policies launched recently and they are more comprehensive and detailed.

Hydropower Europe recommended R&I themes	Consultation Feedback				
	Challenges	Research Themes	Priorities	Recommended Call	Recommended Funding Scheme
	Increasing flexibility	3.1.1. Innovation in flexibility, storage design and operation	Very High	before 2025	€ 26-35 million
		3.1.2. Innovative design of turbines including reversible pump-turbines and generators	High	before 2030	€ 16-25 million
		3.1.3. New models and simulation tools for harsher operational conditions	High	before 2030	€ 8-15 million
		3.1.4 Development and application of a business model for flexibility	Very High	before 2025	€ 8-15 million
	Optimisation of operations and maintenance	3.2.1. Digitalisation and artificial Intelligence to advance instrumentation and controls	High	before 2030	€ 16-25 million
		3.2.2. Monitoring systems for predictive maintenance and optimised maintenance intervals	High to Very High	before 2030	€ 2-7 million
	Resilience of electro-mechanical equipment	3.3.1. New materials for the increased resistance and efficiency of equipment	Medium High to High	before 2030	€ 8-15 million
	Resilience of hydropower infrastructure and operation	3.4.1. New materials and structures for increased performance and resilience of infrastructure	Medium High to High	before 2030	€ 8-15 million
		3.4.2. Databases of incidents and extreme events, integrated structural risk-analysis models and innovative solutions for multi-hazard risk analysis	High	before 2030	€ 8-15 million
		3.4.3. Innovative sediment management technologies for sustainable reservoir capacity and river morphology restoration	High to Very High	before 2025	€ 8-15 million
		3.4.4. Innovative techniques for enhancing the working life of concrete structures	Medium High to High	before 2030	€ 8-15 million
		3.4.5. Innovative techniques for enhancement of overtopping safety of embankment and rockfill structures	High	before 2035	€ 2-7 million
	Developing of new emerging concepts	3.5.1. Development of innovative storage and pumped-storage power plants (e.g. multipurpose PSH, sea water PSH, etc.)	Very High	before 2030	€ 16-25 million
		3.5.2. Marine energy	Medium High to High	before 2030	€ 8-15 million
		3.5.3. Hybrid & virtual power plants	High to Very High	before 2030	€ 8-15 million
	Environmentally compatible solutions and mitigation of the impact of global warming	3.6.1. Flow regime management, assessment of environmental flow release, innovative connectivity solutions for fish and biodiversity protection and improvement of stored water quality in reservoirs	Very High	before 2025	€ 16-25 million
		3.6.2. Assessment of the general impact and contribution of hydropower to biodiversity and the identification of innovative approaches and guidelines to support more sustainable hydropower development	Very High	before 2025	€ 8-15 million
	Mitigating the impact of global warming	3.7.1. Innovative concepts of hydropower infrastructure adaptation and tapping hidden hydro	Very High	before 2030	€ 16-25 million

Figure S-1 Summary of the consultation feedback with the HPE R&I themes

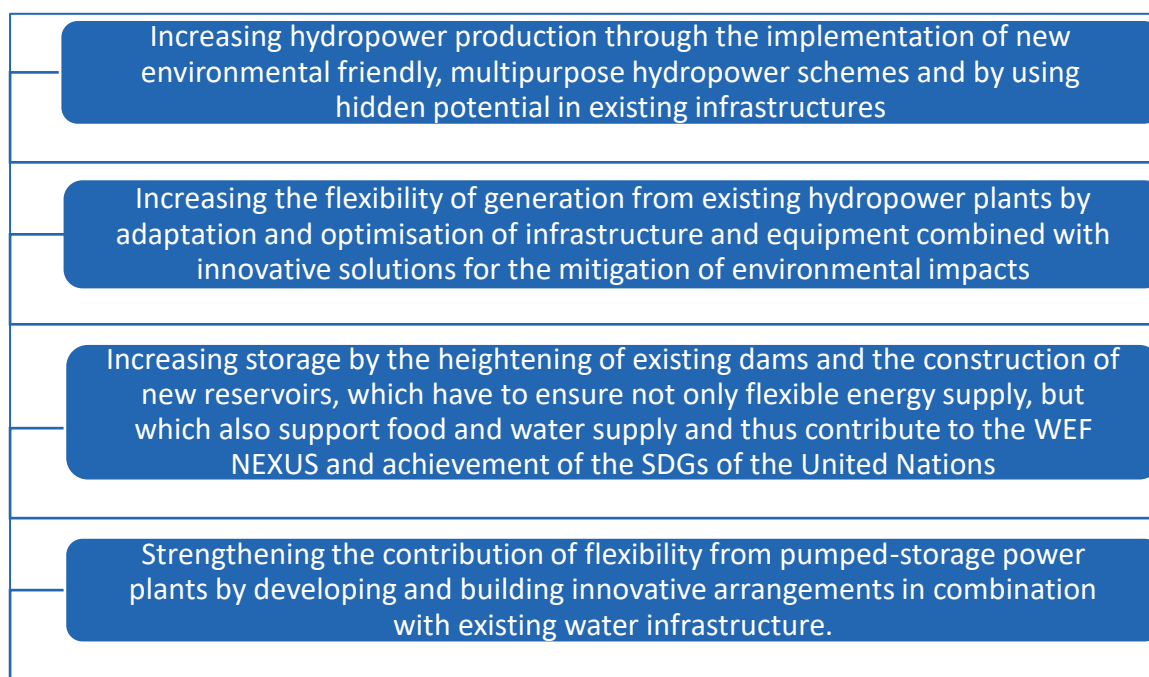
The priority categories of the research themes obtained from the feedback of the Consultation Expert Panel are also confirmed by the results of a complex system analysis, carried out for hydropower in Europe (HPE, 2020). Nevertheless, it should also be noted that important active factors such as *Communication Hydropower* and *Benefit Sharing with Local Communities* are not directly addressed by the research themes which are, by definition, more oriented towards technological innovation and development. However, these non-technical factors are discussed in the Strategic Industry Roadmap (SIR) (HPE, 2021b) and the required strategic actions are recommended there.

# 1 Introduction

## 1.1 Main messages from the HYDROPOWER EUROPE vision

The ambitious plan for European energy transition towards becoming carbon-neutral by 2050 is the greatest endeavour of our generation. The uptake of renewable energy sources (RES), mainly solar and wind, is consistently growing in many European countries, proliferated by the mandatory fossil fuel phase-out. This uptake of RES also creates obstacles, such as difficulty in aligning electricity generation with demand. Hydropower already supports the integration of wind and solar energy into the supply grid through flexibility in generation as well as its potential for storage capacity. These services are, and will be, indispensable on the path to achieve the desired energy transition in Europe, and worldwide. **Hydropower has all the characteristics to serve as an excellent catalyst for a successful energy transition.**

There is still untapped potential, which allows hydropower to perform this role. However, this requires a more flexible, efficient, environmentally friendly and socially acceptable approach to increasing hydropower production to complement other renewable energy production. The future development of hydropower in Europe is based upon the following vision (Figure 1-1):



*Figure 1-1 Vision for the approach to increasing hydropower production to complement renewable energy production*

## 1.2 Objectives of the Research and Innovation Agenda (RIA)

The Research and Innovation Agenda (RIA) presents the contribution of the European hydropower community towards the technological and scientific response to the current challenges in this sector. This document is an integral outcome of the HYDROPOWER EUROPE project, which is built on the ambition to develop a Research and Innovation Agenda (RIA) and a Strategic Industry Roadmap (SIR) for the hydropower sector, based on the synthesis of technical fora and transparent public debates through a forum that gathers all relevant stakeholders of the hydropower sector. To achieve these goals, three specific objectives have been pursued:

1. Engaging relevant stakeholders in the hydropower sector.
2. Addressing the challenges and prioritising needs for hydropower development in Europe.
3. Writing and disseminating the RIA and the SIR for hydropower.

This document also aims to fill the gap created by the current lack of a comprehensive report on the R&I needs for the hydropower sector in the foreseeable future. Building on this need, this document aims to provide insights for EU policy makers and to transparently and clearly communicate concrete needs for timely financial support to achieve these R&I priorities.

The RIA is complemented by the Strategic Industry Roadmap (HPE, 2021b), which discusses the non-technical barriers to hydropower deployment. The SIR addresses the following issues:

- understanding why communities support or reject hydropower projects.
- identify best practices in bridging the gap between the different parties involved.
- identify new financing sources for hydropower and pumped storage by overcoming the concerns of investors.

The target is to disseminate the knowledge acquired at the EU level between basic science, the research and industrial value chain, civil society and European and national authorities.

## 1.3 The process

This document is the synthesis and the result of a thorough consultation process that engaged all relevant stakeholders who contributed their inputs regarding research needs from a technological and regulatory point of view. The consultation process has allowed a structured program of stakeholder consultation through workshops (both regional and Brussels-based) and online discussion groups to seek perceptions, views and expectations on the current and future research and innovation needs of the hydropower sector. The stakeholder base included more than 600 hydropower experts from across Europe (see Figure 1-2 Geographical distribution of stakeholders registered for the HYDROPOWER EUROPE Forum (October 2021, within Europe. The number next to the country name indicates the number of registered

stakeholders.)). The scope of the consultation on the RIA was to collect relevant feedback from hydropower stakeholders on the relevant R&I themes and topics, the rationale behind them and their expected outcomes. The HYDROPOWER EUROPE consortium first drafted a list of 48 potential topics spanning the whole hydropower value chain. These topics were then clustered into 8 thematic groups. All themes and topics were included in the on-line consultation process, allowing respondents to choose only the themes and topics that they deemed relevant. Following revision in the first Consultation Expert Panel (CEP) workshop and consequent consolidation, 12 themes comprising several topics each were selected and presented in the 1<sup>st</sup> draft of this document. Following revision in the second Consultation Expert Panel (CEP) workshop, consolidation and extension of the themes and respective topics, the number of themes was then amended to address 16 themes. The consequent 3<sup>rd</sup> and 4<sup>th</sup> expert consultations produced:

1. priority levels for each research theme and their respective topics;
2. time perspective for the proposed R&I themes and their respective topics;
3. budget required for the proposed R&I themes and their respective topics; and
4. desired TRL levels for the proposed R&I topics.

Furthermore, based upon the recommendations of the Consultation Expert Panel (CEP), two research themes identified during development of the SIR were transferred into the RIA, which finally comprises 18 research themes and a total of 78 detailed topics.





Figure 1-2 Geographical distribution of stakeholders registered for the HYDROPOWER EUROPE Forum (October 2021, within Europe. The number next to the country name indicates the number of registered stakeholders.)

## 1.4 How to read the RIA

This document presents research and innovation priorities with the aim to make hydropower more flexible for integrating variable intermittent and non-dispatchable renewable energy sources in the electric system and to make it even more productive over the coming decades. Chapter 2 presents the current state-of-the-art of hydropower and engineering trends. The heart of this document is in Chapter 3, which presents and explains the top 18 R&I themes. Chapter 4 then takes stock of the proposed priorities and sets them out against the EU energy transition objectives – especially those connected to the EU Green Deal as well as differentiating from the 2015 Hydro Equipment (Industry) Technology Roadmap. Chapter 5 offers observations on the outlook for the hydropower sector and closing remarks. Finally, Annex I shows the proposed R&I themes ranked according to their timing priority.

## 2 Hydropower in Europe: Current Situation and Engineering Trends

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Since the late 19<sup>th</sup> century, hydropower has developed as a clean, safe, reliable and inexpensive source of power (short-term) and energy (long-term) services. Today, more than 180 countries utilise hydropower worldwide and in Europe (EU-28), hydropower generation corresponds to about 12% of the European net electricity generation and 36% of electricity from renewable resources<sup>1</sup>. Hydropower is mastered, and an adept candidate to be competitive under liberalised market conditions. It can also provide significant benefits to the whole power system; in fact, the fast response capabilities provided by hydropower reservoirs and pumped storage plants provide critical energy and flexible power to electricity networks with considerable long-term reserves, helping to match fluctuations in electricity demand and supply from intermittent and less flexible electricity sources. Moreover, since hydropower is situated at the crossroads of two major issues for development – water and energy – hydropower reservoirs can often deliver services beyond electricity supply, such as mitigation of freshwater scarcity by providing security during low flows and drought and for drinking water supply, irrigation, flood control, fish farming or navigation services. Furthermore, many reservoirs in Europe have created new biotopes and have become a tourist attraction with high potential for leisure activities. Accordingly, multipurpose hydropower projects may have an enabling role beyond the electricity sector to secure freshwater availability and thus contribute directly to the Water-Food-Energy Nexus approach.

The next generation of hydropower professionals has a huge responsibility in preserving a centenary legacy of excellence not only in Europe but also for the worldwide market. To successfully achieve these goals, it is important that the industry (i.e., promoters, consultants, engineers, project/asset managers, etc.) embraces a structured approach to knowledge management and organisational culture to encourage its creation, transmission and retention.

### 2.1 Technological state of the art and anticipated development

Since hydropower generation has been continuously improved and optimised, this form of energy generation has lasted for over a century and has been able to adapt to different contexts (i.e. organisation and rules) of electrical systems. Since the late 19<sup>th</sup> century, hydropower plants have converted a very simple physical concept – gravitational energy of water – into mechanical and then electrical energy. Hydropower plants have two standard classifications: run-of-river power plants (with no or only marginal storage capacity and limited flexibility) and plants with reservoirs, which can be further sub-divided into storage (with flexible storage capacity for all time scales from minutes up to weeks and years) and pumped storage power plants (typically for all time scales from minutes to days and up to a

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<sup>1</sup> EUROSTAT, 2019

week). Run-of-river plants can be sub-divided into pure run-of-river and pondage plants (with flexible capacity typically over hours). Additionally, it is also important to consider newer types of hydropower plant, such as offshore and tidal power plants and hybrid power plants.

Hydropower plants require high upfront investments but have an expected lifetime longer than one hundred years. Electromechanical equipment has a shorter lifespan, which is nevertheless very long (typically 40 years or more). In terms of hydropower potential, about 60 % of the economically viable potential in Europe has already been exploited. However, the increase in electricity generation from hydropower can be achieved not only by building new power plants (greenfield projects) but also by refurbishing, retrofitting and upgrading existing infrastructure (Quaranta et al., 2021). The current main types of hydropower projects are:

- greenfield – hydropower projects;
- renovation, modernisation and upgrading projects;
- multipurpose schemes<sup>2</sup>.

Over the past decades, hydropower equipment has already been optimised and improved to achieve even higher performance, availability and flexibility. Regarding hydropower infrastructure, innovative measures to mitigate environmental impacts have been developed. Moreover, significant improvements have been enabled by computer technologies in many areas, including design, construction, monitoring, diagnostics, protection and control. Investments into research and development are fundamental to meet advances in technology and deal with market competition. The main research avenues for technical improvements include:

- Further increasing the efficiency of hydropower infrastructure over a broader operating range and flexibility in power generation and storage. In particular, improving the working efficiency of turbines when operating at part-load.
- Further innovation and more efficient design (e.g. cost efficiency) tools and methods.
- Further optimisation of operation and maintenance in hydropower plants.
- Increasing resilience of electromechanical equipment.
- Increasing resilience of infrastructure (“water to wire”), especially in view of climate change, which also opens new opportunities for future hydropower development and its role in the energy transition.
- Developing new emerging concepts (e.g. multi-purpose and/or hybrid schemes, tidal barrage, seawater pumped storage hydropower, virtual power plants, etc.).

Furthermore, to manage social, environmental and economic aspects at a regional level, there is a need to build links with local entrepreneurs and stakeholders, associated to industry, academies (R&D), policy institutions and other organisations.

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<sup>2</sup> Multipurpose schemes combine energy production with environmental and socio-economic aspects to create value for their host communities and regions. Hydropower reservoirs can contribute to, among others, appropriate water management including potable water supply, flood and drought management, irrigation, navigation, fisheries, and recreational activities.

## 2.2 Flexibility and integration of renewable energy sources (RES)

With the rapid growth of other variable renewables (e.g. solar PV and wind), the need to ensure grid stability is more important than ever. Overall, hydropower has great potential to enable the transition towards a decarbonised economy in Europe as it plays an important role in balancing the grid, mitigating the negative effects of intermittent generation from other renewable energy sources. Small and medium scale hydropower plants have a key role in local and regional grid balancing too, in addition to their fairly decentralised nature. The recent EU DIRECTIVE (EU) 2018/2001 on the promotion of the use of energy from renewable sources puts a lot of emphasis on renewable energy communities (RECs). Within RECs, a possible new role could be played by many small hydropower plants if they were turned to small, pumped storage powerplants in smart grids of local energy communities. This solution can take advantage of the benefits of small hydro, pumped storage and smart grids:

- Small hydro (Reliability, predictability, flexibility).
- Pumped storage (Load levelling, quality of electric supply, energy storage, backup facility to intermittent RES, standby and reserve duties, environmentally friendly).
- Local energy communities (Demand response, integration of RES, distributed generation, price signalling).

If large fluctuations in voltage and frequency occur, they can lead to blackout of supply grids and damage electrical devices and facilities with tremendous socio-economic consequences. The increasing penetration of variable renewable energy in the power grid poses new challenges to the stability and safety of the system. The main strength of hydropower is the fact that it can serve as a dispatchable, responsive source of bulk power; therefore, hydropower generation can substantially contribute to stabilising the grid. The units can stabilise the system as sources of flexible power working over a very wide operational range over many hours per year. They can even compensate failure events when other sources of generation disappear, with energy reserves in hydropower reservoirs able to cover lost generation over long periods. Pumped storage plants can additionally serve as controllable loads, drawing electricity from the grid to charge their reservoirs when excess energy is available. For these reasons, hydropower is more and more used to provide ancillary services to the grid, including:

- **Balancing services**, such as frequency control, spinning reserve and energy storage. Frequency control can be provided by hydropower through different mechanisms, namely: a) inertia (a passive response due to rotating masses in generators, which becomes even more important when large coal and nuclear generation units get shut down and only non-synchronous variable RES remain), b) primary frequency response (active, unmanned response implemented through an electronic, digital, or mechanical device) and c) frequency regulation (active response to adjust generation to maintain interchange schedule and frequency). These functions can stabilise the system over a very wide operational range and over many hours per year. Spinning reserve offers generation that is reserved to quickly respond to system events by increasing or

decreasing output; hydropower offers an excellent source of reserve because it has fast ramping capability throughout its range. Additionally, water storage allows the power system to balance variability existing in the load over longer timeframes than frequency response, from multiple minutes to several hours and even weeks under critical events.

- **Reactive power:** By adjusting reactive power, hydropower facilities are operated to follow a voltage schedule to ensure sufficient voltage support.
- **Black start capability:** Thanks to the capability of many hydropower plants to start generator units without the need for external power from the grid, these are best suited to support restoration of the electricity network after a blackout.

These functions require a new market design or regulatory mechanism suited to reward storage and flexibility services. Energy transfer between peak hours and off-peak hours, and often also between seasonal periods, as well as the stability role, need to be promoted based upon innovative market mechanisms that grant fair compensation to incentivise players to invest. Hence, there is a need for a new market design and regulatory mechanisms to be implemented promptly. In particular, the business case for pumped hydro storage plants must be improved, for instance, by removing double grid fees and charges, and by allowing storage operators to simultaneously participate in various markets, offering various flexibility services to strengthen the business case. Long-term revenue streams must also be available.

The massive and fast penetration of solar PV and wind generation will undoubtedly place enormous pressure on grid stability and balancing requirements. Consequently, creating a market and regulatory mechanisms which stimulate the entry of players that provide storage and flexibility is a high priority. In this context, hydropower's advantages as a well understood technology with low lifecycle costs will enable it to compete with other recent technologies in the power market. Political, regulatory and market aspects are discussed further in the Strategic Industry Roadmap (SIR) (HPE, 2021b).

## 2.3 Environmental sustainability and public awareness

Whilst hydropower provides supplementary solutions to mitigate the negative effects of climate change (by storing and supplying water), the development of hydropower projects has both positive and negative environmental and social impacts. When discussing environmental issues, one must consider that land use for urbanisation and agriculture has already changed many river basins in the past. In many cases, the main driver for building a dam was not for power generation but rather for hydrological needs; and together with hydropower plants, the concept of multipurpose systems was developed. Such multipurpose approaches should be considered the other way round when future plant projects are developed.

Hydroelectric structures typically have a direct impact on the river connectivity. This includes immediate abiotic effects up and downstream (changes in flow, water quality, sediment load

etc.) and longer-term impacts such as changes in the channel and floodplain morphology and biotic changes, until a new ecological equilibrium is achieved. When sustainably managed, hydropower schemes can enhance ecosystems and constitute support for new precious biotopes.

As for social impacts, whilst hydropower may affect land use and the socio-economic conditions of local communities, a hydropower project typically brings investment to the region, leading to sustained socio-economic growth. In addition, local communities may benefit from hydropower projects not only by generating taxes and jobs, but also by enabling multiple other water-dependent activities, such as irrigation, navigation, tourism, fisheries or sufficient water supply to municipalities and industries, as well as protection against floods and droughts. Site infrastructure and associated reservoirs can become important tools to help mitigate climate change effects. As a local industry, hydropower can also support development in remote areas.

The main environmental and social issues related to hydropower projects, as well as the extent of positive and negative effects, are typically site dependent. Sustainability considerations for the siting and design of a hydropower plant are crucial to fit the site-specific characteristics, social and environmental needs.

Due to the close interactions of the water-energy-food nexus, the development, operation and maintenance of hydropower plants have to be managed carefully. From an environmental point of view, hydropower projects should address five main challenges, including through the use and development of fair evaluation methods:

1. Ecological continuity (including fish migration, sediment transport, hydro-morphological changes, land use and loss of biotopes).
2. Water quality in reservoirs.
3. Environmental flows.
4. Hydropeaking, i.e., environmentally compatible flow regimes.
5. Mitigation hierarchy for biodiversity.

These environmental challenges must be addressed and balanced towards the significant contribution of hydropower schemes namely the flexibility, storage and climate change adaptation and mitigation. Also, since hydropower may enable other renewables into the system, reduced environmental effects from alternative ways of enabling these renewables should also be considered.

As mentioned above, hydropower reservoirs can provide flexibility and enable the inclusion of variable renewable energy sources into power systems. However, the impounding can alter the carbon transport and processes in the area and produce GHG flux changes. In certain conditions, a reservoir will release GHG due to the decomposition of flooded organic material. In other conditions, a reservoir may act as carbon sink: absorbing more emissions than it emits.

As temperature is one of the variables that has a significant effect on reservoir emissions, international research projects show that methane emissions do not play a major role in temperate zones as found in Europe. However, temperature is only one of the many variables that influence the GHG emissions. According to a worldwide study of hydropower reservoirs, the global median GHG emission intensity of hydropower reservoirs was 18.5 gCO<sub>2</sub> – eq/kWh (less than 6 gCO<sub>2</sub> in Europe), significantly lower than coal, gas or solar PV and in the range with wind and nuclear (Bauer et al., 2017).



### 3 Priority Issues for Further Developing Hydropower in Europe: Research and Innovation Needs

This chapter presents the research and innovation needs addressing issues for further developing hydropower in Europe. Each research theme is described in detail with the background and challenges as well as suggested research topics. Each research theme, and its suggested research topics, have assigned priorities ranging from moderate to very high. The priorities were obtained through consultation of the wider stakeholder group registered on the consultation platform of the HYDROPOWER EUROPE project via the 2<sup>nd</sup> Wider Stakeholder Consultation event (2<sup>nd</sup> WSC) that took place in late summer / autumn 2020 and refined during subsequent consultation with the Consultation Expert Panel (February 2021). In the 2<sup>nd</sup> WSC event the consultees were asked to rate every research theme and associated research topics from 1 (low importance) to 10 (high importance). For each research theme, as well as the suggested research topics, an average rating was calculated out of the average ratings from each sector considered (CP; 7 sectors). Through the subsequent Online CEP Consultation event and online workshop, the HYDROPOWER EUROPE project team, together with the CEP, verified the ratings for every theme and associated topics. The resulting average ratings were divided into priority level bands, as shown in Table 3-1 below:

Priority score given by CEP	Priority level
8.1 - 10.0	Very High
7.6 - 8.0	High to Very High
7.1 - 7.5	High
6.6 - 7.0	Medium High to High
6.1 - 6.5	Medium High
5.6 - 6.0	Moderate to Medium High

*Table 3-1 Priority ratings for sub-themes and topics*

The information regarding priority, recommended timeline, TRL level and funding (resulting from the 4<sup>th</sup> CEP workshop in June 2021) allocated for each theme and topic are given in the in the themes' title box. The recommended timeline indicates the time horizon by which the call should be initiated.



### 3.1 Increasing flexibility

#### Background

**Flexibility is a requirement inherent to all power systems and in recent years there has been an increasing focus on how to manage it. Large organisations such as IEA, NREL and EURELECTRIC have launched initiatives to quantify future requirements for flexibility to permit increased inclusion of variable renewables, whilst maintaining a secure power system<sup>3,4</sup>. A general conclusion in these reports is that, due to its quick response and good ramping capabilities, hydropower represents an important asset for the system operator. Improving the ability of hydropower installations to provide services to the grid will increase their value and permit increased integration of variable renewable energy into the power system. Despite already being one of the most flexible and versatile renewable power sources, several organisations have pointed out that further increasing hydro turbine flexibility will increase the value of hydropower in a future energy system<sup>5,6,7</sup>. Hydropower in combination with modern converter technology may not only provide better balancing in the grid, but also a set of other ancillary services, such as frequency control, reactive power compensation, power oscillation damping and increased transient stability of other units in the power system.**

**Upgrading the flexibility of existing hydropower plants is urgently needed to improve the resilience and flexibility of the energy system, as Europe transitions to a net-zero emissions energy system. All types of hydropower plants, including run-of-river power plants with pondage, storage and pumped storage, are sources of flexibility. Hydropower is currently used to stabilise the power system without all of its balancing services being properly recognised, as for decades the system has relied on these services as part of normal operations. This is especially the case for the very high dynamic performances from hydropower units, that are not revealed when using standard models. Identifying and upgrading these performance aspects is critical for the new energy system. The key challenge to access current fast response markets for hydropower is the lead time to build a new plant and high initial CAPEX, whilst the lifecycle cost is low. Technological and regulatory issues such as environment or market design must be explored to give the right investment signal.**

**The increase of storage through new reservoirs or by increasing the volume of existing reservoirs, is urgently needed; not only for flexibility in electricity generation, but also to**

<sup>3</sup> International Energy Agency. (2014). *The Power of Transformation: Wind, Sun and the Economics of Flexible Power Systems*. Paris: IEA.

<sup>4</sup> EURELECTRIC. (2011). *Flexible Generation: Backing up Renewables*. EURELECTRIC.

<sup>5</sup> The Norwegian Research Centre for Hydropower Technology (2019). [www.hydrocen.no](http://www.hydrocen.no)

<sup>6</sup> International Energy Agency. (2012). *Technology Roadmap: Hydropower*. Paris: IEA.

<sup>7</sup> Hydro Equipment Association. (2013). *Hydro Equipment Technology Roadmap*. Brussels: Hydro Equipment Association.

provide other services that help mitigate the potential effects of global warming in some sensitive regions (e.g. addressing flood and drought risks).

Transformation of the energy system will require a massive increase in energy storage to achieve a decarbonised economy, and to compensate for volatile production from renewables like solar PV and wind. Energy storage is one of the major strengths of hydropower, as the technology is mature and already exploitable at a large scale. Reservoirs and pumped storage plants are currently the most efficient and cheapest technology for providing long-term storage. Pondage traditionally provides up to two hours of storage and also offers significant potential for storage (i.e., as much as batteries). Investments are highly predictable and safe, and the long lifetime of hydropower infrastructure ensures profitability under certain framework conditions (regulation, energy price, etc.) which need to be sustained or established. The carbon footprint of hydropower projects in Europe is the lowest amongst all new renewable technologies such as solar and wind, as well as emerging storage technologies like batteries (Bauer et al., 2017). The potential to increase storage volumes in the short-term lies in upgrading or renovating existing projects, rather than starting new projects. This includes, for example, retrofitting existing reservoirs with hydropower plants and the expansion of power plants with pumped storage units. These investments should aim to increase flexibility performance, allowing for a broader operating range, quicker response and effective cooperation with other technologies. However, in the Alpine and Nordic regions, there are also opportunities for new-build projects, as glacier retreat caused by climate change leads to new site availability for storage lakes in formerly glaciated regions. Besides electricity production, the existing and future reservoirs in the Southern Mediterranean region are vital for drinking water supply and irrigation. Climate change will increase the water stress in these regions and new reservoirs, which can also contribute as multi-purpose projects to hydropower generation and pumped storage powerplants, will be needed.

### 3.1.1 Research Theme:

#### **Innovation in flexibility, storage design and operation**

**Priority: Very High**

**Recommended call: initiate research before 2025**

**Recommended funding scheme: € 26-35 million**

#### **Background and challenges**

Today, storage and pumped storage hydropower (PSH) are currently the cheapest and most mature large-scale technology for energy storage and balancing the electricity network. In addition, hydropower has a long lifetime, offers attractive grid services (e.g. black start capability, synchronous inertia response, and island grid build up) and is not dependent on rare materials. However, there can be significant environmental and social barriers to PSH deployment and projects also have high CAPEX. Nevertheless, it is a key enabler for reliable electricity supply in the context of increasing variable RES generation.

European reservoirs are large and can be used for flexible operation. Today's storage capacity in European hydropower reservoirs exceeds 185 TWh hence is the largest battery available, and an energy storage system for other renewables. Further expansion introduces technological and regulatory challenges and will affect power ramping rates and downstream flow conditions. Flexible operation will benefit from more precise inflow modelling that will reduce operational risk of scheduling new hydropower technology and increase the revenue potential.

Storage capacity is huge and available from a technical point of view and there is still considerable untapped potential in Europe. Significant potential exists in uprating of existing hydropower storage schemes either by increasing installed capacity (adding new parallel waterway systems and powerhouses) or increasing storage capacity by heightening of dams. Only relatively few of the existing reservoirs are equipped with pumps or pump-turbines, and therefore "active" electricity storage (i.e., storing excess electricity by pumping up water) is not possible in most hydropower reservoirs. Transforming conventional storage power plants into pumped storage power plants would contribute to increasing the current active electrical energy storage capacity by several orders of magnitude. Pump-turbines normally need to be set deeper than conventional turbines to avoid cavitation issues. To prevent the excessive costs of modifying and enlarging the powerhouse, new turbines or variable speed generators must be developed. Variable speed PSH technology can provide sub-second and faster frequency response, which is an attribute not very well known. Furthermore, innovations in reducing the frictional losses in waterway systems (tunnels, penstocks) could contribute to higher overall efficiency in PSH.

However, such upgrading would only work if (a) there are already two substantially large reservoirs, (b) options to build a second reservoir, or (c) an existing water body that allows for additional offtakes. It must also be noted that even pure reservoir storage power plants (without pumping) provide passive electrical storage (i.e., dispatchable generation), since generation can be stopped and flexibly controlled during periods of high RES generation.

The massive and fast penetration of solar PV and wind generation will undoubtedly place enormous pressure on grid stability and balancing requirements. By consequence, this means that the creation of market and/or regulatory mechanisms to stimulate entry of storage and flexibility providers is a high priority. In this context, hydropower has advantages as a well understood technology with low lifecycle costs which will enable it to compete with other technologies in the power market. By connecting existing large seasonal reservoirs with PSH, they can, under certain conditions, also enhance the seasonal transfer of energy storage requirements.

Most of the existing PSHs built in the last century have not been designed to provide all the flexible capabilities that will be needed for optimal variable RES integration. For example, units will have to operate under much harsher conditions and load ranges, which may induce fatigue problems on machinery. In the last decade, new innovative PSH concepts have been designed to deal with such harsh operational regimes, representing best practice examples for future projects. In pumped storage technology, a key challenge is the development of variable speed units based on frequency converter technology (e.g. FSFC), or alternative electric generator design (e.g. DFIM). Equipment and machinery need to be adapted to the new requirements, allowing a wider range of operation (ideally 0-100% load) both in turbinning (generation) and pumping mode. Similarly, fast start/stop and change-over times will need to be realised when modernising existing assets, where classical pumped storage schemes have to adapt to highly fluctuating operations. Furthermore, PSH 'hybrids' in combination with new technologies (Power-to-X, batteries, wind & PV, etc.) and demand side management will also help to integrate RES and service grid stability. All in all, future developments should have a holistic perspective, i.e., taking various effects on the environment and stakeholders (power stations, other water uses) into consideration. The required extension of transmission lines is an issue in all future developments in the energy transition.

### **SUGGESTED RESEARCH TOPICS AND PRIORITIES**

**Developing and optimising hydraulic design and control strategies for pump turbines and waterway system in existing PSH**

**Expected TRL: 6-7**

**Budget range: €7-10M**

**Priority  
Very High**

Most existing pumped storage powerplants have been built for a clear operational range in combination with thermal powerplants mainly to absorb energy during the night and weekends and to furnish peak energy during hours of high demand during the day. In

combination with RES, the operation of existing PSH has become much harsher, which was not foreseen in the initial design. The research objective is to maximise the operational range of the electro-mechanical equipment in turbine and pump modes in combination with an innovative adaptation of the waterway system, especially the surge tank, to allow harsher transient operation of existing pumped storage power plants. Another research goal is the optimisation of start/stop times and change over times, which should include a life cycle analysis for new robust designs operating under the expected harsher conditions. Furthermore, strategies to enhance change over times (by C&I upgrading or auxiliary systems redesign) should be developed to ensure that PSH will have the same behaviour as competing storage and flexibility technologies. The outcome of the research is that wide capacity ranges in both turbine and pump modes can be achieved (possibly without restrictions). The market impact will be increased value of existing PSH assets by enabling higher operational flexibility.

**Enhancing flexibility of run-of-river power plants and using existing run-of-river cascades for energy storage**

**Expected TRL: 6-7**  
**Budget range: €4-6M**

**Priority  
Very High**

There is still potential for short-term storage (hours) in the reservoirs created by the backwater of run-of-river power plants, especially if they are arranged as cascades along a river. This would enhance the flexibility of run-of-river power plants using existing run-of-river cascades for energy storage. An option would be increasing storage using flood plains (e.g. a dam in the floodplain creating at the same time a biotope) or using underground volumes with revisited function. For existing run-of-river cascades for energy storage, the research challenge is to develop an intelligent cascade storage “controller” using integrated solutions for water management at a catchment area level and improving sediment management to ensure more storage availability. The outcome of the research would be improved water management schemes which allow for intra-daily regulation. By using underground water storage or an existing river cascade, the impact of the research would minimise the cost of construction of new low-head, small PSH with low environmental impacts which are also economically viable. A further outcome is also that a synergy between hydropeaking, energy needs, and mitigation of negative ecological effects can be achieved<sup>8</sup>.

**Developing design algorithm and innovative construction technologies for new PSH parallel to existing storage powerplants by using existing upper and lower reservoirs**

**Expected TRL: 6-7**  
**Budget range: €4-6M**

**Priority  
High to Very High**

<sup>8</sup> see section 3.6.1

In Europe there are many large reservoirs close to each other, or even in cascades, which are mainly only used as storage power plants without or with only little pumping ability. By building new waterways parallel to existing ones and linking or interconnecting existing reservoirs, they can be equipped with PSH having large storage capacity. The research goal is to develop powerful design methodologies which can generate a large number of alternatives which allow us to find optimised solutions. This includes innovative uprating of existing storage power plants to enhance flexibility by increasing installed capacity with innovative adaptation of machinery and waterway systems (surge tanks etc.). Guidelines to aid the transformation of conventional hydropower plants into pumped storage plants is an expected outcome. Another research objective is the technical investigation into low-cost and efficient methods for transforming conventional HPP / storage power plants without the ability to pump into pumped storage plants equipped with fully fed synchronous machines. Furthermore, regarding research outcomes, there is still the need of innovation in the fast and safe construction of large high-pressure tunnels and large-span powerhouse caverns, using advanced rock excavation techniques not only based on mechanical but also on rock-melting technologies by high-power lasers. Such techniques could also create safe rock support at the same time. The impact of the research would not only show the higher potential of economical sites for PSH but also solutions for overcoming social and environmental barriers and boosting the deployment of PSH in Europe.

**Overall assessment models of run-of-river, storage and pumped storage power plants regarding market and socio-economic issues**

**Expected TRL: 6-7**

**Budget range: €1-3M**

**Priority  
High to Very High**

The first research objective is to characterise the costs of flexible and harsher operating conditions on hydropower plants including a comparison with other generation and storage technologies, especially in terms of costs and resources, lifetime and impact. Current criteria as well as those expected to occur more strongly in the future, should be evaluated. A further research goal is to develop a future market model, based upon the assessment model described above, through which services provided by hydropower could be recognised accordingly. The basic conditions for a fair and stable market design should be that it is open for all technologies without subsidies. An outcome should be a study on developments in the wholesale market and in the balancing energy markets, together with political and social development as well as on the potential benefits regarding performance increase, storage capacity, damming height or use of flood retention space. Further outcomes include:

- development of an assessment model, which includes economic and ecological aspects in addition to the operational and energy economic criteria;
- quantified cost impact of flexible operations on hydropower plant equipment, in terms of CAPEX/OPEX, residual lifetime, amongst other relevant metrics;



- quantified cost comparison of PSH plants vs. other generation and storage technologies, in terms of CAPEX/OPEX, residual lifetime, amongst other relevant metrics;
- characterising the prospective vision and market design of storage and flexibility required in the system by 2040 – 2050 focusing on a) grid system issues and requirements related to flexibility, and technical issues related to hydropower performance under high flexibility; b) economic issues related to valuing and assessing the hydropower market services, and also the potential value of flexibility, in modern power market models; and c) regulatory issues, such as the European electricity market design, grid code impact and international benchmarks; especially in terms of understanding barriers for market entry of energy storage and flexibility providers;
- understanding the required storage capacity in the future, mapping the amount of available reservoir/storage potential and the relation between flexibility of the hydropower station and river dynamics (e.g. sediment transport, erosion, hydro peaking);
- investigation into which services, or combination of services, can PSH provide the best, including which requirements are needed to provide a profitable business case;
- investigating the CO<sub>2</sub> relevance of pumped storage power plants via a life cycle analysis;
- identifying potential natural threats for PSH and risk mitigation solutions.

This overall assessment model, which includes socio-economic issues as well as market issues, should have the following impacts:

- supporting political and public discussion with realistic facts about needs and capabilities;
- enhancing public acceptance and political responsibility as well as raising awareness amongst stakeholders and decision makers about the need for flexible operation, flexibility & storage and the potential contribution of hydropower, as well as the innovation needed at market design level;
- better prediction of the role of hydropower in future electricity systems;
- better assessment of untapped hydropower potential (run-of-river, storage and pumped storage);
- better assessment and understanding of the value side of flexibility, as opposed to just the market side;
- increased investments in hydropower (especially in pumped storage);
- reducing obstacles for the implementation of storage facilities as climate change adaption measures;
- reducing burdens from environmental regulation and accepting the need of social-environmental-economic-compromises.

**Developing new designs and concepts for distributed pumped storage systems and improving the feasibility and cost-efficiency of underground PSH**

**Expected TRL: 4-5**

**Budget range: €1-3M**

**Priority  
High to Very High**

The research challenge is the design of innovative schemes (e.g. closed loop systems) by using mining structures or existing underground openings as lower reservoirs or dedicated excavations to provide the placement of PSH close to consumption centres, in either industrial or urban situations. Besides the use of old mining caverns and tunnels as basins for underground PSH, for smaller applications water supply infrastructure, large building facilities, urban or community decoration (e.g. artificial lakes, fountains etc.) could also be used. The research goal is to identify innovative concepts for such smaller applications, which improve the feasibility and cost-efficiency of underground PSH. Outcomes would include new shaft construction methods, the modularisation of equipment and caverns by better understanding of required geological conditions and environmental concerns. The impact of the research would be a higher attractiveness of distributed small to medium scale PSH.

**Improving the feasibility and cost-efficiency of seawater PSH**

Expected TRL: 6-7

Budget range: €4-6M

**Priority**  
High to very high

The main research objective is to improve the feasibility and cost-efficiency of seawater PSH. This can be done by optimising the design, construction and maintenance of seawater intake/outlet structures for high flow rates (50 - 150 m<sup>3</sup>/s) and medium head (20m-100m) designs. The following challenges need to be addressed by the research:

- hydraulic efficiency and structural design requirements;
- fish friendliness (e.g. reduced approach velocities, top caps, screens, environmental barriers, etc.);
- durability (new material and coatings);
- constructability (e.g. design for installation at sea (prefabrication), reduced weight, suitable installation vessels);
- maintainability and low-cost cleaning solutions (in particular regarding biofouling growth on the screens).

The impact of the research would be to increase the number of PSH schemes which could be built in or along the coastline, using the sea as a reservoir (ideally situated close to wind farms to minimize offshore grid extension costs) as well as seawater PSH as an energy storage system on islands with limited water supplies.

A further outcome should be a multi-criteria inventory/screening of European potential sites for seawater PSH. The opportunities of marine PSH installations along European coastlines or islands, where topographic conditions are relevant, should be considered. In principle, the marine PSH technology has been known for a long time. Nevertheless, only one installation has been constructed and operated at an industrial scale (in Japan at Okinawa). Europe could become a world leader in the development and deployment of this technology which could have an impact on the competitiveness of European hydropower technology. There is a need to help identify further potential sites against



different criteria (i.e. limited impact on the environment; grid proximity; topography; geology; etc).	
<b>Further improving the efficiency and operation range of variable speed pump turbines</b>  <b>Expected TRL: 8-9</b> <b>Budget range: €4-6M</b>	<b>Priority High</b>
Variable speed pump turbines have become a trend in the design of new PSH due to their flexibility. An ongoing research question is how to further increase their efficiency and operational range. The outcome of the research will be enhanced performance, hence profitability, which will have an impact on the attractiveness of PSH projects due to CAPEX and OPEX reduction.	
<b>Developing suitable equipment for low-head PSH</b>  <b>Expected TRL: 4-5</b> <b>Budget range: €4-6M</b>	<b>Priority High</b>
Low head PSH is of interest in countries with less extreme topographies as perhaps found along shorelines and thus is an interesting storage option for wind power generation. The general objective of the research is to develop suitable equipment for low-head PSH. More detail in the design of pumps and pump-turbines requiring a smaller level of submergence is of special interest. An outcome of the research should be to make small-sized PSH and standardised off-the-shelf equipment (i.e. small bulb pump-turbines for low and medium head) more profitable. A more detailed research goal is the development of 5-6 types of hydraulic profiles of small reversible Francis turbines that could be used for most of the available small storage reservoirs (e.g. mines, carriers, etc.) as well as to develop calculation tools to easily define small pump turbine design. Furthermore, developing single stage improvement of PAT as low-cost alternatives for very low heads is of high interest. By proposing reliable, efficient and economic small reversible turbines, based on systemised design in order to eliminate the need for dedicated model tests without detracting from the quality, would have a high impact on the profitability of low and medium head PSH.	
<b>Development of novel black start and grid stability services</b>  <b>Expected TRL: 6-7</b> <b>Budget range: €1-3M</b>	<b>Priority Medium High</b>
The research goal is to develop Intelligent C&I systems for the integration of new technologies (e.g. batteries, power-to-x, redox-flow, etc.). Furthermore, a challenge is to investigate how the potential of hydropower could be even more effective considering the inertia of hydropower supporting the stability of electrical systems concerning voltage and frequency. The outcome should be the identification of the role of hydropower regarding	

**a lack of large generators in “black start scenarios” after the shutdown of fossil and nuclear plants. The impact is related to the safety of the electricity grid.**

### 3.1.2 Research Theme:

#### **Innovative design of turbines including reversible pump-turbines and generators**

**Priority: High**

**Recommended call: initiate research before 2030**

**Recommended funding scheme: €16-25 Million**

#### **Background and challenges**

Today, single-regulated hydraulic turbines (except Pelton turbines) are designed for a narrow range of operation (40% to 100% load). At lower loads, pressure pulsations, vibrations and cavitation may damage the turbine and make operation impossible, leading to lower efficiency. Furthermore, pumped storage plant pump-turbines and motor-generators are designed for 2-3 stop-starts per day, but these will need to increase significantly, potentially to 20-30. Similar performance is expected from pure-generation hydropower plants. Amongst the components that can fail are the generator's high voltage insulation system, which could be damaged by thermal cycling and the higher temperatures associated with power converter technology. Stop starts also cause fatigue in moving parts. The aim is to achieve the highest flexibility in turbine mode with operation from 0-100 % load and no limitation for the minimum load.

Increasing peak power has long been a trend in hydropower projects and it has been made possible by increasing the head, discharge rate or efficiency. The head is specific to the site and cannot easily be changed after plant construction. Boosting power in a refurbishment project is generally accomplished by increasing efficiency and discharge. In pumped storage plants, the trend towards higher heads requires double or multi-stage pump turbines. These will achieve higher power density and deliver higher output.

It is also important to take into consideration the research already done in this area and build upon it. Future research lines should look to build upon what has been addressed in the XFLEX HYDRO and HydroFlex projects, which are large EU funded projects exploring how hydropower may contribute with much-needed flexibility in the system.

#### **SUGGESTED RESEARCH TOPICS AND PRIORITIES**

**Analysing the relation between flexible operation and lifetime reduction**

**Expected TRL: 6-7**

**Budget range: €4-6M**

**Priority  
High to Very High**

Most existing hydropower plants built in the last century have not been designed to provide flexible capabilities as they already experience today due to market liberalisation and as they will be required to do so even more for optimal variable RES integration. Hydromechanical and electromechanical units will have to operate under much harsher operational and load ranges, which may induce fatigue problems in machinery and increase the risk of severe incidents. The main research question is therefore how flexible operation affects the lifetime of the units. The outcome of the research is an adapted maintenance management regime based on continuous risk assessment with the goal being to find a balance between maintenance intervention and risk acceptance. The research outcomes will have an impact on the safe and economic operation of hydropower plants under harsher operational conditions.

**Improvement of operation at minimum load**

**Expected TRL: 6-7**

**Budget range: €4-6M**

**Priority  
High to Very High**

By performing a large number of experimental tests of hydraulic machines operating outside of normal design conditions the research objective is to understand the relation between the machine design and its potential operating limits. The outcome of the research should be calibrated by numerical models that allow empirical relationships to be captured as well as the optimised design of units for (partial) pump load operation, in particular for ternary pump storage machine sets, in order to keep the units and auxiliary systems as small as possible. The impact of the research will be increased reliability, with a positive influence on OPEX.

**Developing reversible pump-turbines fit for purpose in a seawater environment**

**Expected TRL: 6-7**

**Budget range: €4-6M**

**Priority  
High to Very High**

The focus of the research should be on hydraulic heads in the ranges of 50-100 m for seawater pumped storage plants and 3-12 m for tidal range plants. The main research questions are comprising strategies for protection against corrosion and biofouling, and constructability and maintainability of the turbines in high grade stainless steel (super duplex) as well as novel materials. Besides new opportunities for seawater PSH, the impact is related to better exploitation of tidal effects with more efficient pump-turbines.

**Cost reduction of variable speed turbines and ternary set systems**

**Expected TRL: 6-7**

**Budget range: €4-6M**

**Priority  
High**

The goal of the research is to allow the application of variable speed machines at any scale or size through optimised design. The design of pump-turbines for small hydropower

application should be characterised by little technical effort and the operation with as low maintenance costs as possible. The outcome would be methods for low-cost installations. Besides creating new low-head opportunities for PSH, the impact is also related to achieving better profitability.

#### Developing robust designs of hydropower components

**Expected TRL: 6-7**

**Budget range: €4-6M**

**Priority  
High**

The goal of the research is to achieve both electricity production between 0-100 % of peak power and to allow frequent stop-starts for both variable and fixed speed operation. Considering fluid-structure interaction (FSI) a design should be developed which allows a rapid and stable operation mode change in pump-turbines. To address unacceptable vibrations and reduction of cavitation stress on turbine components, air feed-in for stabilisation should be avoided or reduced to a minimum. A further challenge is to develop measures to reduce air bubbles going into the pump, in order to avoid cavitation, therefore developing methods for hydraulic short-circuit operation which do not require air for stabilisation. The outcome will be the application of variable speed machines at any scale or size through optimised design including and considering the following:

- guidelines to design hydraulic machines with a larger operating range;
- evaluation of realistic needs from grid operators to ensure security of supply without high burdens against robust and traditionally designed generators;
- reducing cavitation stress on turbine components;
- enhanced use of electromechanical equipment characterised by:
  - increased maximum possible operating temperature of the high-voltage insulation system to 180 °C;
  - increased number of thermal cycles of the high voltage insulation system according to IEEE standards by a factor of 2.5 (from 1 000 to 2 500 in the case of pure-generation hydropower plants);
  - robust design for turbines and generators;
  - lifetime prediction reliable for all operating conditions including increased stop-starts (today: only for 70% to 100% load);
  - increased lifetime of turbine runners and critical rotor parts (generator) from 1 000 to 10 000 stop-starts in pure-generation hydropower plants and from 10 000 to 100 000 in a pumped storage plant;
  - turbines can be operated at 0 to 100% load;
  - optimised generator design and assembly;
  - evaluate realistic need of grid operators without high burdens on robust and traditionally designed generators.

The research will have an impact on the robust design for turbines and generators.

### 3.1.3 Research Theme:

#### **New models and simulation tools for harsher operational conditions**

**Priority: High**

**Recommended call: initiate research before 2030**

**Recommended funding scheme: €8-15 million**

#### **Background and challenges**

As flexibility will be key for electricity network balancing, and the situation will put considerable pressure on turbines and generators, it will also lead to harsher operational conditions (increased number of start/stops, cavitation, fatigue strength). Most of the present machine sets are not primarily designed to operate under these conditions. Operation at off-design conditions (also referred to as balancing-driven conditions) is therefore expected to be frequent. However, under such conditions, there is high uncertainty about the power plant performance. Accurate prediction of the power plant performance can be helpful for a wide range of activities, such as e.g. power plant design, real-time operation, maintenance plan development, etc. Simulation of system behaviour helps to understand, train and optimise for the management of flood as well as drought situations.

Many problems arising from harsher operating conditions can be solved by applying mathematical modelling, optimisation and simulation models to better understand and estimate the system behaviour including hydromechanical equipment and civil infrastructure. Furthermore, models with neural networks can be created based upon the optimisation and simulation models, as well as on monitoring data under many situations, to ease real-time operation of the systems. The neural network model would link past knowledge of the system and its new prospective operation. Complex tools have been developed at a scientific level, but their complexity makes them difficult to be applied or used by operators. These tools have to guarantee that there is no worsening according to public safety caused by the harsher operating conditions.

In the future, changing conditions in the electricity market and the advancement of digitalisation will change the operational management of hydropower plants. In this context, it must be examined to what extent the technical requirements are met. If not, plants must be technically and digitally upgraded for these future operating regimes.

#### **SUGGESTED RESEARCH TOPICS AND PRIORITIES**

**New simulation tools (also for power system level modelling) for new harsher operational**

**Priority: Very High**

<p><b>conditions in conjunction with the material properties of the machine sets</b></p> <p><b>Expected TRL: 6-7</b> <b>Budget range: €4-6M</b></p>	
<p>Estimating the <b>response needed by the plant to face certain events, and possibly estimating the probability of such events, is very beneficial for reliable and safe operation of the hydropower plant. The main research objective is developing new simulation tools and approaches for power system level modelling, including simulation under new harsher operational conditions in line with the material properties of the machine sets. The expected outcomes are:</b></p> <ul style="list-style-type: none"> <li>• <b>developing modelling tools based on artificial intelligence;</b></li> <li>• <b>better response tools enabling better planning and implementing predictive maintenance measures;</b></li> <li>• <b>developing guidelines to help planners and designers to define the extent of the problem they are facing, to mitigate the problem by using simulation and optimisation models and determining the effects of possible solutions on the existing system;</b></li> <li>• <b>on site use of easily applicable simulation models.</b></li> </ul>	
<p><b>Understanding and numerically predicting the power plant performance under off-design operating conditions</b></p> <p><b>Expected TRL: 4-5</b> <b>Budget range: €1-3M</b></p>	<p><b>Priority: High</b></p>
<p>The <b>main research objective is understanding and numerically predicting the power plant performance under off-design (i.e. balancing-driven) operating conditions. The following research challenges need to be addressed:</b></p> <ul style="list-style-type: none"> <li>• <b>experimental tests at both laboratory and real scale power plants;</b></li> <li>• <b>development and calibration of numerical models.</b></li> </ul> <p><b>The impact of this research will be better operation and management strategies.</b></p>	
<p><b>Demonstration of an integrated approach to address extreme natural events in a harmless and optimised way involving universities, authorities, operators, insurance companies and equipment suppliers</b></p> <p><b>Expected TRL: 6-7</b> <b>Budget range: €1-3M</b></p>	<p><b>Priority: High</b></p>

Modelling of flood operation and/or **operation under extreme weather events is a common task for authorities, operators, insurance companies and equipment suppliers. Accordingly, there is a need to develop an integrated approach between these stakeholders to develop research tools for managing these events in a harmless, environmentally sustainable (e.g. levees or inundating areas for restoring wet areas) and optimised way. The impact will be a reduction of risk (i.e. other than directed against the hydropower infrastructure itself) of damages due to extreme weather or floods and related natural hazards, as well as developing toolboxes with broader possible implementation.**



### 3.1.4 Research Theme:

#### Development and application of a business model for flexibility

**Priority: Very High**

**Recommended call: initiate research before 2030**

**Recommended funding scheme: €8-15 million**

##### Background and challenges

The hydropower business case is representative of some of the issues facing the development of an adequate market model for a new energy system. The energy market has traditionally been based upon competition driven by fuel costs. In the past hydropower was in competition with fossil fired thermal plants. In recent years the decarbonisation policy has led to decommissioning of fossil fired plants. A new energy system, where renewable energy sources (solar, wind, water) will only be developed, needs a new appropriate market model.

The revised Renewable Energy Directive (RED III) increases the overall European Union target for renewable energy in 2030 to 40%. The RED III proposals, however, fall short in terms of supporting energy storage deployment to facilitate renewable energy sources (RES) integration. More precisely, the main challenge for hydropower is the limited payoff in today's markets for flexibility, although hydropower is unique in its ability for providing system flexibility across all timescales.

This lack of compensation for many flexibility services is called: "the missing money problem". In France, the missing remuneration for flexibility could reach 2,2 G€/y up to 2050 (FHE, 2020), with services for the shortest timescale controls (<15 min) to storage needing to be better paid. Grid operational support also needs to be better paid. The incentives for long-term investments are currently insufficient to attract funding for the huge investments needed in developing flexibility technologies.

Moreover, the RED III should address barriers to deployment of hybrid RES and storage projects, simplify and speed up administrative procedures and permitting for energy storage facilities.

The solution to the "missing money" problem is to provide incentives for long-term investment and remuneration for flexibility services according to:

- shortest timescale controls (<15 min),
- voltage regulation on the distribution network,
- capacity made available just in time,
- capacity deferred to deal with congestion,
- power made available for network restoration.

To demonstrate the solution and to give an accurate value to flexibility, a market design must be built on an economic model taking into account the wide portfolio of renewable energy sources, the interconnection and the liquid power markets.

### SUGGESTED RESEARCH TOPICS AND PRIORITIES

**Development and application of a business model for flexibility to decarbonise the energy sector**

**Expected TRL: 6-7**

**Budget range: €8-15M**

**Priority: Very High**

The main research objective is development of an efficient market model suited to a carbon-neutral energy system, where flexibility and storage are properly valued, thanks to an economic model taking into account the wide portfolio of renewable energy sources, the interconnection and the liquid power markets.

Flexibility should be priced through improved day-ahead, intraday, balancing and ancillary services markets. The design of the current balancing and intraday markets must be improved, introducing, for instance, possibilities for electricity trading, with a forward market and a pay-bid balancing mechanism and more sophisticated products, with timeframes that better fit the flexibility requirements (e.g. fast ramp-up, ramp down rates, etc.).

Current projections of Europe's energy system typically assume that the two 'pillar' renewable energy sources will be balanced primarily by battery storage and power-to-gas, with a contribution from demand side measures and sector coupling (EC 2018). This ignores or simplifies the reality, in which Europe has a wider portfolio of renewable energy sources - a mixture of wind, PV, hydropower, CSP, geothermal, ocean energy, heat pumps, solar thermal, etc. All of these will work together to ensure that EU citizens have the power when and where they need it. Flawless operation of such a system is, however, only possible on the back of greater interconnection and liquid power markets.

A system modelling exercise, which specifically considers this wider scenario, has not been identified to date. A comprehensive modelling exercise simulating a 100% renewables-based European energy system would build quantitative evidence to support policymaking in pricing flexibility.

The terms of reference for this system modelling exercise should take into account (IEA 2021):

- 1) characterising hydropower flexibility (PSH, reservoir, pondage, run-of-river, small hydro);
- 2) assessing what are likely to be the most important flexibility services for hydropower in future electricity markets;

- 3) identifying instances of long-duration energy storage solutions currently being provided by hydropower;
- 4) assessing impacts of climate change on precipitation, reservoir inflows, and hydropower operation (including frequency of draught and flooding events);
- 5) identifying current contributions to flexibility needs and assessing future flexibility needs in the 2050 decarbonised power system;
- 6) identifying technologies to fill the gap and role of hydropower;
- 7) developing a set of more specific guidelines for the design of flexibility services and corresponding compensation mechanisms across the timescales in future electricity markets on the one hand and across local issues in future grid operation on the other;
- 8) investigating price formation in a zero marginal cost world and its implication for different types of hydropower plant;
- 9) investigating ancillary services remuneration versus grid code requirements in regard to hydropower services.

Based on such comprehensive modelling, future market designs should be further developed to reward energy, capacity and all ancillary services and associated benefits.

The research impact would provide:

- 1) a value to all flexibility services that hydropower provides to the grid
- 2) a market design of the flexibility within the European Union at different dates
- 3) a business model for the hydropower sector.

## 3.2 Optimisation of operations and maintenance

### Background

Next to efficiency, the availability of a power plant determines productivity. Minimising outage time including by optimising the operations and maintenance intervals is a considerable challenge for hydropower projects delivering balancing power.

Reducing the maintenance cost and effort by keeping high safety standards of hydropower schemes is one of the main challenges of the next ten years. One of the methods that may contribute to the reduction of the maintenance cost is predictive maintenance (condition monitoring). To carry out predictive maintenance of hydraulic installations, better knowledge of the past and future behaviour of the monitored structure is essential. This knowledge involves defining, measuring and analysing behaviour and health indicators. To date, predictive maintenance has been discussed by many companies, while practised by only a few. Industrial Internet of Things (IIOT) sensor solutions seem to be one of the best ways to collect this information to achieve predictive maintenance. The sensors, based on wireless technologies, are often low cost and easy to install, sometimes even revolutionising the way a structure is monitored. This implies a change of approach that involves placing dozens of non-intrusive sensors at low cost (but with degraded measurement accuracy), rather than placing one or two precise and intrusive sensors. Nevertheless, the IIOT sensor technology, differently from other areas such as biomedical or aeronautics, is currently an emerging technology in the field of optimisation of hydropower maintenance. Two main technical issues are:

- the significant increase in the number of sensors requires additional maintenance (battery change, calibration, etc.);
- the collection and storage of large volumes of data are still quite expensive at an industrial level.

The integration of intelligence analysis in the sensor seems promising but to date keeps creating poorly performing solutions because the approach is too general and not mature enough. In addition, environmental sustainability issues require this quantity of sensors to be environmentally friendly, without negative impact on the environment or the ecosystem (e.g. autonomy in energy, eco-friendly constituent materials, etc.).

In view of climate change and the increased risk of flooding, hydropower dams and reservoirs can contribute to the attenuation of the flood peak through proactive management. This needs sophisticated real-time meteorological and hydrological simulation models which can predict the probability of inflowing floods to the reservoir. Loss of energy production due to preventive lowering of the reservoir or changing turbine operation because of the downstream flooding risk, if not foreseen in the concession agreement, and has to be negotiated with the authorities taking advantage of that protection. Artificial intelligence, combined with proved methods and long-standing

**expert systems will help convince the Authorities to reduce production losses whilst improving hydrological warning alerts to pass floods and hence improving resilience.**

### 3.2.1 Research Theme:

#### Digitalisation and artificial intelligence to advance instrumentation and controls

Priority: High

Recommended call: initiate research before 2030

Recommended funding scheme: €16-25 million

##### Background and challenges

The evolution in sensors has led to the era of big data, in which industries increasingly base their activity on the management of information and data. Likewise, for the extraction of useful information from heterogeneous and incomplete datasets, (corresponding to systems whose processes are not well known) tools have been developed in the field of machine learning. In general, dam monitoring databases do not reach the size corresponding to big data, but machine learning algorithms can be a useful tool for extracting the maximum amount of information. However, the efforts made to date are limited in time and application. In many cases, they are academic examples, preliminary results, or cases of application to specific structures. The published results demonstrate the ability of this technology to improve performance, but specific efforts are needed to make this a commonly used tool.

State-of-the-art control systems and instrumentation are at the centre of the digitalisation of operations in hydropower plants and should become standard to increase the efficiency of hydropower operation. There is a need for instrumentation to analyse the impacts, reactions and actual condition of hydraulic structures. At the same time, it is important to optimise maintenance intervals and to achieve higher safety levels, as accurate risk assessment, integrated into a monitoring system, is becoming increasingly important for operation and maintenance, and the resilience of infrastructures. There is also the need to better exploit sensor data to reliably track failure patterns and make use of big data as the basis for predictive maintenance.

**The further automatisation and digitisation of hydraulic power plants will allow** them to improve their competitiveness, flexibility and operational safety. Remote monitoring of the behaviour of machines and infrastructure **makes it possible to increase** hydropower availability, to optimise **maintenance and its cost (i.e. conditional and predictive maintenance)**, to improve the performance (yield) and to control the risks associated with operation. Existing data analysis tools may not be efficient in cases where there is **strong coupling between different monitoring devices or when there are strong non-linearities in their response**. Sensor data and AI give promising tools to overcome these limitations and are key elements to reliably track failure patterns and make use of big data for

**predictive maintenance. Also, plant fleet optimisation will need much more data than currently used.**

**In addition, many hydropower plants (reservoirs) are still operated following conventional methods, e.g. based on rule curves, pool-based rule curves or other if-then-else logic. These operational protocols have been designed to fit a wide range of hydrological and meteorological conditions. To make better use of the system, weather forecasts should be used for water management more frequently. Better forecasts enable more sustainable, profitable and secure operation of reservoirs. Several physical and statistical models are now available in order to forecast the inflow at specific points within the catchment area, but they are often expensive and with no appropriate level of accuracy (especially for medium/long term scenarios). Remote data from satellites are promising for advanced precipitation and inflow forecasting.**

### **SUGGESTED RESEARCH TOPICS AND PRIORITIES**

**Integration of weather and flow forecast with production plans, flood risk reduction, environmental flows and other water uses**

**Expected TRL: 6-7**

**Budget range: €4-6M**

**Priority: Very High**

**The main research objective is the integration of weather and flow forecast with production plans, flood risk reduction, environmental flows and other water uses, as well as making optimisation and ensembles operational. The following challenges, which also consider the effect of climate change, need to be addressed:**

- **applying artificial intelligence to existing data;**
- **combining weather and flood forecasts with flood passing routines;**
- **developing both more accurate weather forecast models and high performing models to transform meteorological data in inflow forecasts by using satellite data;**
- **integrating societal acceptability and responsibility definition for anticipating floods by discharging more at the beginning of the flood by lowering the reservoir by preventive turbinning (or pumping) or release of water through bottom outlets;**
- **improving the planning of hydropower production (especially for run- of- the- river power plants) and at the same time (especially for long term scenarios) optimising general purpose water usage (e.g. irrigation, tourism, etc.);**
- **developing optimisation methods that find the global near-optimum for nonlinear and integer problems and improving existing generic algorithms in view of more reliable flow forecast;**
- **further development of decision support from ensemble forecast for operators.**

**Expected outcomes of such research include:**

<ul style="list-style-type: none"> <li>• <b>better use of the system flexibility</b>, including reservoirs <b>under conflicting usage</b> (e.g. yield (i.e. hydropower), <b>societal benefits</b>, <b>environmental obligations</b>, <b>mitigation of climate change</b> etc.) <b>identifying potential societal difficulties and responsibility issues with stakeholders and proposed solutions</b>;</li> <li>• <b>reduction of forecast uncertainty leading to better production forecast increasing market opportunities and profitability</b>, <b>less load balance violations and less violation of obligations</b>;</li> <li>• <b>higher quality of forecasts and enabling of long-term forecasts</b>;</li> <li>• <b>optimisation of reservoir management with more precise operation of hydraulic structures in case of floods, sediment deposition in reservoirs etc.</b>;</li> <li>• <b>development of a methodology to make real-time meteorological and hydrological simulation approaches reliable and acceptable from the dam resilience perspective</b>;</li> <li>• <b>scientific comparison of existing applications to assess the effectiveness of different measures and installed devices with additional modelling and simulation to help to optimise best practice solutions.</b></li> </ul>	
<p><b>Developing a seamless, integrated and knowledge-based system from components and system conditions, as well as resources to optimise revenue generation from energy and flexibility markets</b></p> <p><b>Expected TRL: 6-7</b> <b>Budget range: €4-6M</b></p>	<p><b>Priority: High to Very High</b></p>
<p>The main research challenge is the development of digital twins of generation units/plants, market and business models, environmental monitoring/imaging/prediction, inflow modelling and prediction. The desired outcomes include improved decision-making processes with the use of numerical twins and more accurate models and algorithms to replicate <b>hydropower plant performance</b>.</p>	
<p><b>Development of criteria and methodologies for the application of machine learning algorithms, (including jointly with numerical models for different objectives related to the resilience of dams) and creation of a common repository for the storage of dam and powerplant monitoring data including incidences</b></p> <p><b>Expected TRL: 4-5</b> <b>Budget range: €1-3M</b></p>	<p><b>Priority: High</b></p>
<p>The main research objective is the development of criteria and methodologies for the application of machine learning algorithms (including jointly with numerical models) for different objectives related to the resilience of dams. This would include necessary</p>	



**creation of a common repository for the storage of dam powerplant monitoring data including incidences. The following challenges need to be addressed by the research:**

- development of predictive models;
- definition of alert thresholds;
- interpretation of the behaviour of the structure in response to the acting loads;
- development of criteria for standardisation and anonymisation of the data;
- developing case studies, benchmarks and systematic analyses without the need to include dam identification to avoid sharing sensitive data among HPPs;
- detailed analysis of aspects related to data preparation and exploration as it is common for dams with several decades of operation to have heterogeneous data series, with different reading frequencies in different periods,
- conducting R&I studies on the behaviour of dams of different typologies and the effect of influential variables for the early detection of anomalies **including aspects such as location, climatic conditions, or date of construction.**

The **outcome** will be common criteria and methodologies that **enable comparison of data from different dams and hydropower plants with a valid reference, providing valuable information for further learning.** Further impact would be an improvement in resilience and enhanced risk assessment of hydropower infrastructure.

**Enhancing computer models to optimise control system structures, including for run-of-river power plants**

**Expected TRL: 6-7  
Budget range: €1-3M**

**Priority: High**

The **main research objective** is optimising the control system structures, including for run-of-river power plants, via enhanced computer models. To achieve this, the following **challenges need to be addressed:**

- covering chains of barrages with super-ordinated control systems, flush operation modes and other complex discharge management processes, optimisation of flush mode energy production, etc.;
- optimisation of control leads to the maximisation of electricity production without increasing the impact of the barrages.

The **outcome** will be the **availability of accurate models and algorithms to replicate the hydropower plants performance.**

**Further development of the high-performance approach for the Hydropower Modernisation Initiative (HMI) designing and development of devices satisfying dynamic demands**

**Expected TRL: 4-5**

**Priority: High**

<b>Budget range: €1-3M</b>	
<p>The research objective is further development of the high-performance approach for the Hydropower Modernisation Initiative (HMI) designing and development of devices satisfying dynamic demands. The challenge here is combining sensors with regulation devices. The impact is the better use of hydropower in a volatile market with economic benefits.</p>	
<p>Developing cheap, easy-to-install, industrial WIFI enabled sensors/actuators/controllers and energy-independent sensors</p> <p><b>Expected TRL: 4-5</b> <b>Budget range: €4-6M</b></p>	<p><b>Priority: Medium High to High</b></p>
<p>The main research objective is increasing the data quantity and quality from HPPs (e.g. water flow meters for penstocks are still very expensive and difficult to implement), thus delivering relevant indicators of the state of health of the machine being monitored. This will allow the operator and the maintenance teams to program the associated maintenance before a breakdown occurs, and at times when the machines can be stopped. The main research challenge is developing the process of data gathering and HPPs' real time monitoring. The outcome would be availability of accurate information on the actual conditions of equipment and infrastructure, providing data input for the optimisation of maintenance. Other research challenges are conducting R&amp;I activities focused on edge computing (including cyber security), energy harvesting and eco-friendly connected sensor technologies. Overcoming these will enable reliable diagnostics of the abnormal behaviour of machines, to be used by engineers in the remote monitoring centre to:</p> <ul style="list-style-type: none"> <li>• make a reliable diagnosis following the detection of a behavioural fault;</li> <li>• win in anticipation of breakdowns (i.e. speed of diagnosis);</li> <li>• support to the operator by formulating recommendations.</li> </ul> <p>For this purpose, a diagnostic assistance tool is needed, in order to:</p> <ul style="list-style-type: none"> <li>• take advantage of experts' knowledge providing support;</li> <li>• model the diagnosis of the experts;</li> <li>• test these models through collective intelligence.</li> </ul> <p>This should lead to the development of a "medical type" help tool for machine diagnosis based upon the exploitation of collective intelligence by artificial intelligence. R&amp;I on this should include the following steps:</p> <ul style="list-style-type: none"> <li>• initial modelling of the diagnostic process of the multi-parameter monitoring of a hydraulic machine;</li> <li>• application of AI methods for proposal of machine diagnostics, based on business references, reference databases and capitalised diagnoses;</li> <li>• realisation of a proof of concept of an expert diagnostic tool;</li> <li>• validation of the tool under real surveillance conditions by operators;</li> <li>• developing and implementing reliable and high-capacity connection systems and networks.</li> </ul>	

**Outcomes** would include the **availability of intelligent, autonomous and sustainable IIOT sensors / automatic diagnostic tools automatically delivering predictive asset maintenance recommendations** allowing operators to:

- **retrieve and collect data from remote sensors located in isolated areas;**
- **anticipate failing by detecting anomalous precursors;**
- **guarantee the resilience and performance of the fleet;**
- **enhance availability and lifetime of equipment;**
- **reduce maintenance costs (anticipation); and**
- **use less resources dedicated to maintenance activities.**

**Further impacts** would include:

- **better knowledge about relations** between operation, loads, degradation and lifetime;
- **suitable cyber-protection systems for improved security of generation and grid infrastructure from cyber-attacks;**
- **incorporation of new digital technologies into professional practice in safety studies to open new possibilities for increasing the resilience and efficiency of hydroelectric generation schemes;**
- **better social acceptance of hydropower and hydro related projects in general;**
- **availability of highly trained personnel to operate these innovative digital systems.**

**Developing novel environmental scanning methods and tools**

**Expected TRL: 4-5**

**Budget range: €1-3M**

**Priority: Medium High to High**

The **main research objective** is to develop **special scanning tools and machines for environmental aspects** such as river scanning for sediment control and transport. The **impact would be greater mitigation of environmental impacts.**

### 3.2.2 Research Theme:

## Monitoring systems for predictive maintenance and optimised maintenance intervals

**Priority: High to Very High**

**Recommended call: initiate research before 2030**

**Recommended funding scheme: € 2-7 million**

### Background and challenges

**Higher** availability of hydropower plants, as with any machinery and equipment, actually translates into minimisation of the outage times of these plants. Such plants need to be available when required. For this reason, more effort must be focused on the deployment of intelligent sensor-based condition **monitoring systems** within the hydropower **plants**, to detect early failure mechanisms or postpone unnecessary maintenance actions, i.e. **avoid unplanned outages (failures), limit planned outages, thereby providing higher** overall plant availability. Moreover, additional **investigations are required to develop a strategic asset management** approach in power**plants based** upon the exploitation of predictive maintenance software, facilitating the design of optimal predictive maintenance strategies for optimising HPP machinery maintenance **management in combination with sediment management**.

**Today's monitoring systems are used mainly to avoid equipment failure** rather than to optimise maintenance intervals. Knowing when to maintain the plant will become more important as plants are **operated in ways that will tend to wear out components faster, such as** operating at low-load or as a spinning reserve.

**Obtaining data from existing systems is of high value, allowing deeper knowledge of the system and its functioning condition. It serves as input data for the design of future systems and knowledge of system behaviour improves our understanding of its yield under different operational strategies. Older infrastructure are often poorly equipped with monitoring systems, and very often only geodetic survey and traditional piezometers are the only available data for systems including dams and reservoirs. To be more efficient, e-Monitoring systems need improved wear and tear models, data process management and qualification. This is of great importance to secure efficient operation and maintenance practice for European hydropower resources.**

### SUGGESTED RESEARCH TOPICS AND PRIORITIES

**Developing monitoring techniques that isolate the effect of materials on lifetime needs and modelling the cost of service (wear and tear) in relation to expected gains**

**Priority  
High to Very High**

<b>Expected TRL: 6-7</b> <b>Budget range: €4-6M</b>	
<p>Maintenance intervals and lifetime are also affected by the choice of material (like coating) used for <b>different hydropower components</b>. <b>The purpose of the research is to increase operational resilience and optimise</b> power generation. The outcome of the research should be better selection criteria including structural fatigue <b>and durability for coatings</b> as well as improved coating of hydraulic machinery and equipment taking into account sediment abrasion problems. <b>The research impact will be an increase in operational resilience and optimisation of hydropower generation.</b></p>	
<b>Develop new online monitoring and diagnostic systems with intelligent sensors that predict the optimal maintenance interval based on the method of operation</b>  <b>Expected TRL: 6-7</b> <b>Budget range: €4-6M</b>	<p><b>Priority High</b></p>
<p>In collaboration with operators and OEMs the <b>objective of the research is to build prototype monitoring systems and to install them into plants (integrating them into plant SCADA)</b>. The goal should also be to <b>develop innovative monitoring concepts by using intelligent sensors measuring equipment form</b> (e.g. non-destructive materials). Furthermore, new and intelligent models to support the decision-making process should be developed which can be used for both operation and maintenance. The <b>outcome will be improved hydropower plant operating efficiency by early detection of sub-optimal operation and impact</b>. Furthermore, <b>machinery efficiency and reservoir level management can be optimised</b>. <b>Intelligent monitoring systems allow</b> for a broader implementation of predictive maintenance (Predict/early detect faults; Identify root causes automatically and minimise downtime), thus anticipating major and minor failures, <b>optimising maintenance planning and reducing outage time (increasing the availability of machine units) and lost production</b>. Thus, this will have an impact on operational resilience and optimisation of generation as well as on O&amp;M costs. The residual life of key components can be estimated by optimising checks and maintenance intervals. Furthermore, the risk of severe accidents can be reduced significantly to very low and acceptable levels. The tracking of consumption of hazardous materials can be improved.</p>	

### 3.3 Resilience of electromechanical equipment

#### Background

Over the past decades, hydropower equipment has been optimised to achieve high performance, availability and flexibility. Nevertheless, hydromechanical equipment manufacturers are under continuous and growing pressure to innovate. In Europe, the EU's decarbonisation agenda is requiring the improvement of hydropower equipment, whilst abroad, other manufacturers are threatening to take market share from a sector that is a valuable source of export earnings for the European economy.

**Flexibility in power generation and storage** can be defined as the capability to increase the operating range, both in generating and pumping mode, allowing the power plant to operate at deep part load and to quickly change power output and input. Variable speed generators provide an answer to these needs. However, flexibility implies trade-offs in the design of the electro-mechanical equipment as more flexible designs entail lower efficiency rates. The efficiency of electromechanical equipment, especially turbines, can be improved through better design and by selecting a turbine type with an efficiency profile that is best adapted to the duration curve of the inflow. Therefore, it is important to quickly and accurately model turbulent flow and performance for a wide range of discharge rates.

Upgrading offers a way to maximise the energy produced from existing hydropower plants and may offer a less expensive solution to increase hydropower production. Gains of 5 - 10% in production and even more in peak capacity are realistic, cost-effective targets for most hydropower plants. Potential gains could also be higher at locations where non-generating dams are available. Investment in repowering projects, however, involves both technical and legal risks (e.g. risks associated with the re-licensing of existing installations, often designed several decades ago, with only limited records of technical documentation). As a result, significant potential is left untapped. However, today's technologies allow for an accurate analysis of geology and hydrology, as well as precise assessments of potential gains.

Renovation, modernisation and upgrading of old power plants is less costly, requires less time and usually has a smaller or even zero additional environmental and social impact than developing a new power plant. These types of projects usually consist of selectively replacing or repairing components in the powerhouse (such as runners, generator windings, governors or control panels). Normally, electromechanical equipment needs to be renewed or replaced after 30-50 years, whilst the civil structures last longer before requiring renovation. The overall lifespan of a hydropower plant exceeds 100 years when properly maintained. As well as extending plant life, upgrading projects may lead to incremental increases in hydropower generation due to more efficient turbines and generators. Moreover, retrofitting a power plant, using generating equipment with

improved performance, often helps to answer market demands for more flexible, peaking modes of operation.

### 3.3.1 Research Theme:

#### New materials for the increased resistance and efficiency of equipment

**Priority: Medium High to High**

**Recommended call: initiate research before 2030**

**Recommended funding scheme: €8-15 million**

#### Background and challenges

The flexible use of hydropower can cause some problems for electromechanical equipment as many hydropower plants have not been designed to provide balancing power continuously. Amongst the components that can fail is the generator high voltage insulation system, which could be damaged by thermal cycling and higher temperatures associated with power converter technology. Therefore, advances in generator insulation systems would lead to increased machinery lifetime and decrease the number of repairs. On top of that, cavitation, draft tube pressure pulsations and vibrations are also likely under the conditions arising from a more flexible operational range, thus damaging electromechanical equipment. Moreover, high concentrations of hard particles in the water, especially hard and angular ones such as quartz and feldspar, can harm certain turbine parts, quickly abrading surfaces and causing the turbines to become less efficient. Surfaces exposed to a high relative water velocity are damaged the most.

Higher material resistance to cavitation and erosion would lead to an increase in hydraulic machinery lifetime and decrease the number of repairs. Considering lessons in propeller design from other fields of engineering (i.e. naval) might be useful, to increase the endurance of components subject to cavitation and to improve their resistance against erosion, in particular in transient situations where cavitation can occur.

#### SUGGESTED RESEARCH TOPICS AND PRIORITIES

**Development, testing and industrialisation of innovative smooth non-metallic repairing techniques for penstock, gates, using polymers, resins and other materials**

**Expected TRL: 6-7**

**Budget range: €4-6M**

**Priority: High**

The **research objective** is development, testing and industrialisation of innovative smooth non-metallic repairing techniques using polymers, resins, etc. The **outcome of this research will be the development of alternative “smooth” non-metallic repairing techniques and**



**materials that can be applied on-site, avoiding heavy disassembly/reassembly and loss of time in remote industrial workshops to avoid significantly long shutdown and loss of generation during the repair of mechanical equipment on a key component of the hydropower system (e.g. penstock, gates, valves, pipes, etc.).**

**Development of novel metallic coating material**

**Expected TRL: 6-7**

**Budget range: €1-3M**

**Priority: Medium High to High**

The majority of the world's hydroelectric projects utilise coating and lining systems that enhance the structural integrity and serviceability of these infrastructures. Coatings and linings are key to managing the structural integrity and serviceability of penstocks, **providing corrosion protection, water tightness, and aesthetics. The research challenge is the development of novel coating materials (e.g. steel). The impact will be better resistance against cavitation and abrasion due to suspended sediment in water and improvement of maintenance cycles (i.e. power plant outage).**

**Development of near-superconductive materials and innovative insulation materials that are carbon based**

**Expected TRL: 4-5**

**Budget range: €1-3M**

**Priority: Medium High**

The **research challenge** is the **development of near-superconductive materials and innovative insulation materials that are carbon based. Desired outcomes include:**

- **Increase max. possible operating temperature of the high-voltage insulation system to e.g. 180 °C**
- **Increase the number of thermal cycles of the high voltage insulation system according to IEEE standards by a factor of 2.5 (from 1 000 to 2 500 in the case of pure-generation hydropower plants)**

The **research objective** is also conducting scientific assessment on the effectiveness of using **near-superconductive materials and innovative insulation materials** in hydropower plants responding to the technical demands to new generators or grid connected devices. The study should be based on a realistic portfolio of generators and grid constellation in European areas. This assessment would highlight the real needs for a change in the transient behaviour and robustness against unsteady grid situations.

### 3.4 Resilience of hydropower infrastructure and operation

#### Background

**The resilience of hydropower structures means the capacity and adaptability to operate in adverse situations, which may range from extreme events to slightly different changes in hydrological patterns from those for which the power plant and related infrastructure have been primarily designed (including civil, hydromechanical and electrical systems).** Extreme adverse situations for hydropower plants and infrastructure resilience derive mainly from extreme flood events that can cause landslides, slope instabilities, GLOF (Glacial Lake Outburst Flood) or other natural hazards such as earthquakes. The priority is, therefore, to maintain or even increase the resilience of infrastructure against these threats. Another source of risk is the ageing of infrastructure, which causes a decrease or variation in structural material strength properties. In the coming decades, more and more infrastructures are going to reach the end of their expected life span (100 years) and most of them will need retrofitting. Through regular monitoring and risk assessment, infrastructure owners can manage risks from natural events. Moreover, it is important to consider that climate change will increase the risk of natural hazards (such as floods, droughts, wood fires, wind storms, sediment yield into reservoirs, landslides, rock falls etc.), multiplying threats for hydropower infrastructure in the future.

Since the end of World War II, nearly half of the failure of embankments that have occurred was due to overtopping. This can be due to the settlement of the embankment crest or embankment deterioration as well as changes in hydraulic loading. For concrete dams and appurtenant structures, the small number of failures that have occurred have been mainly associated with foundation problems. Since the third quarter of the last century, concrete swelling cases have occurred in some dams and infrastructure, which led to investigations into their causes and effects and forced the dam owners to implement important preventive and rehabilitation works.

Earthquake resilience is also a priority to ensure infrastructure safety. Most existing dams were designed using old methods and it is highly advisable to re-evaluate their seismic resilience. Many small dams are very sensitive to earthquakes and reinforcement works may be necessary. Multiple seismic hazards associated with rockfalls, landslides, ground settlements, liquefaction, and other factors, should also be considered.

Pumped storage schemes usually result in daily variations in the reservoir levels which can cause fatigue problems in structural materials of the retaining structures - an issue that deserves attention and research. Civil infrastructure also includes spillways, waterways (i.e. channels or underground tunnels), powerhouse structures and other appurtenant works, which are also subject to the conditions stated above. All these structures have to be monitored, using the best technologies and practices available, to ensure their safety and resilience. Accordingly, the implementation of Automatic Data Acquisition Systems

**(ADAS) is highly advisable at most dams, associated with reliable safety assessment models, risk analysis and warning emissions.**

Hydropower infrastructure **also needs** to be rethought through a **multi-purpose perspective**. Indeed, **multipurpose hydropower infrastructure is often mentioned as a provider of co-benefits such as regulating river flows and managing floods<sup>9</sup>** but also for delivering additional services such as water supply, irrigation, fish farming, navigation, tourism and leisure activities.

**Finally, even if dams and hydropower plants are critical infrastructures in view of operation and safety, the associated risks are small compared to other energy technologies. However, since the consequences may be significant in the case of failure,** continuous efforts for managing and reducing the risks are required. That is why dam safety has been one of ICOLD's highest commitments for almost a century<sup>10</sup> and IHA has launched the Climate Resilience Guide for the hydropower sector to identify, assess and manage climate change risks associated not only with the infrastructure but also with the operations.<sup>11</sup>

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<sup>9</sup> International Renewable Energy Agency, (2020). *Global Renewables Outlook: Energy transformation 2050*

<sup>10</sup> ICOLD, (2019). World Declaration on Dam Safety

<sup>11</sup> IHA, 2019.

### 3.4.1 Research Theme:

**New materials and structures for increased performance and resilience of infrastructure**

**Priority: Medium High to High**

**Recommended call: initiate research before 2030**

**Recommended funding scheme: €8-15 million**

#### **Background and challenges**

New materials for sealing and abrasion **resistance of hydraulic structures are needed. The use of geomembranes is widespread** for managing leakage issues. Nevertheless, ageing of these geomembranes is of great concern for dam owners/operators. Many chemical products and injection methods exist for sealing and strengthening **old concrete structures**, but the general application and design procedures are missing.

**To illustrate, new materials could be used in the lining of** hydropower waterways. Friction losses in tunnels, shafts and penstocks represent about 10% of gross head and are thus a considerable hidden energy potential. Inspired by biology, there are special surface morphologies which can significantly reduce friction. Geomembranes could be developed with such surfaces that could be applied in concrete-lined tunnels in parallel with rehabilitation (i.e. tightening) works or as corrosion protection in steel-lined tunnels and shafts.

**In the same manner, the durability and longevity of hydraulic structures need to be increased to improve the** overall efficacy and life-cycle cost of hydropower. Improving service life of appurtenant water-conducting structures (e.g. canals, tunnels, shafts, inlets and outlets) would reduce damages/loss of structural integrity and increase the life span of water containing structures (**e.g. penstock tunnels**).

**More intense impacts, such as from increased sediment yield due to climate change, endanger the cost-effectiveness of hydraulic structures and machinery. Ageing water retaining structures may lose their watertightness and require costly refurbishment.**

In addition, a better understanding of **how operations and hydropower generation output are affected by extreme events is necessary to include structural and functional adaptation measures into the design of rehabilitation projects and new projects. Examples of structural measures could be additional sediment management facilities, raising of the dam crest, increased spillway capacity, additional intakes at different levels, flood defences for the powerhouse, etc. Amongst functional measures can be changes in minimum operating level, changes in operating rules, sediment management operations,**

increased maintenance and **re-thinking the type of schemes and ancillary services provided by hydropower.**

### SUGGESTED RESEARCH TOPICS AND PRIORITIES

**Research into extreme flood events for a better assessment of risks to hydropower operation and structures**

**Expected TRL: 6-7  
Budget range: €4-6M**

**Priority: High to Very High**

There is high uncertainty related to predicting the frequency and magnitude of extreme events, which have been **occurring at increasing rates** due to climate change. **Better understanding of how hydropower operations and generation output are affected by changes in extreme events is needed. The impact of research would be reduced uncertainty in the assessment of extreme flood events, and more reliable assessments to quantify the risks to hydropower hence more cost effective operation and maintenance of hydropower infrastructures.**

**Better understanding of the hydro-abrasion process and wear of hydraulic structures and associated mechanical equipment**

**Expected TRL: 4-5  
Budget range: €1-3M**

**Priority: High**

There is a need for new materials for sealing and abrasion resistance of hydraulic structures and associated mechanical equipment (**e.g. spillways, sills, gates, tunnels, etc.**). **The challenge is to cross-compare different materials regarding their life-cycle cost and develop new watertight materials for refurbishment works. The impact of this would be better durability, longevity and increased resilience of hydropower structures, including improved watertightness of water retaining structures.**

**New compound and combined materials for construction**

**Expected TRL: 4-5  
Budget range: €1-3M**

**Priority: Medium High to High**

There is a need for new compounds and combined materials for construction, which are adapted to the requirements of hydraulic structures. The **impact** would be increased operational reliability **and lowered maintenance costs.**

**Monitoring and diagnosis of geomembranes**

**Priority: Medium High**

<b>Expected TRL: 6-7</b> <b>Budget range: €1-3M</b>	
<p>Geomembranes are widely used for sealing structures. However, ageing of these geomembranes is a critical issue for dam owners/operators. The research <b>challenge is to develop novel approaches to monitoring and diagnosis of geomembrane</b> performance. <b>The impact would be better sustainability and security of hydraulic works through better evaluation of existing</b> geomembrane condition <b>and</b> the need for <b>rehabilitation works</b>. <b>This would allow</b> an extended lifespan for some existing structures as well as more timely rehabilitation works, where required.</p>	
<b>Development and application of geomembranes with friction reducing surface morphologies</b>  <b>Expected TRL: 4-5</b> <b>Budget range: €1-3M</b>	<b>Priority: Medium High</b>
<p>A reduction in friction losses in tunnels, shafts and penstocks has the potential to unlock hidden energy production gains. To achieve this, there is a need for the development of geomembranes with friction reducing surface morphologies, as well as development of equipment, which allows the fast application of such geomembranes in existing tunnels (i.e. 1 to 2 km per week). The <b>impact would be reduced friction in waterway systems of high head power plant and increased energy generation by about 5 %</b>. The <b>interval time between maintenance activities (e.g. power plant outage) would be increased, together with the availability of the power plant</b>.</p>	

### 3.4.2 Research theme:

**Databases of incidents and extreme events, integrated structural risk-analysis models and innovative solutions for multi-hazard risk analysis**

**Priority: High**

**Recommended call: initiate research before 2030**

**Recommended funding scheme: €8-15 million**

#### **Background and challenges**

Dams are complex structures involving many elements and components including **civil engineering structures, electromechanical equipment and data acquisition systems (SCADA – Supervisory Control and data acquisition/ADAS – Automated Data Acquisition system)** which are applied to safety structural monitoring, support maintenance teams, hydrological forecast systems, **energy placement in electricity markets, human organisation etc.** **Consequently, a systemic functional approach based on risk analysis is a necessary tool to** identify and address the main risks and improve dam resilience and dam operation.

**However, whilst considering the ageing of dams and associated structures, the modernisation and optimisation of monitoring programmes and devices should be carried out** with a view to improving structural resilience. Automated data acquisition systems with trigger alerts should be implemented, incorporating new monitoring devices based upon the development of recent technologies.

Whilst increasingly more accurate hydrological data is **available, and climate change effects can be better foreseen, the effect on existing dams needs to be studied and, in many cases, geological studies need to be updated and geotechnical parameters must be evaluated or confirmed.** More information about earthquake effects on dams and appurtenant structures are also available, but this data is scattered. Their collection and interpretation would allow for feedback and recommendations to be made. Moreover, research on dam engineering, especially seismic safety and regulations, is one of the most important priorities. Multi-hazard risk analysis is required for up-to-date safety assessments and intervention prioritisation. Related to this topic is the hydraulic and seismic resilience of structures, especially embankments. The EC legislation on design for floods and seismic action has to be harmonised by taking into account unique regional conditions.

**Integrated structural analysis and risk analysis models and related R&I activities include structural analysis of the dams with appurtenant structures (i.e. diversion tunnels and spillways) and intake and headrace structures employing advanced numerical tools.**

Furthermore, technical monitoring and measuring of various data for dam and appurtenant structure behaviour can be used for comparison with calculated data (output results) from the numerical analyses. In such a case, calibration can be carried out, thus allowing verification of the numerical calculations and monitoring instrumentation or identification of any required modifications. Embedding enhanced structural analyses and material models into the design process increases financial benefits and allows the sites to align better with their environment.

There is a need for a larger number of dams to be equipped with seismic monitoring systems (preferably automatic) to increase knowledge about actual dam behaviour under seismic conditions, in particular under medium-strong earthquakes. Masonry dams that are old and designed according to outdated technical standards, are the most likely to require reinforcement. The most commonly used techniques are the installation of an earth backfill and the setting up of active or passive anchors within the foundation. Other techniques, such as the construction of concrete facings on the upstream dam face, also improve the strength and reduce leakages. Moreover, the drilling and rehabilitation of old drainage systems is also a typical intervention to improve the dam resilience from sliding.

Today, these solutions are often designed using pseudo-static approaches using simplified models that do not take into account the complex interactions that exist between the dam and its reinforcement. In particular, during a seismic event, the effect of the reinforcement can have negative consequences and damage the masonry structure. The impact of seismic loading on these strengthened dams is, therefore, an open question. Amongst the different technologies that can be applied for the reinforcement of dams, is the use of FRCM (Fiber Reinforced Cementitious Matrices).

### SUGGESTED RESEARCH TOPICS AND PRIORITIES

Collecting and/or updating international data regarding the dynamic behaviour of structures, seismic accidents and the behaviour of hydraulic systems, structures and mechanical equipment (gates etc.) during earthquakes

**Expected TRL: 6-7**

**Budget range: €1-3M**

**Priority: High to Very High**

To resolve the issue of scattered data on the effect of earthquakes on dams and appurtenant structures, there is a need to compile and/or update relevant international data. This can be achieved by collating feedback on seismic accidents and the behaviour of structures during earthquakes with the goal of sharing this information amongst HPP operators.

Another goal would be implementing a sensor network (e.g. type BARTEC-SYSCOM) over a one-year period on a dam structure (and/or a sectional valve) to collect data that would



characterise the vibratory response of the structure under natural micro-seismicity or ambient vibrational noise, along with assessing the structural dynamic behaviour variations according to natural conditions and seasonality (e.g. by the execution of periodic forced vibration tests and **by the implementation of Dynamic Structural Health Monitoring systems**).

Further steps might include the creation of guidelines to guarantee a general standard of seismic monitoring systems suitable for different dam typologies and sites. **Additionally, there is a need to improve diagnosis and monitoring of specific hydraulic systems potentially linked with the seismic risk. This can be achieved by using passive seismic techniques** based on measurement of the ambient noise that allows a very sensitive analysis of the ground (or concrete) and of any change in its state (e.g. stiffness, homogeneity, etc.).

The research **outcomes** would be:

- **broadened knowledge about seismic event effects on dams and appurtenant structures;**
- **defining of appropriate margins used in calculations / improved design;**
- lowered cost of upgrading or rehabilitation of structures;
- enhanced monitoring and warning of structures;

**New probabilistic design and risk analysis approaches**

**Expected TRL: 4-5**

**Budget range: €1-3M**

**Priority: High to Very High**

The **main research objective** is the development of **new probabilistic design and risk analysis approaches to overcome uncertainties related to floods and earthquakes**. Priority actions should include **developing and implementing nonlinear numerical models associated with safety evaluation to support risk analyses, focusing on AI, expert systems and neural network systems**. Developing failure modes analysis of dams and appurtenant structures (a system analysis approach is required). Another priority is the preparation and issuing of guidelines on the use of dam risk analysis. The impact would be improved efficiency for the design and verification of structures under main hazards (e.g. earthquakes and floods); more appropriate design for the reinforcement of dams when required; safer, more resilient and more efficient hydropower infrastructures; better knowledge of the eventual structure weaknesses and improved understanding of them, which enables prioritisation of efforts in managing a dam resilience program either for a specific dam or for a set of dams; as well as financial benefit (maintenance/design) and better alignment with the site environment.

**Collecting, updating and interpretation of international data on large and extreme floods in Europe**

**Expected TRL: 4-5**

**Priority: High**

<b>Budget range: €1-3M</b>	
<p>The <b>research challenge</b> is collating feedback on <b>large floods and</b> the behaviour of structures during floods with the goal of sharing this information <b>amongst</b> HPP operators. Key points are:</p> <ul style="list-style-type: none"> <li>• nature of the flood hydrograph;</li> <li>• <b>floating debris which might block spillway;</b></li> <li>• <b>reliability of gates (mechanical and control);</b></li> <li>• <b>organisation</b> (response) and flood management.</li> </ul> <p>An <b>update of</b> this data would allow an investigation of hydropower systems with large reservoirs, in order to better understand their flood resilience and possible effects on downstream valleys, as well as allowing a detailed comparison of observed peak floods and different <b>methods</b> used in the determination of flood events. <b>The impact would be reduced erosion risk for concrete chutes, plunge pools and dissipation structures, as well as lowered margins used in calculations, improved design and increased overall flood resilience.</b></p>	
<b>Management of concrete swelling in dams and HPP structures</b>  <b>Expected TRL: 6-7</b> <b>Budget range: €1-3M</b>	<b>Priority: High</b>
<p>The <b>research challenge</b> is <b>to review and support investigation</b> into the causes and process of swelling concrete, <b>including</b> the implementation of techniques for the expansion distribution characterisation in the structure and for the prevision of its duration. Further steps towards this goal might include implementation of numerical models to simulate expansion development and to assess structural resilience and the review and analysis of preventative actions and of structural rehabilitation interventions. The <b>impact would be</b> in ensuring infrastructure has <b>adequate resilience levels</b>, improved knowledge of potential interventions <b>to</b> either prevent or mitigate the phenomenon and <b>optimising</b> the cost of structural rehabilitation and reinforcement.</p>	
<b>Development of data merging tool to improve the prediction of design floods based on the spatial-temporal characteristics of the catchment area</b>  <b>Expected TRL: 4-5</b> <b>Budget range: €1-3M</b>	<b>Priority: Medium High to High</b>
<p>The <b>research objective</b> is improving the prediction of design floods, which can be achieved by developing data merging tools <b>based on the spatial-temporal characteristics of the catchment area. This tool has to also be flexible enough to accommodate changes due to</b></p>	

<b>climate change. The impact would be improved design guidance (design floods) and hence improved risk management.</b>	
<b>Research on the settlement behaviour of rockfill dams</b>  <b>Expected TRL: 6-7</b> <b>Budget range: €1-3M</b>	<b>Priority: Medium High to High</b>
<p>The <b>research challenge</b> is improving the sustainability of rockfill dams whose lifetime is threatened by time dependent settlement. There is a need to provide new insights into the settlement behaviour of rockfill dams, specifically into the settlement process through time tracking the <b>mechanics from the particle to the whole structure scale</b>. <b>The outcome of this research would be the introduction of an innovative and promising multiscale approach in the field through new insights into the long-term behaviour of such dams, for example concerning the role of grain breakage and grain shape at the macroscopic (structure) scale.</b></p>	
<b>Implementation of complex nonlinear dynamic models and post-earthquake design approaches for dams</b>  <b>Expected TRL: 4-5</b> <b>Budget range: €1-3M</b>	<b>Priority: Medium High to High</b>
<p>The <b>research objective</b> is implementing nonlinear dynamic models and post-earthquake design approaches in concrete <b>and embankment dams located in risk zones</b>. <b>These dynamic models and design approaches should explicitly take into account the dam-reinforcement interactions (i.e. masonry / backfill, anchors / dam, anchors / foundation) for masonry and embankment dams</b>. An additional challenge is to establish methodologies and recommendations for the justification of interventions on concrete and masonry dams reinforced by passive and active anchors or reinforced embankments affected by earthquakes, as well as further research and innovation on aftershock activity and site effects, including the related design of structures. There is a need for renewing structural resilience systems using devices based on recent developments. Such updates would lead to improved structural condition assessments.</p> <p>The <b>outcome</b> would be the implementation of innovative technologies for the reinforcement of dams, including the creation of <b>guidelines on the use of innovative technologies (e.g. FRCM) for the reinforcement and retrofitting of dams</b>. These would lead to a reduction of costs and improved structural performance.</p>	
<b>Better determination of geotechnical parameters and non-elastic properties of materials</b>  <b>Expected TRL: 6-7</b> <b>Budget range: €1-3M</b>	<b>Priority: Medium High</b>

Due to regional variabilities and scale effects, there is a significant gap between material parameters obtained from onsite tests and laboratory tests. **Thus, there is a need for improved methods for the assessment of geotechnical parameters and non-elastic properties of materials to be used in modelling. The impact of novel methods would improve the reliability of embankment stability analysis, more reliable design bases and safety margins.**

### 3.4.3 Research Theme:

#### **Innovative sediment management technologies for sustainable reservoir capacity and river morphology restoration**

**Priority: High to very high**

**Recommended call: initiate research before 2025**

**Recommended funding scheme: € 8-15 million**

#### **Background and challenges**

Reservoir sedimentation is known as the process of gradual accumulation of the incoming sediment load from a river in natural lakes and manmade reservoirs. The sediment load transported by rivers as suspended fine material or bed load settles in the reservoirs when flow velocities drop as the river flow enters into large open areas of reservoir water. Anthropogenic activities such as deforestation and overgrazing, combined with climate change effects exacerbate soil erosion and deposition. Reservoir sedimentation is one of the most serious problems endangering the sustainable use of worldwide reservoir capacity. The worldwide loss in reservoir storage capacity is reported to be 1 % per year<sup>12</sup>, and based on filling rates observed in Asia, on average the existing hydropower reservoirs will be 85 %<sup>13</sup> filled by 2035. The situation is even more severe for other reservoirs used mainly for irrigation and water supply.

In the Alpine and Nordic regions of Europe, the reservoir capacity loss rate is significantly below the world average. In narrow, long and deep reservoirs, the main process is the formation of turbidity currents, which transport the fine sediments nearer to the dam, where they can increase sediment levels by up to 1 meter per year. Flow outlet devices, such as intakes and bottom outlets, are therefore already affected in many reservoirs after just 40 to 50 years of operation, resulting also in an increased abrasion of hydromechanical equipment. The effects of climate change, especially glacier retreat and droughts in Europe, will increase the future sediment yield entering reservoirs during floods.

Although the reasons and the processes involved in reservoir sedimentation have been well known for a long time, sustainable and preventive measures are still rarely taken into consideration in the design of new reservoirs due to assumptions to offset the sedimentation in the design lifespan. In existing reservoirs, urgently needed actions are often delayed due to short-term economic considerations. Sedimentation is often mitigated only after operational problems occur at powerhouses and water supply facilities and then through short-term measures, which are only efficient during a limited

<sup>12</sup> White, 2001.

<sup>13</sup> Basson, 2009.

time. Since most of the measures will lose their effect, sustainable reservoir operation and thus the water supply, as well as the production of valuable renewable energy are endangered. Today's worldwide yearly mean loss of reservoir storage capacity due to sedimentation is already higher than the increase of capacity through the addition of new reservoirs for irrigation, drinking water, and hydropower.

It is commonly agreed that any reservoir intake for a hydropower plant should be combined with a flushing device located just below to ensure the regular release of sediments and thus sustainable operation of the reservoir. Any new dam in the world should be built in a manner that limits sedimentation as much as possible, which is a challenge. This is also an ecological requirement for maintaining river morphology and biotope richness downstream of dams, thus improving or maintaining the connectivity and ensuring the sustainability of floodplains.

Over the last decades, many technical and operational mitigation measures against reservoir sedimentation have been developed. Unfortunately, there is not a single solution which is successful for all reservoirs. Nevertheless, the wide and rich portfolio of confirmed measures supports finding tailor-made solutions for each reservoir. Still, finding the best solution requires highly innovative engineering competence with a scientific understanding of the processes involved and the impact in the cost of maintenance and the loss of energy production and other valuable services. Solution-oriented research and development are still urgently needed<sup>14</sup>.

### SUGGESTED RESEARCH TOPICS AND PRIORITIES

**Development of innovative resistant coatings for turbines for turbid waters during suspended sediment release**

**Expected TRL: 6-7**

**Budget range: €4-6M**

**Priority  
High**

There is an increasing interest to release fine sediments in a controlled concentration through the hydropower intakes and turbines. The fine sediments may be entrained by mechanical and hydraulic devices in front of the intakes or directly pumped into the intakes, for example by airlift dredging. The resulting reduction in reservoir sedimentation is without doubt beneficial for the sustainable use of hydropower. The controlled and continuous transit of suspended sediments under controlled concentrations will also have a positive impact on the quality of ecosystems in the river downstream (aquatic biotopes) and on the flood plains. Nevertheless, increased turbine wear due to high suspended sediment concentration has to be expected. Thus, the main research question is what type of turbine coating can protect against certain sediment types, under varying sediment concentrations whilst also considering different maintenance intervals. The outcome of

<sup>14</sup> Schleiss et al., 2016.

the research will be the development of **suitable turbine coatings** allowing for the continuous transit of suspended sediments which will have a favourable impact on the river ecology downstream as well as sustainably maintaining **reservoir volume**.

**Developing innovative and sustainable sedimentation management methods and solutions enabling sediment continuity at dams and weirs**

**Expected TRL: 6-7  
Budget range: €4-6M**

**Priority  
High**

The **research challenge** is to develop new sedimentation management methods and solutions which can ensure environmentally compatible hydropower plant operation. Environmentally compatible measures for **sustainable and site-specific sediment management, ensuring reservoir sustainability**, are still needed including, for example, **eco-friendly flushing methods** and addressing the problem of **downstream impacts due to sediment trapping and/or flushing**. The **research objective** is to develop tools and procedures to identify the real impact of different sediment management practices on the **long-term storage capacity of reservoirs** whilst minimising downstream impacts. Economic criteria have to be considered by minimising production losses and investment costs for sediment management measures. The consequences of significant reservoir capacity loss when no mitigation measures are undertaken have to be highlighted in order to increase the awareness of decision-makers. Furthermore, a research question is also how the negative effects on aquatic and terrestrial ecology on the river downstream can be minimised. The following impact of the research topic on hydropower is expected:

- **More sustainable as well as more economically viable reservoirs in the longer term;**
- **Lower costs for companies since easier to keep the reservoirs clean from sediments;**
- **Preserved river characteristics downstream whilst also maintaining flood plain ecology.**

The research should be based on a systematic review of successful sediment management technologies presented in a worldwide catalogue. Regarding sediment release techniques, a key **open research question** is still to understand **under what ecological conditions** given **turbidity limits in the downstream river can be accepted**. In the case of reservoir dredging, the reuse of extracted sediment material is also an open question regarding practical and economic opportunities. Finally, regulatory frameworks are often not adapted to new innovative sediment management technologies and thus an outcome is also to promote new guidelines based on new solutions.

There is still a need for more reliable, physically based, **3D numerical sediment modelling** to better understand the **consolidation and remobilization of sediments deposited in a reservoir**. Reliable and powerful 3D simulation models are important for the long-term efficiency assessment of any sediment release techniques. An innovative and promising approach is the creation of turbulence in reservoirs by mechanical and water jet mixing



devices as well as air bubble screens and water jets which keep fine sediment permanently in suspension so that it can be continuously evacuated through the intake and the powerhouse. The challenge of improved 3D simulation models is that they are able to assess such multiphase processes in relation with turbulence generation in a reservoir.

Developing innovative and sustainable sedimentation management methods and solutions enabling sediment continuity at dams and weirs have not only a high impact on the sustainability of the reservoir volume and consequently on the sustainable flexible hydropower generation, but also on the scheme profitability.

**In situ experimentation and impact assessment of suspended sediment monitoring concentrations on fish behaviour on a case-by-case basis**

**Expected TRL: 4-5**

**Budget range: €4-6M**

**Priority  
High**

The **research question** is related to an increasing interest to release fine sediments in a controlled concentration through the hydropower intakes and turbines, which can be achieved with innovative sediment release techniques. Such fine sediments in combination with replenishment of coarse sediments downstream of dams will also have a positive impact on the quality of ecosystems in the river downstream (aquatic biotopes) and on the flood plains. Nevertheless, there is a **gap in knowledge** regarding the maximum fine sediment concentration allowable without harming fish. The **research challenge** is therefore to identify the threshold for acceptable fine sediment concentrations taking into account the local context, river morphology and sediment transport regime, season, life cycle of fish, species, etc. The **outcome of the research** would allow for safe operation of the above-mentioned innovative fine sediment release techniques, which can highly contribute to the mitigation of ecological impacts in the river and on flood plains downstream of dams.

**Estimation and analysis of increased sediment yield into reservoirs due to climate change and the impact on hydropower generation**

**Expected TRL: 4-5**

**Budget range: €4-6M**

**Priority  
High**

Actual observations indicate that the effects of climate change will increase the sediment yield transported into reservoirs. The **main research question will be** to establish **under what climate scenarios the sediment yield (i.e. land surface erosion) will increase**, and by how much under different conditions of soil, rock, vegetation cover and local climatic conditions. A comprehensive worldwide applicable estimation tool based on remote sensing would allow for the prediction of **increased rate of reservoir sedimentation and**



the expected loss of hydropower generation and benefits from other reservoir uses. The outcome of the research would increase the awareness and understanding of the economic impact of sediment related risks due to climate change.

**Synergies between sediment venting and the release of artificial floods at dams combined with bedload replenishment downstream**

**Expected TRL: 4-5**

**Budget range: €1-3M**

**Priority  
Medium High to High**

During high floods, instead of operating spillways, low level outlets should be used for **sluicing and venting of sediments**. **Turbidity currents in reservoirs** already occur for frequent floods when no spillway operation is needed. When venting turbidity currents during frequent floods through low level outlets as bottom outlets, not only can **significant fine sediments be released but also a more natural flow regime, having regular floods downstream of the dam, can be restored**. Furthermore, coarse sediment can be replenished downstream of the dam which has been dredged, for example, in the delta area of the reservoir or retained in sediment traps at the entrance of reservoirs. Such an approach has a **high impact** since it allows a **synergy between reservoir sedimentation management and ecological restoration of the downstream river**. There are still many open research questions about the efficiency of the venting process combined with artificial flood release and bedload replenishment and the response of the downstream river morphology comprising alluvial vegetation. Furthermore, knowledge of the occurrence of turbidity currents which depend on reservoir geometry and the inflowing flood hydrology, is still lacking and it represents a research challenge which could be addressed **by systematically analysing field experiences using advanced monitoring techniques**. Using synergies between sediment venting and the release of artificial floods at dams combined with bedload replenishment downstream has not only a high impact on the sustainable use of precious reservoir storage but also on the river ecology downstream.

### 3.4.4 Research Theme:

## Innovative techniques for enhancing the working life of concrete structures

**Priority: Medium High to High**

**Recommended call: initiate research before 2030**

**Recommended funding scheme: €8-15 million**

### Background and challenges

Due to the ageing portfolio of dams across Europe (average age of 50 years), new investments are necessary. In this context, the application of new technologies and innovation is needed to help manage the structural condition of dams. Long term information about dam behaviour needs to be collated to allow decisions about operational continuity or the adoption of remedial or rehabilitation measures, along with strengthening or even demolition of relevant dams. Improved prognosis models/tools for maintenance management are required. Specifically, those that accurately meet the requirements to optimise the costs and resilience-related aspects of the operation of concrete infrastructure.

The most alarming issue affecting concrete dams and appurtenant structures is the concrete swelling phenomena, which is associated in particular with the Alkali-Aggregate-Reaction (AAR). Concrete swelling (AAR) and sulphate attacks, which affect a large number of dams worldwide, can undermine dam/HPP operation influencing their structural and hydraulic resilience. More investigations are required to obtain a more comprehensive explanation of the observed phenomena in existing dams. Efficient methods to stop and manage AAR in existing concrete dams are still missing and research efforts should be undertaken to overcome this.

### SUGGESTED RESEARCH TOPICS AND PRIORITIES

Improving instrumentation systems, visual inspection procedures and methodologies for monitoring data interpretation to facilitate the timely detection of AAR

**Expected TRL: 6-7**

**Budget range: €1-3M**

**Priority  
Medium High to High**

The research objective is to improve instrumentation systems, visual inspection procedures and methodologies for monitoring data interpretation to facilitate the timely

<b>detection of AAR. This would enable more accurate diagnoses, allowing more appropriate planning and subsequently the most appropriate type of interventions to be performed.</b>	
<b>Developing new products and procedures to rehabilitate old concrete structures with regards to structural resistance and imperviousness</b>  <b>Expected TRL: 4-5</b> <b>Budget range: €4-6M</b>	<b>Priority Medium High to High</b>
<b>The main research objective is to develop and launch new products and procedures to rehabilitate old concrete structures with regards to structural resistance and imperviousness. The impact would be a reduction of costs for upgrading and the loss of generation due to construction works.</b>	
<b>Enhancing structural models and methods for the detailed analysis of concrete behaviour (incl. concrete cracking, steel rebars and pre-stressing)</b>  <b>Expected TRL: 4-5</b> <b>Budget range: €1-3M</b>	<b>Priority Medium High</b>
<b>The main research objective is upgrading the structural models and methods for the detailed analysis of concrete instantaneous and delayed behaviour, including concrete cracking and the steel rebars and pre-stressing. This would lead to reduced maintenance costs, while increasing structure performance at critical levels.</b>	
<b>Developing a pool of common and advanced techniques to improve the resilience of civil works for hydropower infrastructure</b>  <b>Expected TRL: 4-5</b> <b>Budget range: €1-3M</b>	<b>Priority Medium High</b>
<b>The research challenge is developing a pool of common and advanced techniques to improve the resilience of civil works for hydropower infrastructure<sup>15 16</sup>. The challenge is to analyse the problems posed by the ageing of infrastructure (i.e. dams and appurtenant</b>	

<sup>15</sup> ITCOLD has established a Working Group that has carried out a collection of the rehabilitation interventions carried out in the last 20 years on Italian dams and appurtenant structures (e.g. penstocks, gates, galleries, etc.). At present, a continuous observatory has been established to guarantee the updating of the information. Verifying if a similar initiative has been undertaken by other countries and pooling the common and advanced techniques to improve the resilience of civil works of hydropower infrastructures could lead to the development of innovative solutions.

<sup>16</sup> Mazzà & Frigerio, 2016

structures), as well as analysis of the advanced solutions already at our disposal. The outcome would be a widening of the vision towards the development of more innovative solutions.

**Rejuvenation and consolidation of old concrete loose material**

**Expected TRL: 6-7**

**Budget range: €1-3M**

**Priority  
Moderate to Medium High**

Some old concrete or masonry gravity dams and civil structures may have been significantly altered over time under different processes and may have lost structural properties at a critical level, when compared to existing or hypothetically enhanced structural **safety standards**. Therefore, there is a need to develop and demonstrate the performance of concrete/masonry rejuvenation/consolidation techniques through specialised injection or grouting of cement-based material together with appropriate adjuvants to ensure mechanical properties and durability. The impact of these “smooth” techniques might be significant cost reduction or savings in repair or even reconstruction.

### 3.4.5 Research Theme:

## Innovative techniques for the enhancement of overtopping safety of embankment and rockfill structures

**Priority: High**

**Recommended call: initiate research before 2035**

**Recommended funding scheme: €2-7 million**

### Background and challenges

Overtopping is one of the major causes of embankment dam failures - especially those constructed from earth fill. Many dams were designed decades ago, and current hydrological data is now both more extensive and reliable. Although the South of Europe is experiencing a drought period, extreme events become more frequent and old dams sometimes do not have enough free-board or spillway capacity. Several measures can be taken to avoid overtopping. These include, amongst others, lowering the normal water level, raising the dam height, improving the discharge capacity, establishing strict operation rules, and creating an emergency spillway. Innovative solutions are focused on crest and downstream protection (i.e. mainly for embankment dams). In addition, more satisfactory and simplified technologies for sealing embankment and rockfill structures are required, applicable during the operation of dams for those whose reservoirs cannot be emptied.

### SUGGESTED RESEARCH TOPICS AND PRIORITIES

**Innovative techniques for enhancement of the overtopping safety of embankment and cemented structures**

**Expected TRL: 4-5**

**Budget range: €4-6M**

**Priority  
Very High**

The erosion processes that occur during overtopping is still not well known for embankment dams. The erosion resistance depends upon the characteristics of the materials used for the embankment and in the foundations. There is a need to **improve the understanding of physics of complex flows and validating predictive numerical models through large scale experimental tests.**

**The main research objective is to improve understanding and methods for avoiding dam failures. The challenge is to monitor and understand the physics of high-velocity multiphase flows as occurring either on embankment overtopping or on spillways and in low-level outlets. Embankment erosion relates to different soil types ranging from granular**

to cohesive, whilst flows on spillways and in low-level outlets should be better understood in terms of cavitation potential, pressure induced fatigue and malfunctioning of concrete.

There is a need to monitor and understand the physics of erosion processes, as well as to validate predictive numerical models. For concrete dams, better design recommendations for aeration requirements of these flows are also needed, as well as developing a rich catalogue of solutions and specifications for their implementation.

The research outcomes would be better estimation of the occurrence of erosion and the associated probability of failure, which would lead to better protection against this major risk of dam failure (i.e. overtopping). Also, this would lead to improved understanding of the conditions leading to overtopping erosion and the development of more accurate models simulating embankment dam performance under extreme hydrological situations along with efficient solutions which increase the resistance of embankment dams to erosion. These actions would also provide guidance for dam owners to help optimise their maintenance costs.

**Bioconsolidation of embankment dams and foundations**

**Expected TRL: 4-5**

**Budget range: €1-3M**

**Priority  
Medium High to High**

In a few European countries like France, the Netherlands and Switzerland, some laboratory and field testing of bioconsolidation of soils and embankment structures have shown promising results for the reinforcement of structure properties against either internal erosion or liquefaction<sup>17</sup>. Bioconsolidation of soils is typically obtained through the injection of bacteria, urea and calcium chloride, where bacteria act as a catalyst to boost the calcification reaction that bridges and links soil grains together. It has already been demonstrated that the use of non-pathogenic bacteria ensures that there are no environmentally adverse effects arising from this technique. The advantages of such consolidation (i.e. both in the main body and foundations) can include more localised treatments, and treatment cost reduction. Europe is currently leading research activity in this area, but there is a need for industrial demonstrators under various conditions (e.g. embankment characteristics, water quality, issues to be solved: erosion, liquefaction etc.) before deployment at a larger scale. This technique could evolve into a business with a leadership role for European companies.

The research outcomes would provide solutions for the best protocols for injection, demonstration of the durability of the process, and confirmation of the structural performance of such reinforcement techniques.

<sup>17</sup> Esnault-Filet A. et al, 2018 (BOREAL project)

### 3.5 Developing new emerging concepts

#### Background

Whilst hydropower is a highly mature technology, there remain avenues for novel approaches such as innovation in planning, design and operation of HPPs and PSHs. In Europe, around 60% of the available and economically viable hydropower potential has already been utilised. Accordingly, when investigating break-through technologies, it is sensible to also discover innovative ways to improve the yield from existing infrastructure. Moreover, as “easier” sites for projects are already tapped, the hydropower equipment industry increasingly needs to provide innovative equipment capable of adapting and performing well under more challenging design constraints.

Some of the emerging technologies in hydropower include increased development and deployment of kinetic energy technology that can support agriculture and industry (irrigation pumps, food production, industrial production etc.) but also wider society (community infrastructures, off-grid villages, small businesses etc.). This technology is based on water velocity (tidal, canals and waterways) and chemical energy (osmotic systems). But emerging technologies also include technological developments for turbine operation to achieve higher flexibility, developments in pumping technology for PSH and developing fish-friendly infrastructure. The environmental performance of hydropower is very much dependant on its further technological development. Here, the concept of embracing innovation, and thinking in a novel way should be employed. For instance, fish ladders have been used for over 100 years and even though the hydropower industry faces continued criticism for declines in fish numbers, fish ladders are still popular solutions for the passage solution of their operations. This can not only be turned around but increased clean power production may also be realised. Currently, a fish ladder requires approximately 5%-10% of river flow to spill down the ladder. If that is no longer required, that amount can be used for a corresponding increase in carbon-free power production. Multiplying this across several dams and a 5-10% addition to the grid may be realised with technology that is easy to implement and which helps put EU hydropower operators more in compliance with the WFD.

When developing hydropower projects, there is a need for a multidisciplinary approach. In a field that is traditionally highly engineered and technology-driven, there is room for more cross-disciplinary work with expertise drawn from natural sciences, legislation or social sciences sectors. In particular, more research is needed in the field of social sciences to help understand and improve societal aspects of power production. Gaining public acceptance is essential for the sustainability of hydropower projects. All relevant stakeholders, including public authorities and local communities, need to be involved from the early stages of any discussions. Best practice and example cases exist in this regard, and the following actions need to be considered, to enhance public perception:

- providing clear information to stakeholders;

- **developing a concrete stakeholder communication plan, conceived with local agents, to identify the stakeholders involved, their interests in the project and to address the most important issues;**
- **consultation to empower citizens and to make them part of the decision process;**
- **gathering insights from local communities;**
- **highlighting the positive impact and success stories of dams, i.e. storage power plants;**
- **developing and disseminating emergency plans to support trust and perceived safety by the population.**

**The optimisation of multi-purpose schemes to achieve a win-win situation, i.e. the best synergy between all purposes, is a difficult task and confirmed methodologies including the evaluation of non-monetary goals and cost-sharing approaches are still missing.**

**Each project is unique and has the potential to generate new knowledge, hence why projects should be co-designed with the customers. The use of systemised equipment is cost-effective for small to medium projects. However, because of the challenge of working with old installation layouts, refurbishment projects and large hydro projects demand custom-designed components.**



### 3.5.1 Research Theme:

#### **Development of innovative storage and pumped storage power plants (e.g. multipurpose PSH, sea water PSH, etc.)**

**Priority: Very High**

**Recommended call: initiate research before 2030**

**Recommended funding scheme: €16-25 million**

##### **Background and challenges**

Multipurpose schemes refer to the use of reservoirs to provide other services beyond electricity generation. Hydropower projects present multiple opportunities to create environmental and socio-economic value for their host communities and regions. Through multipurpose schemes, hydropower reservoirs can contribute to water management, including water supply, flood and drought management, irrigation, navigation, fisheries, environmental services and recreational activities. Dams have been built mostly to serve only one of the above-mentioned purposes. However, due to the increasing demand for these various services, their spatial and temporal overlaps, the increasing threat posed by climate change and national and international sustainability goals, construction and/or retrofitting multipurpose use of dams has been favoured in recent years as they can then fulfil several purposes with a single facility. Multi-purpose water infrastructure encompasses all constructed water systems, including dams, levees, reservoirs and associated irrigation canals and water supply networks.

In a multipurpose project, a distinction can be made between primary and secondary purposes. The primary purpose is the main reason to initiate planning and construction and it largely determines the financial arrangements of a multipurpose dam. Secondary uses are planned or attributed as additional functions to make a dam more profitable and have less priority regarding operational management of the reservoir. If hydroelectric power generation is the main purpose, several economic and social benefits can be generated by adding other uses, including:

- storing water during times of high rainfall, to compensate for seasonal variations and meet the high demand of water for irrigation all year round;
- providing a reliable water supply to municipal and industrial water users;
- using the storage reservoir to maintain a sufficient channel flow downstream to allow navigation offsetting seasonal variations;
- exploiting reservoirs for public recreational benefits, such as boating, swimming and fishing;
- storing all or a portion of floodwater and then releasing this water in a controlled manner over time to prevent flooding and drought.

Through these uses, the profitability of storage and pumped storage plants can be improved, whilst at the same time making HPPs amenable for the wider public. However, clarification of the legal framework is needed to put in place some of these uses.

Even if not yet widely used, seawater pumped storage plants and tidal range plants are already mature technologies and these technologies have a potentially large market. They are highly predictable and there is no competition with freshwater resources. To illustrate, seawater pumped storage with offshore renewables is an opportunity for future electricity network development in isolated areas (e.g. islands or lagoons). Hydro marine plants can be combined with other renewables and/or desalinisation schemes; for example, combining a hydro marine plant and a desalinisation plant with a salinity gradient power plant (Blue Energy). The advantage of this arrangement is the production of energy from the residue of the desalination plant. This arrangement not only makes potable water available in areas with hydric stress but can also produce energy, in a decentralised manner, by mitigating the brine residue produced in sea water reverse osmosis (SWRO). Hydro marine plants also have other benefits, such as offering protection against coastal flooding and erosion. But they must endure harsh marine conditions, are usually quite expensive and often have low success rates. Therefore, innovative design (supported by research and development and wide stakeholder consultation in the early design phases) in combination with multipurpose schemes is needed to lead to environmentally friendly solutions, higher success rates and wider social acceptance of hydropower.

Finally, innovative concepts can also reduce the cost of plant infrastructure. Indeed, one of the key challenges is to find ways to develop new capacity with low CAPEX. Apart from developing PSH between existing reservoirs, another solution is, for example, to transform a turbine plant into a pumped storage plant, which is promising as the investment in civil works can be reduced.

### SUGGESTED RESEARCH TOPICS AND PRIORITIES

**Integrating storage and pumped storage in hybrid and virtual power plants**

**Expected TRL: 6-7**

**Budget range: €4-6M**

**Priority: Very High**

**The research objective** is to integrate storage and pumped storage with other available RES generation, such as wind, (floating) PV and water services such as desalination. **The outcomes would be twofold: acceptance of hydropower as part of the energy transition including higher social and public acceptance; and increased flexibility to the system to allow an increased penetration of variable renewable energy sources. The impact is wider hydropower deployment supporting the energy transition.**

<p><b>Transforming a storage power plant into a pumped storage plant</b></p> <p><b>Expected TRL: 6-7</b> <b>Budget range: €4-6M</b></p>	<p><b>Priority: Hight to Very High</b></p>
<p>The research challenge is developing novel approaches for transforming traditional storage power plants into pumped storage plants. This can bring benefits in the form of reduced investment in civil works. The CAPEX structure of a low head project is broadly half for civil works and the other half for mechanical equipment. To maximise the capacity, several challenges have to be solved: either use variable speed technology or conduct minor civil works to increase runner diameter. The research challenge is to optimise the operation mode for the purposes of combined storage, which can include electrical and municipal water supply, and/or heat storage.</p> <p>The outcome of the research will be increased profitability as well as availability of new capacity for flexibility with low CAPEX, whilst reducing the costs of infrastructure.</p>	
<p><b>Development of a new type of heat storage in underground reservoirs of PSH</b></p> <p><b>Expected TRL: 4-5</b> <b>Budget range: €1-3M</b></p>	<p><b>Priority: High</b></p>
<p>The research challenge is to develop a new type of heat storage using the underground reservoirs for PSH. Combining the advantages of pumped storage technology and heat storage using water as a medium with the use of underground reservoirs will enable the storage and supply of electricity, heat and cooling energy as required. This research will lead to the innovative use of underground reservoirs of underground pumped storage powerplants for not only water storage, but also for heat storage by combining both cycles. Moreover, the design of the system will be modified and made more efficient for heat storage use by overcoming stratification in the reservoirs. The research will also have a secondary impact on the development of innovative solutions for decarbonisation of the heating and cooling sector in line with the EU strategy on heating and cooling.</p>	
<p><b>Developing and optimising integrated sea water PSH and desalination plant (SWRO) schemes</b></p> <p><b>Expected TRL: 6-7</b> <b>Budget range: €4-6M</b></p>	<p><b>Priority: High</b></p>
<p>The research challenge is to develop and optimise integrated sea water PSH and desalination plant (SWRO) schemes through a focus on areas with hydric stresses and suitable topography considering socio-economic aspects. This would also allow use of the brine coming from the desalination plant with its good thermal capacity for energy</p>	

**storage, hence coupling SWRO and the so-called Blue Energy. The outcome of the research will be better environmental and social integration of the projects, as well as reduced durations to get construction licenses within marine areas. A further outcome should also be reduced CAPEX and OPEX of the integrated scheme by achieving a very high efficiency (e.g. direct feeding of the RO process with hydraulic energy).**

### 3.5.2 Research Theme:

#### Marine energy

**Priority: Medium High to High**

**Recommended call: initiate research before 2030**

**Recommended funding scheme: €8-15 million**

#### Background and challenges

Marine energy concerns the energy generated by ocean waves, tides, salinity, and ocean temperature differences. As mentioned in the previous chapter, hydro marine plants can be used in multipurpose/seawater PSH schemes, where they are combined with other renewables and/or desalinisation schemes. There are, however, also stand-alone hydro marine plants, such as the Rance Tidal Power Station (240MW installed capacity) in France.

There is certainly space for further developments in marine energy. The hypothetical dam project MEDSHILD at the Strait of Gibraltar aimed at lowering the sea level for the whole Mediterranean region in the face of the threat of rising ocean levels due to global warming. This is a prime example of multi-beneficial and multipurpose use of marine energy.

Hydro marine plants have numerous benefits and can protect against coastal flooding and erosion. However, they are usually quite expensive and most of them have failed in the past. They also suffer from operating in the harsh conditions of the marine environment and they can have a substantial environmental impact. Nevertheless, marine energy supports the increase and diversification of a renewable energy mix and there is a large tidal resource in Europe. Further R&D of innovative hydropower schemes in the marine environment, including tidal range projects, would lead to environmentally friendly solutions and wider social acceptance of hydropower.

#### SUGGESTED RESEARCH TOPICS AND PRIORITIES

**Efficiency and fish friendliness of low-head reversible turbines, suitable for use in a sea water environment**

**Expected TRL: 4-5**

**Budget range: €1-3M**

**Priority: High**

Since turbine and pumping modes have different optimal speeds, fixed speed operation of hydraulic machines can only be optimised for one mode; usually they are optimised for pump mode and then work with reduced efficiency in the turbine mode. **The research**

<p><b>challenge is to increase the efficiency and fish-friendliness of low-head reversible turbines and make them suitable for the sea water environment. The outcome of this research will be increased environmental and social integration of the projects.</b></p>	
<p><b>Development of innovative, multipurpose tidal/kinetic schemes in the marine environment</b></p> <p><b>Expected TRL: 4-5</b> <b>Budget range: €4-6M</b></p>	<p><b>Priority: High</b></p>
<p><b>The research challenge is to develop innovative, multipurpose tidal/kinetic schemes in the marine environment with a focus on underwater kite power systems (UKPS) coupled to the main hydropower plant tailwater channel. The outcome of this research will be better environmental and social integration of tidal plant schemes with breakwaters that can be used as protection against coastal flooding or coastal erosion in areas with tidal range and/or coastal vulnerability. Additional benefits will include reduced durations to get construction licenses in marine areas.</b></p>	
<p><b>Low-cost breakwater solutions, complying with specific technical challenges</b></p> <p><b>Expected TRL: 4-5</b> <b>Budget range: €1-3M</b></p>	<p><b>Priority: High</b></p>
<p><b>The technical challenge for breakwater solutions is the feasibility of construction in a high current environment (i.e. closure of the breakwater where water levels can quickly change). The research objective is the development of low-cost breakwater solutions complying with these technical challenges. The outcome of this research will be reduced LCOE.</b></p>	

### 3.5.3 Research Theme

#### Hybrid & virtual power plants

**Priority: High to Very High**

**Recommended call: initiate research before 2030**

**Recommended funding scheme: €8-15 million**

##### Background and challenges

In a hybrid power plant scheme hydropower works with one or more different types of generation as an integrated unit. Hybrid power plants can occupy a single site or comprise a microgrid. Hybrid power plants may be connected to the grid or be far from the grid in remote areas, where they might represent the main source of power.

The generation/storage technology can also share the same injection point on the power grid (hybrid systems), or alternatively each storage technology can have its own existing point (VPP).

At a local level, integrated community energy systems are emerging as a modern development to re-organise local energy systems allowing simultaneous integration of distributed energy resources and engagement of local communities. In this perspective, small and medium hydropower in virtual power plants (VPP) and hybrid configurations can play a significant role in balancing the local grid and the new power system. Integrated community energy systems are rapidly emerging due to common objectives, such as cost and emission reductions as well as resiliency. However, assessment and evaluation are still lacking on the value that these systems can provide both to local communities, as well as to the whole energy system.

In hybrid power plants, combining hydropower with solar or wind power to increase the stability and reliability of electricity generation is possible. The hybridisation allows solar PV panels or wind turbines to produce energy when the sun or wind is available, whilst saving water for hydroelectricity generation capacity during times when the sun or wind energy is intermittent or not available. Another possibility is to couple hydropower with salinity gradient power.

When pumped storage is possible, it allows the storage of excess energy and to release that stored energy to cover periods of peak demand. Another advantage of hybridisation is the possibility to use the same electrical infrastructure for both generators, thus lowering overall CAPEX costs. Additional benefits derive from the combination of hydropower with floating photovoltaic (PV), as the installation of solar panels on 'dead water' space can maximise the use of resources (although attention should be paid to the environmental impact of the floating structure and its anchors). Moreover, by covering a significant surface area on a body of water, these systems can help reduce evaporation

and algal bloom. The cooling effect of water on the solar panels can also improve conversion efficiencies of solar power production.

Furthermore, adding emerging electrical energy storage technologies to the VPP would help mitigate the adverse effects of variable renewable generation on the power system and its integration. Batteries are well suited for electrical energy storage during periods ranging from seconds to a few hours. However, they are not suited to longer duration storage operation and can degrade from continuous cycling over many years. Flywheels and supercapacitors are well suited to continuous cycling operation but have very limited electrical energy storage capacity. Hydropower and pumped storage plants can support not only the variable and intermittent RES integration but also provide long duration storage complementing quick-response technologies, and they can also improve the output of some conventional plants.

### SUGGESTED RESEARCH TOPICS AND PRIORITIES

Pilot projects integrating hydropower with other RE sources and energy storage systems

Expected TRL: 6-7

Budget range: €7-10M

Priority: Very high

The main research objective is to identify and test hybridisation of different systems (not only RE) with HPPs with a focus on the hybridisation of pumped hydropower with other energy storage technologies. This would include delivering more pilot projects combining hydropower with wind, solar PV, hydrogen (H<sub>2</sub>), Power to gas (P2X), batteries, etc. Integrating hydro generation units with other technologies will lead to an increase in flexibility and revenues. The following challenges need to be addressed:

- investigating existing HPP and its role as an enabler of further integration of volatile renewables (e.g. through photovoltaic modules on embankments from upper basin, etc.);
- studying the possibilities, criteria and assessments together with requirements of new system services of various sector coupling concepts;
- investigating the integration of small and medium hydropower (in VPPs and hybrid PPs) into an integrated community energy system;
- demonstrating cost reduction of the energy (i.e. LCOE) supplied through the focus on PSH.

The outcomes would be:

- significantly improved cycle efficiency of the total chain of (electrical) energy;
- creation of new revenues and markets, which would in turn make hydropower more profitable and attractive to investors;
- improvement of flexibility characteristics (e.g. fast response, ramp rate, etc.) of HPP by hybridising with batteries or other ESSs;



- **development of guidelines for the operation of VRG as a VPP, i.e. existing hydropower and/or pumped storage plants, batteries and flywheels or supercapacitors, in different electric power systems.**

**An additional research goal is technical research to enable the serial production of floating PV in rivers and streams with positive outcomes for flood protection, entrapment of ice blast & flotsam and possible (positive) impacts on the environment. In a similar manner, additional technical research is needed for floating PV in reservoirs. The impact would be enabling of secondary use of hydraulic resources, as well as improving the social acceptance of hydropower.**

**Investigation of possible synergies of hydropower with e-mobility or water companies<sup>18</sup>**

**Expected TRL: 4-5**

**Budget range: €1-3M**

**Priority: Medium High**

**The main research objective is investigation into possible synergies between hydropower and the e-mobility sector. An example might include investigation into the possibility of hydropower supplying recharge points for electric vehicles. The impact will be the contribution of hydropower to decarbonisation of the transportation sector.**

<sup>18</sup> See section 3.7.1

## 3.6 Environmentally compatible solutions

### Background

Hydropower is an excellent way of producing electricity from a renewable energy source. It is therefore very important to find environmentally compatible solutions to minimise the impact on flora and fauna. It is necessary to improve innovative freshwater connectivity solutions for biodiversity protection and to better understand the potential and effects of connectivity improvement in regulated rivers on a “case by case” basis, allowing for better solutions for site specific hydropower plants.

Finding solutions to reduce negative impacts of hydropower plants on the environment are high on the priority list of the hydropower community. Important actions are to ensure sustainable hydropower development and operation, and to preserve public and social awareness of hydropower as a clean, renewable and environmentally compatible energy source. Key principles for successful solutions are an open evaluation of all aspects and a (legal) framework for requested compromises and compensation options.

Many environmental measures do not influence production and thus the contribution of hydropower to solving climate change. It is precisely these measures that need to be in focus. In general, there is a need to strike a balance between negative environmental impacts and the socio-economic benefits from hydropower. Water uses and services supported by hydropower infrastructure should be highlighted under this rationale.

### 3.6.1 Research Theme:

**Flow regime management, assessment of environmental flow release, innovative connectivity solutions for fish and biodiversity protection and improvement of stored water quality in reservoirs**

**Priority: Very High**

**Recommended call: initiate research before 2025**

**Recommended funding scheme: €16-25 million**

#### Background and challenges

To reduce the negative impact of hydropower plants on the environment, further R&I actions are needed to address the impacts of hydropower on upstream and downstream ecosystems, to improve the ecological conditions and re-establish connectivity. One of the key issues is to determine and re-establish environmental flows that mimic natural water flow in the river whilst maintaining the necessary climate conditions (e.g. one of the tools to determine the necessary environmental flow is the use of airborne laser bathymetry data with high resolution). Another issue is to also ensure sustainable ecosystems and population consistent with human needs for land use and water use, sometimes in heavily modified water bodies (e.g. appropriate measures and approaches need to be developed to balance different needs in a fair way). Nevertheless, environmental measures, such as environmental flows, need to be site-specific – there is no one size fits all (e.g. concerning the Water Framework Directive). More research should also be undertaken on ecological flows within Mediterranean environments as well as for high altitude alpine environments and on the assessment of the impacts of hydropeaking on the dynamics and resilience of biological community populations based on the typology of rivers and the multiple pressures they experience. Other important issues are bearing the costs invested in hydro morphology (e.g. private companies, public organisations, etc.) and the fact that public services provided by operators (cleaning waste from rivers, flood protection, grid stabilisation, climate change mitigation etc.) are typically not taken into account.

The protection of fish populations by reducing mortality at power plants is another key issue and there is still the need for development of solutions for downstream fish migration devices and the guiding of fish to such downstream bypass systems. Hydropower (together with climate change and exotic invasive species) is one of the main causes for fish mortality and the worsening of habitat conditions of amphihaline or protected migratory fish species. Hydropower impacts biodiversity in several ways, such as with substances accidentally released into the waterways but also depending on turbine type (Kaplan, Francis, Pelton, etc.), turbine size/diameter, number of blades, blade characteristics, rotational speed and other aspects. To reach Water Framework

Directive targets, measures and their effects on biological processes have to be better understood. In general, there is a lack of data, understanding of river ecology and reliable technical solutions for fish protection at medium and large-scale hydropower plants. Fish protection measures are often very costly, difficult to implement and designed only for certain plant size (small hydropower plant). Differentiation must be made through studies between fish species, plant size and ecological status of the river. Sharing of experiences between hydropower operators on fish migration support systems (upstream and downstream) should also be encouraged. Moreover, recent analyses have demonstrated that most of the fish passages are not eco-efficient and that, in many cases, river species are not able to use them. However, some innovative solutions, such as the Whooshh Fish Passage System (WFPS) shows very promising results. Optimal design of passages should consider fish behaviour and reaction to external stimuli coming from the turbulent and hydraulic flow field, but also fish swimming ability to determine the most suitable locations to install inlet/outlet passages.

Forecasting systems for peaks of fish migration/densities may provide efficient fish protection and downstream passage solutions. Forecasting systems can be further improved in situ/live (e.g. underwater camera systems), based on abiotic factors (e.g. discharge, water temperature, etc.) and experience (i.e. past recordings). Finally, adapting turbine blades to reduce the risk of fish injury might be suitable for retrofitted turbines, which has the advantage of preventing shutdown and water losses. More research on new promising electrical deterrence system solutions to repel fish from screens are also needed.

All mitigation measures have to be defined by taking into account the future needs of a carbon neutral energy system.

### SUGGESTED RESEARCH TOPICS AND PRIORITIES

**Measures and approaches to protect biodiversity**

**Expected TRL: 6-7**

**Budget range: €4-6M**

**Priority: Very High**

The main research objective is development of measures and approaches to protect biodiversity to safeguard ecosystems in the hydropower plant project area. To this end, fish and other species (e.g. amphibians, etc.) populations are a key indicator. The following challenges need to be addressed by the research:

- developing large scale modelling for the future distribution area of the species to implement prioritised, adapted, cost-effective and long-term measures, which are also consistent with predicted climate change effects;
- investigation of downstream migration flows (new tools under development) and migratory species behaviour (e.g. modelling virtual fish swimming path);
- “fish-based” approaches for the development of upstream and downstream fish passages (e.g. fish passage monitoring, quantify migration paths, etc.);

<ul style="list-style-type: none"> <li>• investigation of individual contributions of various influences on the fish population changes in a specific water body.</li> </ul> <p>The impact would be constant or increased biodiversity via restoration, enhancement and preservation of the (migratory) fish populations currently in danger through the implementation of adapted, pertinent and cost-effective measures. Further outcomes will include:</p> <ul style="list-style-type: none"> <li>• improved ecological status of water bodies and improved river connectivity;</li> <li>• increased range of fish passage applications as a larger range of fish species is studied;</li> <li>• effective technical solutions for fish migration and high fish guidance;</li> <li>• safeguarded ecosystems; and</li> <li>• support to the fishing industry.</li> </ul>	
<p><b>Development and testing of solutions for improved biodiversity and fish protection</b>  <b>Expected TRL: 6-7</b>  <b>Budget range: €4-6M</b></p>	<p><b>Priority: High to Very High</b></p>
<p>The main research objective is the development and uptake of solutions for protecting fish populations and wider biodiversity. The following challenges need to be addressed by the research:</p> <ul style="list-style-type: none"> <li>• developing innovative and feasible devices and concepts (e.g. shaft power plant), testing their practicability and needs;</li> <li>• development and testing of innovative solutions for fish protection in the laboratory, on-site, in natural environments and at pilot plants (e.g. accessibility and flow attraction improvement, effectiveness of technical facilities, etc.);</li> <li>• biological testing on prototype turbine installations, with data reused in design methodologies and prediction tools;</li> <li>• systematic, consistent and case-by-case research on the advantages and disadvantages of the different measures depending on plant size, river characteristics, fish population, etc.;</li> <li>• identification of a high head dam site in the EU that could be used for piloting innovative technological solutions (e.g. WFPS).</li> </ul> <p>The impact will include more flexible hydropower production and more sustainable hydropower schemes.</p>	
<p><b>Investigating linked effects on biological community resilience population dynamics and diversity through analysing different ecological flows in various geographical contexts</b></p> <p><b>Expected TRL: 4-5</b>  <b>Budget range: €4-6M</b></p>	<p><b>Priority: High to Very High</b></p>

The main research objective is to improve the understanding of the hydraulic processes required for ecosystems through investigating linked effects and the development of methods for assessing impacts on biological communities that make it possible to identify appropriate mitigation measures and/or compatibility measures with no or minimal effects on hydropower revenues, (particularly in multi-stress environments) such as Mediterranean or high Alpine regions. The research challenge is to determine which factors cause potential ecological functional deficits and which are the priority levers to remove the constraints responsible for these deficits, as well as understanding the effects of releasing artificial floods in combination with flushing and venting of fine sediments and the replenishment of coarse sediment downstream of dams. The following impacts will be achieved:

- identifying appropriate mitigation measures against harm from peak energy generation;
- delivering sustainability in hydropower and through measures that are truly effective for the environment
- improving river ecology and fish habitat without limitation on grid services, revenues from operation and the important services provided by hydropower in general;
- developing a better understanding of current environmental impacts and hence helping to mitigate future ones (e.g. a holistic EIA could avoid unforeseen environmental damage);
- developing proof of concept, evidence of efficiency, determination of manufacturing and operating costs, scalability studies and greenhouse gas balance calculations.

**Evaluate, study and propose improvement of river ecology and fish habitat**

**Expected TRL: 6-7**

**Budget range: €4-6M**

**Priority: High**

The main research objective is to evaluate, study and propose improvements for biological communities (i.e. river biodiversity and fish habitats) through targeted studies and investigations on various factors affecting the river biodiversity. To do so, the following challenges need to be addressed by the research:

- understanding the effectiveness of measures that have been applied so far to the biological communities;
- studying at different sites, the different pressures that affect biological communities (e.g. chemical, thermal, habitat degradation pressures, etc.);
- proposing a panel of "combined" measures (i.e. not only targeted on a single pressure) and evaluating their effectiveness in the medium term;
- studying the effects of water quantity vs. water quality and reasons for decreasing fish populations (e.g. decreasing environmental flow, connectivity, chemical and pharmaceutical pollutants, etc.);

- investigating the decision-making process, where administrative criteria and interest groups are needed;
- investigating administration cooperation at administrative intersections (e.g. environmental, renewables, climate change, economic development, etc.) and their roles in the respective branches.

The impact of this research will be an improvement of river ecology and fish habitat, information platforms for experts and operators, as well as more balanced and fact-based decision-making processes.

#### **Turbine design**

**Expected TRL: 4-5**

**Budget range: €4-6M**

**Priority: Medium High to High**

The main research objective is better understanding of factors that would enable more environmentally compatible turbine designs. The following challenges need to be addressed by the research:

- biological investigations on turbine design criteria, where investigation is needed on determination of the actual hydraulic conditions for the flow to hydropower plant and the effects of fish protection concepts on turbine efficiency;
- investigation into fish mortality factors present during hydro turbine passage to establish appropriate design guidelines for hydro turbine equipment (e.g. physical tests, numerical simulations);
- developing computational results integrating biological considerations for optimal environmental design;
- researching the effects of fluctuating discharge on the fauna in rivers (e.g. variations in overall velocity, bed shear rates, turbulent quantities, temperatures and water levels).

The impact will be higher acceptability of hydropower and less damage to the environment and biodiversity. A further outcome should be environmentally compatible materials and substances utilised in turbines, where the goal is avoiding oil and grease in all parts of the turbine system by 2030.

**Environmentally compatible solutions for hydropower plants through harsher conditions of operation and interdisciplinary research**

**Expected TRL: 4-5**

**Budget range: €4-6M**

**Priority: Medium High**

The main research objective is assessing environmentally compatible solutions for hydropower plants (e.g. hydropeaking) using a systematic global approach and interdisciplinary research. A secure electricity system has the requirements of high

**flexibility and storage, which means highly flexible operation with impacts downstream. Therefore, the main research question is how to find appropriate mitigation measures to reduce the impacts of hydropeaking without having adverse effects on use. The focus needs to be on developing solutions and mitigation measures beneficial for the environment without imposing too many constraints on operators and machines. The outcomes of the research will be:**

- **Increased investment by operators in environmentally and economically sustainable solutions for hydropower;**
- **Guidelines for a more balanced decision-making process amongst local and national authorities;**
- **A holistic approach regarding the state of the art of appropriate mitigation measures**



### 3.6.2 Research Theme:

**Assessment of the general impact and contribution of hydropower to biodiversity and the identification of innovative approaches and guidelines to support more sustainable hydropower development**

**Priority: Very High**

**Recommended call: initiate research before 2025**

**Recommended funding scheme: €8-15 million**

#### **Background and challenges**

The Global Assessment Report on Biodiversity and Ecosystem Services (IPBES, 2019) has recently demonstrated that: “Nature makes human development possible but our relentless demand for the earth’s resources is accelerating extinction rates and devastating the world’s ecosystems”. In particular, freshwater species populations suffered an 81% decline. The report points out that there is an urgent need for action to better conserve and sustainably use biodiversity. The circularity assessment of materials used for the implementation of hydropower schemes and their reuse is also an issue.

This challenge can be addressed with various actions or measures, both technical and non-technical, through cross-sectoral and multidisciplinary collaboration amongst decision-makers and other stakeholders at all levels.

Such technical measures can include, for example, side channel reconnection, removal of bank protection and river bed protection / structures, restoration of floodplain habitats, reduction of land use intensity, restoration of sediment continuity, hydrological aspects, etc.

Before launching these actions, greater knowledge on ecosystems is needed for the development of the best and most effective solutions. Technical and environmental innovations have to guarantee that there will only be acceptable impacts. Not enough ecosystems around hydropower sites have been identified, monitored and tracked. Impacts on biodiversity are not detailed and quantified sufficiently and the performance of restoration processes are not often assessed to allow for refinement and validation of the applied solutions. Finally, the increasing benefits of reservoirs, in times of climate change, to regenerate biodiversity threatened by droughts and river drying are not measured or assessed nor is the biodiversity of hydropower schemes themselves.

Recently, small hydropower development in the Balkans countries, often on untapped natural rivers, has been seen by NGO’s as more of a problem than a solution for aiding the energy transition in Europe (HPE, 2021a). Some hydropower projects have not been designed and built according to the high standards now used for most new projects or for the refurbishment of existing plants, which should ensure that they are technically sound

and safe, environmentally defensible and socio-economically beneficial. As a consequence, a manifesto entitled “No more new hydropower in Europe” was released in 2020 under the lead of WWF and signed by numerous NGOs.

The question arises as to how to develop new green field hydropower projects in such an environmentally friendly and sustainable way that they can contribute to the achievement of the European Green Deal?

A business-as-usual approach based purely on an engineering focus and only on energy uses is no longer valid. The hydropower sector needs to adopt a holistic position taking into account the new social context, climate change, new grid requirements and more generally the use of water for increasing social welfare. In certain Southern regions, water – besides renewable energy development – is becoming the key issue. This implies that the industry should be pro-active in identifying water challenges beyond the use of energy, in anticipating and mitigating the risk of resource shortages, their collapse and the ripple effects that could occur. In particular, design or modification of new, large, multi-purpose reservoirs built for natural hazard protection used for energy storage and power supply, should also create new sources of revenue and payback for investments. Social benefits should also be taken in account, as they are induced by climate change and economic issues.

To support more sustainable hydropower development, a strategy is needed to bring together environmental groups and the hydropower industry to tackle the climate crisis, to encompass best practice and to prepare guidelines in hydropower development. Biodiversity has to be seen through the future where hydropower is a key factor mitigating climate change issues and supporting humankind.

### SUGGESTED RESEARCH TOPICS AND PRIORITIES

Assessment of the general impact and contribution of hydropower to biodiversity

Expected TRL: NA

Budget range: €7-10M

Priority: High to Very High

The main research objective is to characterise water ecosystems influenced by hydropower plants and to identify the best restoration strategies as well as to quantify their performance.

To characterise the impact of hydropower plants on water ecosystems (impact issues, restoration plan, barriers and enablers for implementing the restoration measures) detailed information will be gathered on:

- living organisms: biotic description, habitat inventories, ecosystem services;
- endangered species and a large-scale analysis of potential up and downstream habitats and co-existing fish species;

- analysis of the “Functional River Units (FRUs)”, based on the minimal space (latitudinal and longitudinal) of a river network or reach that the target species/ecosystem needs to function properly, realising that this varies depending upon species composition and geomorphology of the river system;
- abiotic (non-living) environment of the watershed: climate, hydrology, hydro morphology, geology and geography;
- human activities: urban and industrial development, agriculture;
- biodiversity losses, the factors contributing to the biodiversity losses, the nature, objectives, methods and models of the environmental restoration;
- available models and data on quality and quantity of habitats and monitoring systems of targeted species and processes;
- economic aspects of restoration and the funding strategies;
- policy support, the nature and cost of mitigation actions required by the WFD, the socio-economic context, the stakeholder’s involvement and the governance setting;
- Approach to implementation of the restoration project; barriers and enablers; what has worked and what has not.

Actions should implement additional monitoring and recording of data required for verification of restoration performance (improvement for the targeted species and/or ecosystem services with existing monitoring governance schemes) and demonstrate how restoration of river ecosystems (in biodiversity richness and abundance, structure, function and connectivity) and reservoir ecosystems services can be realised, which in turn deliver social and economic benefits.

Sensitivity to climate change is becoming an important element to take into account. For example, drought-prone systems would benefit from connectivity to higher reservoirs. Future changing meteorological and hydrological regimes in Europe have to be used within the analyses/approaches.

The impact will be:

- in line with the EU Biodiversity Strategy for 2030, to define biodiversity targets, restore degraded ecosystems;
- provide large-scale case studies of best practice ecosystem restoration that can be deployed at regional, national and cross-border levels;
- adapt, integrate and demonstrate innovative methods (technological, non-technological, social and governance, including sustainable financing) on upscaling ecosystem restoration, also in regions and for communities in transition;
- support the development of specific demand and supply chains in restoring ecosystems on land or at sea;
- demonstrate and test how restoration activities and socio-ecological management of ecosystems enable sustainable, climate-neutral and climate-resilient, inclusive, transformative approaches;

- generate knowledge on how large-scale restoration can accelerate transformative change beneficial for biodiversity and climate resilience, and bring this information to UN programmes, as well as to the IPCC and IPBES processes.

**Innovative and comprehensive approaches for successful hydropower projects and win-win situations**

**Expected TRL: NA  
Budget range: €4-6M**

**Priority: Very High**

The main research objective is to develop innovative, comprehensive approaches, appropriate methods, tools and guidelines to deploy future sustainable hydropower based upon a common understanding for all stakeholders (including environmental groups).

The steps towards this approach are:

- to address environmental issues and biodiversity protection, to discuss the classification and reconnection potential of ecologically valuable river stretches, to restore freshwater ecosystems and the natural functions of rivers and to meet WFD objectives by 2027;
- to enhance dialogue between industry, civil society, environmental groups and the European Commission;
- to develop comprehensive approaches allowing for compromises.

Water management and power generation are inherently complex topics. It is thus necessary for the public to be informed and educated about these challenges, so that they are fully aware and able to understand and address the issues. To make this happen, the hydropower sector needs to share knowledge and set participative standards, not only for the development of new projects, but also for established sites. Development of innovative SSH approaches could be helpful to find compromises compatible with the European energy market rules and environmental goals, and to evolve through drawing out the benefits of hydro for social welfare, in line with the energy transition, promoting carbon neutral power generation and a fair national framework, which gives priorities to actions that help preserve the planet.

Some groups consider hydropower as harmful and solely responsible for potential problems within a river system. However, the hydropower community advocates for a local transparent and scientific debate on the best technology to mitigate climate change, respecting the limits of our planet's resources, whilst enhancing our collective well-being for each green field.

Innovative SSH approaches could help starting from an inventory of issues detected on existing or new projects. Hydropower projects are often rejected because of the poor performance of the investor himself in managing E&S impacts and social relations. This global evaluation should be useful to clarify support or opposition from residents, other stakeholders of water use and NGOs. On the one hand, this helps to minimise potential

impacts and on the other, it can demonstrate the efficiency of current mitigation measures and reveal the newest research results.

SSH innovative approaches will work on various factors, such as:

- the nature and amplitude of environmental and social impacts;
- the way that impacts are managed: avoided, reduced, compensated according to high standards / or to low performance;
- the social relationships undertaken by the investors;
- the local, national and international stakeholders involved.

The result should be a Joint Statement of Collaboration on “Climate Solution and Conservation Challenges”, (like for US Hydropower, Dan Reicher in The Financial Times 2021) which identifies areas of common ground to advance the renewable energy and electricity storage benefits of hydropower and the environmental and economic benefits of healthy rivers.

Large hydropower development may only occur if it is included within a coherent national energy policy ensuring water and energy public service and security.

Consequently, the last step should be to prepare guidelines for Strategic Environmental Assessment in hydropower development. The impact would be to support more sustainable hydropower development.

### 3.7 Mitigating the impact of global warming

#### Background

Exploring the theme of ‘Water and Climate Change’, the UN-Water annual report on World Water Day<sup>19</sup> highlighted that hydropower forms an essential part of the solution to climate change. Hydropower is indeed a climate friendly technology preventing (lowest release of CO<sub>2</sub>)<sup>20</sup> and mitigating (water storage) the impact of global warming and climate change. It plays a valuable role in the framework of the European decarbonisation strategy: HPPs produce clean energy and their generation flexibility strongly contributes to balancing the frequency of the power network and ensuring grid resilience, thus fostering the deployment of intermittent renewable energy sources.

Climate change results in an increased frequency and intensity of flood and drought events, so discharge and storage capacities need to be upgraded in many cases. For this, cost-efficient solutions must be developed. On the other hand, the need for additional storage due to climate change could also be seen as a chance to improve water-management alongside hydropower. Moreover, according to the international commission on large dams (ICOLD) about 30 % of dam failures are due to the lack of appropriately dimensioned spillways. The design of the crest and spillway has a significant impact on the output and cost-efficiency of the structure. Yet, climate change, as a prominent hydrologic uncertainty, should be considered in the design. New innovative and robust spillway concepts are still an issue for further research. To ensure that the structure has the desired output and cost-efficiency, the design of the crest, spillway, and stilling basin can be optimised through innovative solutions. Rehabilitation of the dam body can also be necessary and simple and fast technologies can be adopted, as is the case of cemented material dams (CMD).

Existing or new reservoirs play a role to control flood risk and mitigate drought risk. Hydropower also contributes to drastically reducing GHG emissions. To illustrate, the GHG Reservoir (G-res) Tool developed by the International Hydropower Association (IHA)<sup>21</sup>, enables relevant stakeholders (e.g. companies, investors and consultants) to report on the carbon footprint of a reservoir and of hydropower activity. The tool enables accurate assessment of net greenhouse gas emissions in a cost-effective manner<sup>22</sup>. Assessing the net GHG emissions of a reservoir is now an expectation for sustainability reporting and for financing a hydropower project through climate finance. It is also a valuable input in multi-criteria analyses for assessing trade-offs between global warming, biodiversity, costs, social acceptance and other criteria.

<sup>19</sup> The United Nations World Water Development Report, 2020.

<sup>20</sup> IHA, 2018.

<sup>21</sup> Prairie et al., 2017.

<sup>22</sup> Prairie et al., 2017.

One of the first initiatives of power sector expansion planning are the Hydropower Inventory Studies. Through this initiative, every cascade option for the exploitation of hydroelectric potential must be studied to select schemes which give the best balance in terms of energy, economics, and social and environmental aspects. To assist the inventory studies, a manual and a computerised decision support system should be developed. Previous Hydropower Inventory Studies should be updated within the current technological context which allows the use of large-scale surveys based on Geographic Information Systems (GIS).

Also, GHG emissions coming from future hydropower plants that are planned or announced should be researched globally and identified at the national level to support Nationally Determined Contributions (NDCs) to achieve the Paris Agreement. Similarly for those existing reservoirs for irrigation or water supply that could be turned into multipurpose reservoirs by installing hydropower capacity. It is also uncertain how to allocate GHG emissions for the different uses in a multipurpose reservoir.

### 3.7.1 Research Theme:

#### **Innovative concepts of hydropower infrastructure adaptation and tapping hidden hydro**

**Priority: Very High**

**Recommended call: initiate research before 2030**

**Recommended funding scheme: €16-25 million**

#### **Background and challenges**

Europe has a lot of sites with low head potential, where hydraulic structures such as small weirs and old mill sites are already present and perhaps used, for example, for irrigation purposes. These structures are sometimes abandoned. The rehabilitation and optimisation of waterwheels for hydropower production and water services can be a valuable source of renewable energy.

#### **SUGGESTED RESEARCH TOPICS AND PRIORITIES**

**Regional potential of reservoirs mitigating the consequences of floods and long dry periods and their combination with hydropower to mitigate the consequences of volatile renewable energy production**

**Expected TRL: 6-7  
Budget range: €4-6M**

**Priority: Very High**

The main research challenge is investigation into the regional potential of reservoirs for mitigating the consequences of floods and long dry periods including the combination of these reservoirs with hydropower to help mitigate the consequences of volatile renewable energy production within the long-term perspective of the European energy system. The impact will be the mitigation of regional effects of climate change and related more extreme weather conditions.

**Pilot projects validating and exploiting innovative solutions for hidden hydro from existing water infrastructure**

**Expected TRL: 6-7  
Budget range: €7-10M**

**Priority: Very High**

The main research objective is development of pilot projects validating and exploiting innovative solutions for hidden hydro from existing water infrastructure such as arising



from drinking and wastewater networks, ship locks, irrigation canals, tailrace channels of large hydropower plants, non-powered dams, etc. The impact of this research will be to demonstrate the feasibility of innovative projects of hidden hydro and eventually to add more clean power to the grid. Further outcomes will include:

- rehabilitation of old structures and better management of infrastructure in rural areas;
- valorisation of cultural heritage, historic traditions and ancient buildings;
- fish-friendly energy production with fish-friendly weirs and ecological flows;
- market opportunities for local companies and people (i.e. community owned renewable energy);
- rural electrification, especially for remote buildings like mills, farmhouses, mountain retreats, etc.;
- tourism promotion.

**Research on allocation methodologies and future GHG emissions savings for multipurpose use reservoirs**

**Expected TRL: 4-5  
Budget range: €1-3M**

**Priority: High to Very High**

The main research objective is better allocation methodologies for the different uses of multipurpose reservoirs (e.g. improved quantification for the different uses and sectors) and comparison evaluation of GHG emissions and energy gain factor based on life cycle analysis with other energy sector developments. The impact will be quantification of GHG emissions for different uses and sector to justify their activity, access financing or comply with country arrangements in line with the Paris Agreement, as well as calculation of estimated GHG emission savings compared to development of other energy sectors including the energy gain factor based on life cycle analysis. A further outcome includes the creation of a database of future HPPs.

**New electric systems and configurations, improving performance and reducing costs of gearboxes to optimise power production of waterwheels and exploiting hidden hydro at existing water infrastructures**

**Expected TRL: 4-5  
Budget range: €1-3M**

**Priority: High**

The research challenge is supporting new electric systems and configurations of waterwheels, including performance improvement and cost reduction of gearboxes to optimise power production from the low rotational speed of water wheels. The impact of this research will be further development of hidden hydro on low head and very low head

sites, improved water wheel and water mill rehabilitation, as well as improved power generation from small hydro.

**Improvement of dam flood routing and release capacity**

**Expected TRL: 6-7**

**Budget range: €4-6M**

**Priority: Medium High to High**

The main research objective is the development of innovative improvements for dam flood routing and release capacity considering climate change. The following challenges need to be addressed by the research:

- new innovative, cheap and robust spillway concepts;
- developing innovative solutions using several types of Cemented Material Dams (CMD) for rehabilitation of existing dams or for the construction of new small dams, associated to new spillway concepts;
- research on flood conveying structures and energy dissipation at dam toes;
- detailed investigation of practices used for design of spillway capacity, as well as hydrological methods;
- improvement of flood mitigation in combination with advanced real-time weather and flood forecast systems;
- combination of physical models with numerical simulations, so-called hybrid modelling, which can improve efficiency and cost of studies;
- developing tools for the accurate assessment of the capacity of spillways and bottom outlet structures as well as strategies for pass through waterway solutions in the case of emergencies;
- enabling generation associated with the release of ecological flows.

The outcomes of this research would be:

- regularly elaborated and detailed assessment of the release capacity of dams as a preparation tool for climate change impacts;
- more reliable spillway and outlet systems with a reduced risk of malfunctioning, improved storage management and energy generation of the reservoir and improved flood management as well as dam resilience;
- adoption of environmentally compatible solutions in the rehabilitation or construction of small dams;
- significantly improved public safety due to improved flood mitigation;
- adopting a regulatory framework to allow proactive flood management with preventative releases;
- development of a rich catalogue of solutions and specifications for implementation.

**Investigation of the potential for using low calorific waste heat recovery**

**Priority: Moderate to Medium High**

**Expected TRL: 4-5**  
**Budget range: €1-3M**

Capturing waste heat from machines or processes is increasingly being utilised as it enables the energy to be redirected to a function that would otherwise be using energy from the grid. The **main research objective is investigating the potential for using low calorific waste heat recovery (i.e. especially from generators and transformers) aiming to increase the overall efficiency of existing plants.**

## 4 Comparing the Proposed Research Themes with the European Green Deal Goals and Broader EU Energy Transition Priorities

### 4.1 Comparison of the proposed research themes with the European Green Deal goals

		European Green Deal (relevant) policy areas				
		Climate change mitigation / Net-zero by 2050	Supplying clean, affordable and secure energy	Mobilising industry for a clean and circular economy	A zero pollution ambition for a toxic-free environment	Preserving and restoring ecosystems and biodiversity
Hydropower Europe R&I themes	3.1.1 Innovation in flexibility, storage design and operations	✓	✓			
	3.1.2 Innovative design of turbines including reversible pump-turbines and generators	✓	✓			
	3.1.3 New models and simulation tools for harsher operational conditions	✓	✓			
	3.1.4 Development and application of a business model for flexibility	✓	✓			
	3.2.1 Digitalisation and artificial intelligence to advance instrumentation and controls	✓	✓			
	3.2.2 Monitoring systems for predictive maintenance and optimised maintenance intervals	✓	✓			
	3.3.1 New materials for the increased resistance and efficiency of equipment	✓	✓		✓	
	3.4.1 New materials and structures for increased performance and resilience of infrastructures	✓	✓			
	3.4.2 Databases of incidents and extreme events, integrated structural risk-analysis models and innovative solutions for multi-hazard risk analysis	✓	✓			
	3.4.3 Innovative sediment management technologies for sustainable reservoir capacity and river morphology restoration					✓
	3.4.4 Innovative techniques for enhancing the working life of concrete structures	✓	✓			
	3.4.5 Innovative techniques for the enhancement of overtopping safety of embankment and rockfill structures	✓	✓			
	3.5.1 Development of innovative storage and pumped-storage power plants (e.g. Multipurpose PSH, sea water PSH, etc.)	✓	✓			
	3.5.2 Marine energy	✓	✓			
	3.5.3 Hybrid & virtual power plants	✓	✓			
	3.6.1 Flow regime management, assessment of environmental flow release, innovative connectivity solutions for fish and biodiversity protection and improvement of stored water quality in reservoirs					✓
	3.6.2. Assessment of the general impact and contribution of hydropower to biodiversity and the identification of innovative approaches and guidelines to support more sustainable hydropower development					✓
	3.7.1 Innovative concepts of hydropower infrastructure adaptation and tapping hidden hydro	✓	✓	✓		

Figure 4-1 The relevant EU Green Deal policy objectives compared with the proposed R&I themes

The European Green Deal aims to provide an action plan for European countries to, amongst other things, decarbonise the energy sector and to achieve climate neutrality by 2050. In this new, decarbonised energy system, electricity flexibility and storage will play a major role. Hydropower is the most widely used solution for flexibility and storage, thus a significant enabler through these functionalities. Europe needs to integrate the storage potential and flexibility capacities of hydropower into the current and future energy system. **The ambitious research and innovation targets identified in this document are demonstrably contributing to the environmental and clean energy objectives and goals of the EU Green Deal and will be critical for bringing forward the next generation of sustainable, efficient and cost-effective hydropower technologies.**

## 4.2 Comparison of research themes with the Hydro Equipment Association technology roadmap

The last attempt to formulate a comprehensive summary of R&I needs for the hydropower sector was published in 2015 by the Hydro Equipment Association (HEA)<sup>23</sup>. The HEA used to represent electromechanical equipment suppliers for hydropower globally but was dissolved in 2016. This document provided stakeholders with a structured view of the major technological challenges facing hydropower over the next 15 years and identified five themes for solutions to meet these challenges.

Since 2015, new renewable energy and climate policies have been launched including the European Green Deal and its 'Fit for 55' package. These represent important references for the future of the hydropower sector and prompted the need for an update of the R&I priorities. With this update, HYDROPOWER EUROPE seeks to ensure good alignment of the R&I agenda with these policies and specify in which areas and through which key activities the hydropower sector can contribute best in order to help achieve the EU goals and strategies.

Both documents are based on extensive consultation, which facilitated prioritisation and present valuable tools for guiding appropriate R&D efforts for supporting the hydropower sector towards desired goals. However, as shown in Figure 4-2 Comparison of HYDROPOWER EUROPE R&I themes with Hydro Equipment Technology Roadmap R&D priorities, the HYDROPOWER EUROPE RIA is more comprehensive, covering more R&I themes and in greater detail. In addition, the RIA is not limited to only technological issues, such as equipment and infrastructure improvement and extension or advanced operation managing systems. It also includes environmental, social and economic issues supporting sustainable development, in order to understand how communities and the wider public reacts to hydropower projects and how social acceptance can be enhanced. However, the RIA looks at these issues exclusively through a research and development perspective.

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<sup>23</sup> HEA was dissolved in 2016

		Hydro Equipment Technology Roadmap R&I themes				
		Providing flexibility in the electricity system	Increased hydroelectricity production from refurbishment, greenfield and multipurpose projects	Expanding the deployment options for pumped storage plants	Small hydropower: dispatchable generation for the electricity system	Maximally environment-friendly deployment
Hydropower Europe R&I themes	3.1.1 Innovation in flexibility, storage design and operations	✓		✓	✓	
	3.1.2 Innovative design of turbines including reversible pump-turbines and generators		✓			
	3.1.3 New models and simulation tools for harsher operational conditions	✓				
	3.1.4 Development and application of a business model for flexibility	✓				
	3.2.1 Digitalisation and artificial intelligence to advance instrumentation and controls	✓				
	3.2.2 Monitoring systems for predictive maintenance and optimised maintenance intervals		✓			
	3.3.1 New materials for the increased resistance and efficiency of equipment					✓
	3.4.1 New materials and structures for increased performance and resilience of infrastructures		✓			
	3.4.2 Databases of incidents and extreme events, integrated structural risk-analysis models and innovative solutions for multi-hazard risk analysis		✓			
	3.4.3 Innovative sediment management technologies for sustainable reservoir capacity and river morphology restoration					✓
	3.4.4 Innovative techniques for enhancing the working life of concrete structures		✓			
	3.4.5 Innovative techniques for the enhancement of overtopping safety of embankment and rockfill structures					
	3.5.1 Development of innovative storage and pumped-storage power plants (e.g. multipurpose PSH, sea water PSH, etc.)					
	3.5.2 Marine energy					
	3.5.3 Hybrid & virtual power plants	✓				
	3.6.1 Flow regime management, assessment of environmental flow release, innovative connectivity solutions for fish and biodiversity protection and improvement of stored water quality in reservoirs					✓
	3.6.2. Assessment of the general impact and contribution of hydropower to biodiversity and the identification of innovative approaches and guidelines to support more sustainable hydropower development					✓
	3.7.1 Innovative concepts of hydropower infrastructure adaptation and tapping hidden hydro				✓	

Figure 4-2 Comparison of HYDROPOWER EUROPE R&I themes with Hydro Equipment Technology Roadmap R&D priorities



## 5.1 Introduction – Network for the hydropower market in Europe

[illegible]

November 2021

The application of the global approach system analysis to the hydropower market in Europe is described in detail in a technical report (HPE, 2020) as well as summarised in the Strategic Industry Roadmap (SIR) of the HYDROPOWER EUROPE Forum (HPE, 2021). In the following section, only the main results comparing the research theme priorities are given.

Based on the feedback from the wider stakeholder consultation of the first draft of the Strategic Industry Roadmap (SIR) and the Research and Innovation Agenda (RIA), a list of 103 factors were identified and considered relevant for the system analysis. They represented seven sectors, namely:

- Hydropower
- Energy and economic policy
- Electricity market
- Environment and public society
- Research and development
- Legal framework
- Climate change

Based on these 103 factors, the network of the hydropower market in Europe was built and is presented in Figure 5-1 above.

Use of a circular visualisation according to Gu et al. (2014) offers an alternative method to represent the network, however, the circular visualisation cannot show in one single figure the activity of the factors (those that are influencing) as well as the reactivity of the factors (those that are influenced). Thus, two different circular visualisations are required to highlight either the activity or the reactivity.

Figure 5-2 shows the activity of the factors in circular visualisation while Figure 5-3 depicts the reactivity. Compared to the network map, these visualisations make it easier to see the most influencing factors (Activity) and respectively, those that are most influenced (Reactivity).

As expected, the activity of hydropower factors on other sectors is very limited (Figure 5-2). Nevertheless, the sectors *Legal Framework*, *Research and Development*, and *Electricity Market* as well as *Energy and Economic Policy* have strong influences on hydropower.



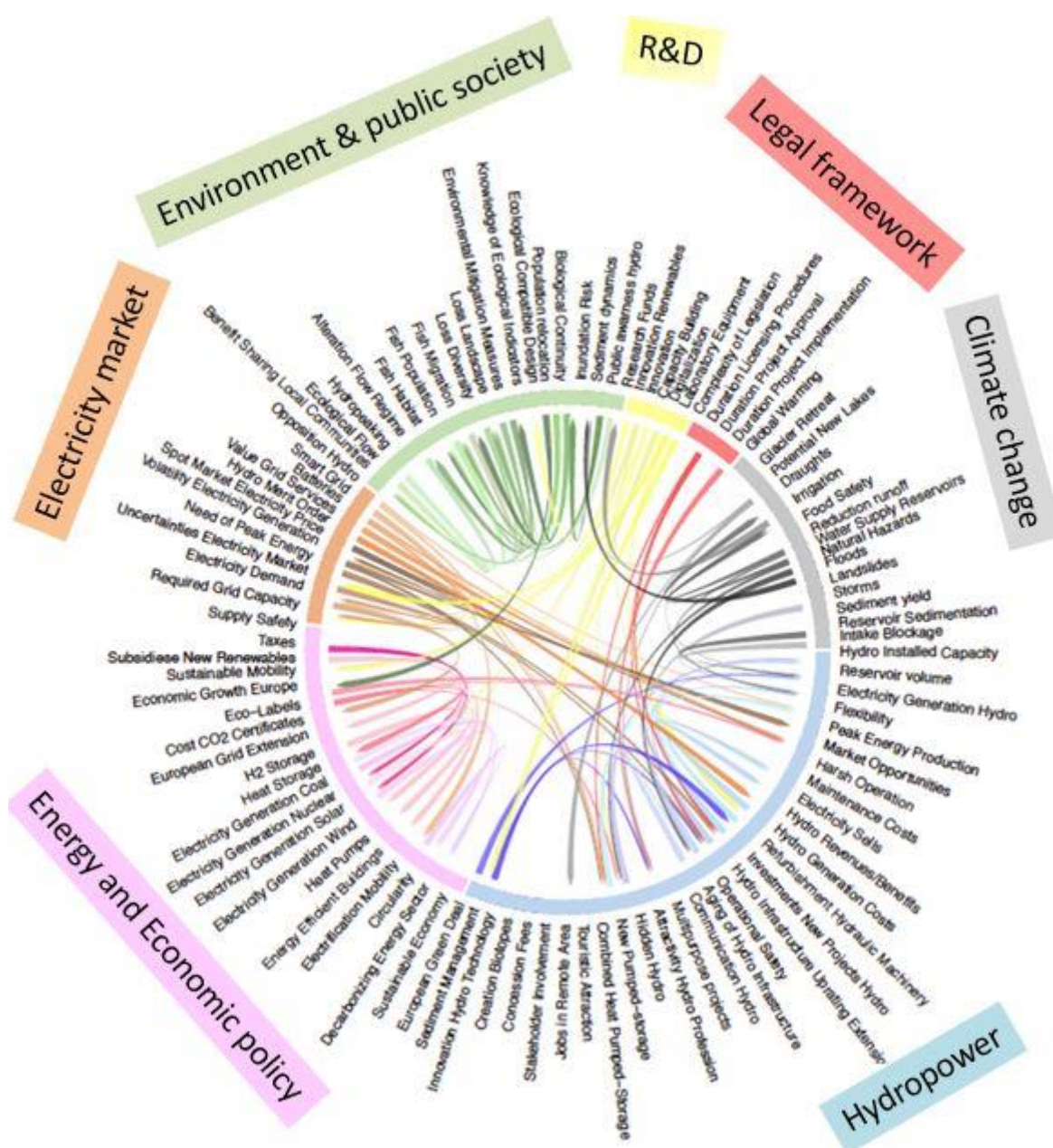


Figure 5-2 Circular visualisation of network factors showing the activity (influencing intensity)

When looking at the reactivity of the factors (Figure 5-3) - which means those being most influenced - it is not surprising that they can be found mainly in the sector of *Environment & Public Society*.

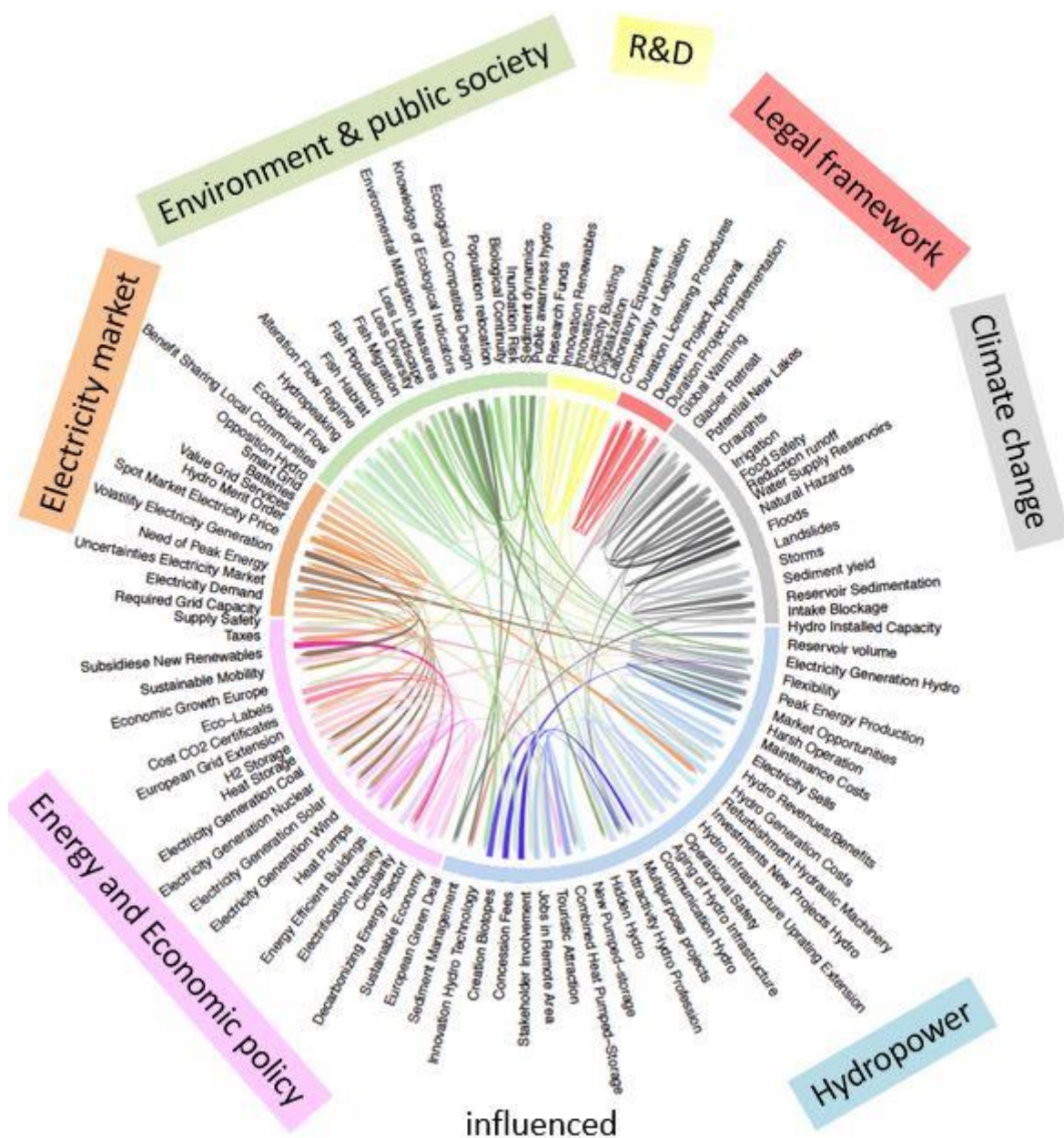


Figure 5-3 Circular visualisation of network factors showing the reactivity (intensity to be influenced)

## 5.2 Analysis of the network and identification of critical and active, controllable factors

The network, as well as the circular visualisation, reveal the complexity of the situation. Nevertheless, it is difficult to draw immediate conclusions. Thus, the interconnection of all factors in the network are reported in a matrix, which allows the activity and reactivity of each factor to be determined. Normally the analysis is started by considering only the direct

connections which comprise the first degree of influences. Then, to have better insight, the second degree connections are also analysed.

In the matrix the activities and reactivities of each factor have been summed up. Regarding the active or critical factors, two important categories have to be distinguished between: those that can be controlled directly by an action and those that are not controllable. The controllable factors can be used as a lever and are therefore important for the prioritisation of any actions. The analysis of the network, considering the second degree of connections between the factors, gives a clear and coherent picture (for details consult the SIR (HPE, 2021b) and HPE (2020)). The following conclusions can be drawn.

- a) Two critical factors could be identified, which are influencing the success of hydropower development in Europe in a dominant way, namely the *Volatility of the Electricity Generation* and the *Public Awareness Hydropower*. Both factors are not directly controllable and have to be influenced by other active factors in the system in a direct or indirect way. The *Public Awareness Hydropower* can be influenced directly by **Communication Hydro**. Any strategic action or research initiative which has a direct or a close indirect effect can be considered as **first highest impact level**.
- b) The controllable active factors are **Reservoir Volume** and **Environmental Mitigation Measures** which have a very high activity and can be considered also as **first highest impact level** when ranking strategic actions or research initiatives.
- c) Being also among the controllable active factors, **Benefit Sharing Local Communities**, **Ecological Flow** and **Population Relocation** from the environment and public society sector, can be used as levers and are very important when defining strategic actions and research initiatives. Any actions which can have an impact on these factors are among the **second highest impact level**. This is also the case for **Innovation Hydropower Technology** but it depends highly on the available research funds.
- d) Finally, a certain number of controllable factors are situated at the border between the passive and active domain, such as *Hydropower Installed Capacity*, *Multipurpose Projects*, *New Pumped Storage* and *Sediment Management* from the hydropower sector. Regarding energy policy also *Eco-labels* play an important role but are difficult to control directly. *Fish Habitat*, *Loss Biodiversity* and *Loss Landscape* can also be used as levers when defining actions. Lastly, *Digitalization* of the research and development sector is an important factor upon which actions should concentrate. Thus, all the factors mentioned under d) may be considered as third highest impact level when ranking strategic actions or research initiatives.



Hydropower Europe R&I themes	Complex System Analysis Hydropower in Europe																
		Communication Hydro	Reservoir Volume	Environmental Mitigation Measures	Benefit Sharing Local Communities	Ecological Flow	Population Relocation	Innovation Hydro Technology	Hydro Installed Capacity	Multipurpose Projects	Sediment Management	Eco-labels	Fish Habitat	Loss Biodiversity	Loss Landscape	Digitalization	
	3.1.1. Innovation in flexibility, storage design and operation		VH					VH	VH	VH							
	3.1.2. Innovative design of turbines including reversible pump-turbines and generators							H									
	3.1.3. New models and simulation tools for harsher operational conditions							H									
	3.1.4 Development and application of a business model for flexibility							VH									
	3.2.1. Digitalisation and artificial intelligence to advance instrumentation and controls		H					H			H					H	
	3.2.2. Monitoring systems for predictive maintenance and optimised maintenance intervals							HVH			HVH						
	3.3.1 New materials for the increased resistance and efficiency of equipment							MHH			MHH						
	3.4.1. New materials and structures for increased performance and resilience of infrastructure							MHH	MHH		MHH						
	3.4.2. Databases of incidents and extreme events, integrated structural risk-analysis models and innovative solutions for multi-hazard risk analysis							H			H					H	
	3.4.3. Innovative sediment management technologies for sustainable reservoir capacity and river morphology restoration			HVH	HVH				HVH			HVH		HVH	HVH		
	3.4.4. Innovative techniques for enhancing the working life of concrete structures								MHH			MHH					
	3.4.5. Innovative techniques for the enhancement of overtopping safety of embankment and rockfill structures								H								
	3.5.1. Development of innovative storage and pumped-storage power plants (e.g. multipurpose PSH, sea water PSH, etc.)			H					H	H	H						
	3.5.2. Marine energy			MHH					MHH	MHH	MHH						
	3.5.3 Hybrid & virtual power plants			HVH					HVH								HVH
	3.6.1. Flow regime management, assessment of environmental flow release, innovative connectivity solutions for fish and biodiversity protection and improvement of stored water quality in reservoirs				VH		VH		VH				VH	VH	VH	VH	
	3.6.2. Assessment of the general impact and contribution of hydropower to biodiversity and the identification of innovative approaches and guidelines to support more sustainable hydropower development				VH		VH		VH				VH	VH	VH	VH	
	3.7.1. Innovative concepts of hydropower infrastructure adaptation and tapping hidden hydro			VH					VH	VH	VH						

Figure 5-4 Comparison of the research themes and priorities with the controllable, active factors of the complex system analysis. 1st (orange), 2nd (yellow), 3rd (green) highest impact level factors in the complex system network. Priority categories given by CEP: Very-high (VH), High to Very High (HVH), High (V), Medium High to High (MHH)

## 5.3 Comparison of the research theme priorities with the controllable, active factors of the complex system analysis

The ranking of the critical and active, controllable factors influencing the hydropower system, according to the three levels of highest impact mentioned above, can be used to validate, from an objective viewpoint, prioritisation of the research themes as obtained by the feedback of the CEP and the wider stakeholder consultation process.

In Figure 5-4, the priorities of the research themes are compared with impact levels of controllable, active factors obtained by the complex system analysis of hydropower in Europe.

It can be noticed that none of the research themes are directly influencing *Communication Hydro* which has the highest impact level. Furthermore, none of the research themes are acting on the second highest level active factor related to *Benefit Sharing Local Communities*. This is not surprising since the research themes obtained by the wide consultation research themes are mainly oriented toward technological innovation and development. On the other hand, and as can be expected, all research themes have an influence on *Innovation Hydropower Technology* which has the second highest impact level in the complex system network. The active factor *Population Relocation* is also not addressed by the research themes. This may be explained by the fact that the construction of large new hydropower reservoirs in Europe, which would require displacement of a significant population, are not planned due to conflicting interests.

The research themes which influence the largest number of factors in the network of the complex hydropower system have without doubt the highest impact potential. According to this criterion the following ranking of the research themes can be obtained:

#### **Ranking Category I**

- 3.6.1. Flow regime management, assessment of environmental flow release, innovative connectivity solution for fish and biodiversity protection and improvement of stored water quality in reservoir (Priority Very High)
- 3.6.2. Assessment of the general impact and contribution of hydropower to biodiversity and the identification of innovative approaches and guidelines to support more sustainable hydropower development
- 3.4.3. Innovative sediment management technologies for sustainable reservoir capacity and river morphology restoration (Priority High to Very High)

#### **Ranking Category II**

- 3.1.1. Innovation in flexibility, storage design and operation (Priority Very High)
- 3.7.1. Innovative concepts of hydropower infrastructure adaptation and tapping hidden hydro (Priority Very High)
- 3.2.1. Digitalisation and artificial Intelligence to advance instrumentation and controls (Priority High)

- 3.5.1. Development of innovative storage and pumped storage power plants (e.g. multipurpose PSH, sea water PSH, etc.) (Priority High)
- 3.5.2. Marine energy (Priority Medium High to High)

The other ten research themes follow in **Ranking Category III**.

This comparison with the impact level of controllable, active factors obtained by the complex system analysis of hydropower in Europe gives a more objective assessment than obtained by the wider stakeholder feedback process and Consultation Expert Panel. Nevertheless, when comparing the above ranking categories related to the complex system analysis with the priorities of the research themes, it can be observed that both are in good agreement.

It can be concluded that the priority categories of the research themes obtained from the feedback of the Consultation Expert Panel (CEP) are confirmed by the complex system analysis. Nevertheless, it can be also noted that important active factors as *Communication Hydro* and *Benefit Sharing with Local Communities* are not addressed by the research themes which are, by definition, more oriented towards technological innovation and development. However, these non-technical factors are discussed in the Strategic Industry Roadmap and the required strategic actions are recommended there.

## 6 Outlook & Closing Remarks

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Hydropower in Europe is facing a great number of challenges. To tackle these environmental, societal, technological and market challenges, the hydropower sector needs to find novel approaches to future development in accordance with environmental and social demand.

So where is hydropower, the world's largest renewable energy source, heading in the foreseeable future? Predictions show that hydropower will hold the lead amongst other renewable energy sources as the world's largest source of renewable electricity generation. Forecasts show that annual additions are in the 20-35GW range.<sup>24</sup> Nevertheless, rising CAPEX costs, as well as costs related to addressing social and environmental impacts, could hinder this annual growth. In the EU, an enormous increase in variable renewables like wind and solar power is expected by 2050. Even if European hydropower capacity does not reach higher growth expectations, the role of hydropower will become even more important in the future energy mix, as a key enabler for the integration of variable renewables.

Climate change will play a decisive role in the development of hydropower energy due to its threat to the entire hydrological cycle. Moreover, the hydropower sector will have to show its worth, in dealing with continuous opposition from critics voicing concerns about the environmental and social damage caused by hydropower projects, as is also the case for other renewable energy sources (onshore and partly offshore wind, distribution/transmission grid projects).

One of the avenues for the future sustainable growth for this sector lies in the development of run-of-the-river plants, considering their multipurpose services for the energy system, as groundwater stabilisation, navigation in flood and draught periods and wetland biotope creation, or in pumped storage plants that benefit from a closed cycle, hence less interfering with natural water bodies. Furthermore, multi-purpose storage power plants and reservoirs will become vital for the mitigation of climate effects such as droughts and floods. There is significant potential for increasing the volume of existing reservoirs by heightening of dams. New large multi-purpose reservoirs may be limited by environmental and socio-economic constraints, but by taking advantage of synergies, compromises may be found. Another avenue of development lies in the increasing digitalisation of hydropower, with several hydropower plant operators utilising various Industrial Internet of Things (IIoT) technologies to make hydropower more efficient, and more competitive in the market.

The future portfolio of electricity generation is still uncertain, since it depends on technological development, public acceptance and the capability of the financial markets to provide the necessary financial resources for new projects. However, storage technologies that are key to introduce flexibility into the energy system will be relevant and PSH can be

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<sup>24</sup> IEA, 2019

competitive within this future portfolio. Moreover, it is quite certain that variable renewable energy sources, in particular wind and solar energy, will account for a significant share of this portfolio. Hybrid solutions, that combine hydropower with wind or solar for example, can thus be important too. Hydropower must be seen as an enabler for other intermittent renewable energy sources and not a competitor. In the end, there will be a need for all solutions to keep the grid running, especially with all the changes coming over the next 20 years. Hydropower plays a strategic role for a series of reasons:

- Hydropower helps to decarbonise the electricity system and to mitigate climate change;
- Hydropower enables the integration of variable renewable energy sources;
- Hydropower provides significant ancillary services to the grid;
- Storage hydropower contributes strongly to the Water-Food-Energy Nexus approach and the achievement of Sustainable Development Goals.

Hydropower delivers many services beyond electricity supply, as an important player in water resources management and water storage. This will be key in the near future due to climate change. However, regulation and remuneration play an important role in this future scenario because of their impact on hydropower revenues. Frequent alteration of regulations is indeed a factor that impacts negatively on the decision-making process for new projects, since it increases the risk of uncertainty in a sector that is already capital intensive.

A key finding of the intensive discussions within the Hydropower Europe Project is that hydropower needs an improved public awareness with a readiness to find compromises between ecological requirements and the needs towards a sufficient low carbon industrial society seeking an energy transition in order to limit global warming according international agreements (see SIR, HPE 2021b).



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## APPENDICES

### Appendix A – Overview of the timeframe for implementation of the R&I themes

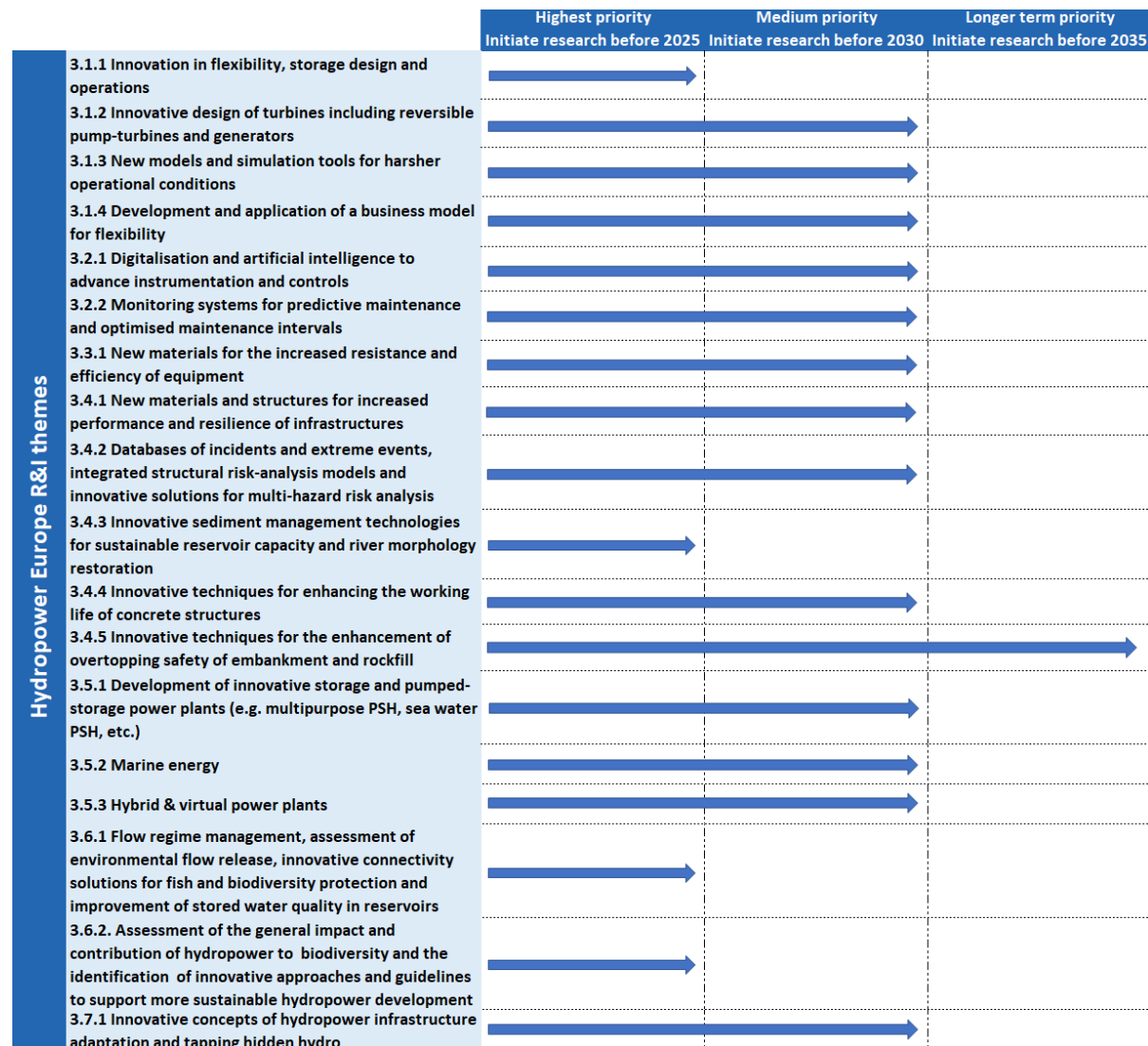


Figure 7-1 Overview of implementation timeframe for the R&I themes

## Appendix B – On-going R&I activities (as reported)

<b>On-going R&amp;I activities (as reported)</b>	
<b>3.1.1 Innovation in flexibility storage design and operations</b>	
<b>Activity leader</b>	<b>Description</b>
Technical University of Munich (TUM)	<ul style="list-style-type: none"> <li>- Development of more efficient hydraulic machines for pump-turbines working in four quadrant mode</li> <li>- Artificial intelligence</li> <li>- Project investigations for pumped storage plants in Austria (Kops 2 mainly)</li> </ul>
RSE S.p.A.	<p>Activities:</p> <ul style="list-style-type: none"> <li>- Identification of sites in Italy potentially suitable for the construction of additional reservoirs for upgrading existing hydroelectric plants to PHS (both conventional and seawater PHS)</li> <li>- Development of the relevant energetic, economic, and sustainability models</li> <li>- Modelling the integration in the Italian electric markets (day ahead, balancing and other ancillary services) of new innovative PHS, equipped with variable speed pump-turbines</li> <li>- Preliminary feasibility study for a new seawater PHS in Sardinia</li> <li>- Support to Italian government (Ministero dello Sviluppo Economico, MISE) to define new policies and regulations to facilitate the construction of new PHS in Italy</li> </ul>
France Hydro Electricité	Studies on the French Case with France Hydro Electricité (French small hydro association), EDF, SHER, CNR and ADEME (French Energy Agency), carried out by COMPASS LEXECON: identification of hydro flexibility performances, value of hydro flexibility, tools to reveal the actual value, suitable future market design
Lulea University	Number of international projects <b>(Topic of these projects are not available)</b>
<b>ETH Zurich and EPFL Lausanne</b>	<p>Different research projects<sup>25</sup>:</p> <ul style="list-style-type: none"> <li>- demonstrator for large hydropower (FLEXSTOR)</li> <li>- demonstrator for small hydropower (SMALLFLEX)</li> <li>- demonstrator for the problem of reservoir sedimentation (SEDMIX)</li> </ul>
Technical University of Madrid	Development of optimisation models for the short and medium term generation scheduling of power plants and systems (with

<sup>25</sup> SCCER-SoE, 2019.

	special emphasis on hydropower and pumped storage plants or systems), in both centralised and decentralised markets, and their application to perform diverse techno-economic analyses
University of Ljubljana – Faculty of Mechanical Engineering	<ul style="list-style-type: none"> <li>- Modelling of energy storage demand</li> <li>- Development of new small PSH water turbines</li> </ul>
Energias de Portugal (EDP)	<ul style="list-style-type: none"> <li>- Seeking enlarged operation ranges in the PSH units</li> <li>- Developing hybridisation strategies</li> <li>- Assessing opportunities for efficiency increase in PSH units</li> </ul>
<b>Studio Frosio in collaboration with the Politecnico di Milano</b>	<ul style="list-style-type: none"> <li>- Investigation of effect of micro and small hydropower plants (an existing one to be turned in PSH and a completely new one aimed to use water in closed-circuit mode) in two case studies on LV and MW grids</li> </ul>
Norwegian Research Centre for Hydropower Technology <b>Research partners:</b> <ul style="list-style-type: none"> <li>- <b>The Norwegian University of Science and Technology, NTNU</b></li> <li>- <b>SINTEF Energy Research</b></li> <li>- <b>Norwegian Institute for Nature Research, NINA</b></li> </ul>	Ongoing research focused on: <ul style="list-style-type: none"> <li>- Tunnels, penstocks and surge chambers</li> <li>- Dam and dam safety</li> <li>- Variable speed, turbine and generator</li> <li>- Turbine fatigue</li> <li>- Pump turbines (Booster pump)</li> <li>- Turbine and generator lifetime</li> <li>- Flexible hydropower unit</li> <li>- Future market and prices</li> <li>- Operational cost, remaining lifetime and reliability</li> <li>- Environmental restrictions and uncertainties for revenues</li> <li>- Water resource management</li> <li>- Social acceptance</li> <li>- Two-way fish migration</li> <li>- Environmental Design</li> </ul>
<b>3.1.2 Innovative design of turbines including reversible pump-turbines and generators</b>	
<b>Activity leader</b>	<b>Description</b>
HydroFlex (H2020) (Coordinator: NTNU)	(Increasing the value of Hydropower through increased Flexibility) is a research and innovation action with a budget of €5,7m funded under the EU Horizon 2020 programme
<b>XFLEX HYDRO (H2020)</b> <b>(Coordinator: EPFL, Demonstrator: EDP, EDF, ...)</b>	XFLEX HYDRO is an ambitious energy innovation project demonstrating how flexible hydropower technologies can deliver a low-carbon, secure and resilient power system. It aims to demonstrate new hydropower technologies such as smart controls, enhanced variable- and fixed-speed turbine systems, as well as a battery-turbine hybrid.

AFC4HYDRO (H2020) (Coordinator: UPC)	The overall objective is to design, implement and validate in full-scale water turbine an active flow control system that permit to increase efficiency and reduce the dynamics loads on the structure at any off-design operating conditions and during transient operations
Vorarlberger Illwerke AG	Model tests to improve Operation at Minimum load and to improve Efficiency factors at Minimum load
Technical University of Munich (TUM)	Developing a new four quadrant <i>Straflo</i> pump-turbine with permanent magnetic generator
TIDETEC	Developing a rotating turret turbine to turn the turbine, to enable optimal bi-directional functionality
Schluchseewerk AG	Cooperation with universities and another research organisation in order to develop in-situ research and improvement of existing systems
Technical University of Madrid	Development of optimization models for the short- and medium-term generation scheduling of power plants and systems (with special emphasis on hydropower and pumped storage plants or systems), in both centralized and decentralized markets, and their application to perform diverse techno-economic analyses
Energias de Portugal (EDP)	<ul style="list-style-type: none"> <li>- Seeking enlarged operation ranges in the units</li> <li>- Assessing opportunities for efficiency increase in the units</li> <li>- Defining strategies for optimization of neighbouring river basins to promote flexibility and power peaking</li> </ul>
Norwegian Research Centre for Hydropower Technology	Ongoing research focused on: <ul style="list-style-type: none"> <li>- Variable speed, turbine</li> <li>- Pump turbines (Booster pump)</li> <li>- Turbine and generator lifetime</li> </ul>
<b>3.1.3 New models and simulation tools for harsher operation conditions</b>	
<b>Activity leader</b>	<b>Description</b>
University Ss Cyril and Methodius – Civil Engineering Faculty	Scientific-research papers on water resources management (optimisation and simulation models in case of complex multi-purpose and multi-reservoir water resources system for Crna Reka basin, N. Macedonia)



Technical University of Madrid	<ul style="list-style-type: none"> <li>- Development of optimisation models for the short- and medium-term generation scheduling of power plants and systems (with special emphasis on hydropower and pumped storage plants or systems), in both centralized and decentralized markets, and their application to perform diverse techno-economic analyses</li> <li>- Development of dynamic simulation models of hydropower plants and electric power systems (usually single busbar models) and their application to perform diverse technical analyses</li> </ul>
Energias De Portugal (EDP)	<ul style="list-style-type: none"> <li>- <b>Sponsoring studies and tests (numeric, model and prototype) to identify limited operation zones and quantify lifetime consumption</b></li> </ul>
<b>3.1.4 Development and application of a business model for flexibility</b>	
No reported on-going R&I activities	
<b>3.2.1 Optimisation of operations and maintenance</b>	
Activity Leader	Description
Technical University of Munich (TUM)	Invention and patent application for an "3D ultra-sonic tomograph" to detect and track sensorless fish in a range of a couple of hundred meters
Schluchseewerk AG	Optimisation of maintenance intervals to achieve a higher safety level
University of Kassel – Department of Hydraulic Engineering and Water Resources	Optimisation of control systems in several rivers with chains of barrages
University Stuttgart	Increase resilience, reduce costs, improve public acceptance of safe and renewable energy supply
TU Wien – Institute for Energy Systems and Thermodynamics	Small research work is done in terms of data harmonization and interpretation of the results by means of visual data analytics
Spanish Ministry for Science and Innovation	TRISTAN - New computational Tools for Reliability-based dam Safety Assessment - Duration: 01/01/2019-31/12/2021
Spanish Ministry for Science and Innovation	NUMA - Development of an environment for integrating physics-based and data-based models for dam monitoring - Duration: 01/06/2016-31/12/2018
Spanish Ministry for Science and Innovation	ACOMBO - Development of a computational tool for the thermomechanical analysis of double-curvature arch dams - Duration: 01/09/2015-31/08/2018
Spanish Ministry for Science and Innovation	AIDA - Definition of warning thresholds for dam safety using artificial intelligence and a non-euclidean affinity assessment metric



	- Duration: 01/01/2014-31/12/2016
Spanish Ministry for Science and Innovation	iComplex - Development of the iComplex software for assessment of safety of critical infrastructures
CIMNE	Development of an application and methodology for dam monitoring data analysis
Deltares	Bringing optimisation techniques towards common practice for operational water management, in particular pump operations (e. g. lowland drainage in the Netherlands) and hydropower operations. <ul style="list-style-type: none"> <li>- Set up an open-source software product, that is already being used by some hydropower operators and water authorities</li> <li>- Investigate the topic of making ensemble forecasts operational</li> </ul>
ENEL	Activities, in terms of short-mid-term scenario (up to five days ahead) focused both on high-accuracy weather forecast models and hydrological models. Both technologies from several providers over different hydrological basins were tested in order to find the solutions which satisfied needs the best. The tests usually consisted of a calibration phase of the hydrological model (employing specific data of the basin as land use, digital model terrain jointly to observation data of precipitations and inflow) followed by a real time monitoring phase when inflow (and weather) forecast was supplied at specific points of hydrological basin. Other limited tests at the same scope was performed by the use of statistical models. Regarding the long-term scenario (up to six months ahead) a seasonal climate forecast model was developed jointly with a partner. The results consist of a bulletin supply containing precipitation and temperature anomaly forecast, over interest areas, with respect to 20 years of historical data
Powervision Engineering	Development of improved decision-making process with the use of numerical twins
<b>3.2.2 Monitoring systems for predictive maintenance and optimised maintenance intervals</b>	
<b>Activity leader</b>	<b>Description</b>
Technical University of Munich (TUM)	Sensors to detect the different types of cavitation in turbines. The idea was to predict lifetime and intervals for maintenance. The project has been stopped
Enel	Investigation focused mainly on scouting and testing predictive maintenance platform. At the same time, opportune strategies/procedure to foster the digitalization of hydro power plant have been defined. This means not just increasing the number of sensor or data, but also make easily available them to advanced analytics model

	- Budget allocated around 2M Euro
VGB Technical Group O&M	Working on O&M cost reduction (Estimate residual life of key components; Optimize checks and maintenance) and the discussion of typical vs. individual effects or experiences
<b>3.3.1 New materials for increased resistance and increased efficiency of equipment</b>	
No reported on-going R&I activities	
<b>3.4.1 New materials and structures for increased performance and resilience of infrastructures</b>	
Activity Leader	Description
Schluchseewerk AG	Cooperation with other stake holders for in-situ testing
ETH Zurich – Laboratory of Hydraulics	Research on hydro abrasive wear of sediment-prone structures; research on turbine abrasion
University Stuttgart	New developments of building materials and application technologies
EPFL Lausanne – Laboratory of Hydraulics	Research on surface morphologies with high friction loss reduction
<b>3.4.2 Databases of incidents and extreme events, integrated structural risk-analysis models and innovative solutions for multi-hazard risk analysis</b>	
Activity Leader	Description
EDP	<ul style="list-style-type: none"> <li>- Implementation and exploitation of ADAS in new and in existing dams</li> <li>- Activities and research in the field of geodetic observation, including the use of Robotic Total Stations (continuous and periodically), the use of GNSS systems (continuous and periodically), integration of continuous observation in ADAS and use of PS-InSAR in the observation of reservoir slopes</li> <li>- Exploitation of hydrometric stations with remote data acquisition, and developments of models supporting floods forecast associated to climate changes</li> <li>- Re-evaluation of design floods and spillways interventions; in three cases new complementary spillways have been constructed</li> <li>- Implementation in new dams of complete seismic monitoring systems for seismic action and structural response characterization, and, in two cases, including remote stations located in the reservoirs surrounding, for induced seismicity detection and event epicentre localization [*]</li> <li>- Installation of continuous dynamic monitoring systems in arch dams (H&gt;100m) in order to identify the dam's dynamic characteristics and their evolution over time, taking in account the variation of ambient and operational conditions [*]; execution of tests with limited duration in some other dams</li> </ul>

	<ul style="list-style-type: none"> <li>- Studies in the field of dam safety, according to specific dam characteristics (including swelling effects); development of statics and hybrid analysis for interpretation of monitoring data</li> </ul> <p>[*] Activities developed with LNEC and FEUP/Vibest support</p>
RSE S.p.A.	<p>Activities:</p> <ul style="list-style-type: none"> <li>- Advanced FEM analysis method for structural modelling of dams fully interacting with the surrounding environment (reservoir and rock foundation) subjected to extreme loading conditions, such as earthquake, floods, ageing (AAR), etc.</li> <li>- Development of simplified risk analysis tools for the preliminary seismic safety assessment of concrete dams.</li> <li>- Budget: rough estimate of €200K/per year</li> </ul>
Schluchseewerk AG	Providing existing structures to develop enhanced structural and material models
University Ss Cyril and Methodius – Civil Engineering Faculty	Scientific-research project "Comparison analysis on the stress-deformation state for rockfill dams with core/diaphragm at variation of the reservoir level"
EDF	<ul style="list-style-type: none"> <li>- Development of gated systems reliability tools</li> <li>- Developing AI tools to integrate dam incidents reports</li> <li>- Developments are currently on going towards the use of incremental methods and better assessment of downstream impacted people</li> </ul>
AVNIR Energy	Measurements on existing dams and sectional valves including experimental modal analysis with shock hammer excitation, in order to tune a FE model dedicated to seismic resistance analyses
University Stuttgart	Improving the model accuracy with high spatial, temporal resolved data
IRSTEA	<p>A project related to dam engineering and multi-scale modelling</p> <ul style="list-style-type: none"> <li>- Budget allocated to this project is around €150k</li> </ul>
PFCConsulting	<p>The activity consists in developing the passive seismic use, for risk analysis (soft ground, settlements, ...) and also for becoming a predictive tool in geotechnical activities such as tunnelling construction. The aim is to give a geological model before works, and compare the changes into the ground after works, after the tunnel has been excavated</p> <ul style="list-style-type: none"> <li>- Budget: 400,000.00 Euro</li> </ul>
<b>3.4.3 Innovative sediment management technologies for sustainable reservoir capacity and river morphology restoration</b>	
<b>Activity Leader</b>	<b>Description</b>
Vorarlberger Illwerke AG	Sediment management research (5M budget, 7 years duration)
EDF/HEPIA partnership	PhD launched in 2019: Study of the behaviour of trout under various conditions of TSS levels in an alpine river: assessment of

	the impact of moderate levels generated by dredging-dilution extraction of a reservoir for several weeks
EDF <b>Partners: French universities, research laboratory, water management agencies</b>	<ul style="list-style-type: none"> <li>- Development of tools for sand and gravel transport measurement in rivers</li> <li>- Development of methods for improving coarse sediment reinjection downstream of dams to improve the ecological functioning on the rivers downstream (sediment continuity)</li> <li>- Development of numerical models for sand and gravel sediment transport</li> </ul>
University of Innsbruck <b>Partners: AHM, spin-off company from University of Innsbruck, and suitable hydropower companies for which there is a need</b>	Possibility to record the riverbed in high resolution by an Airborne LiDAR bathymetric survey, which can be used for both different physical and numerical models
Reykjavik University	Research on nature-based solutions to reduce erosion, and subsequently reduce suspended sediments in downstream rivers and reservoirs
ETH Zurich – Laboratory of Hydraulics <b>Partners: Swiss National Science Foundation and Swiss federal Office of Energy as funding agencies</b>	Focus on sediment routing and sediment replenishment techniques <ul style="list-style-type: none"> <li>- Budget: 100,000 CHF</li> </ul>
CDG; Corporate partners: Andritz Hydro GmbH, Voith Hydro GmbH & Co KG, Association for Ecology and Environmental Research, via donau - Österreichische Wasserstraßen - Gesellschaft mbH	Collecting essential data and trying to work out practical solutions for sediment research and management <ul style="list-style-type: none"> <li>- Duration: 7 years</li> </ul>
IHA <b>Partners: BOKU university in Vienna, World Bank</b>	Global Sediment Management Study – best practices dissemination for sustainable hydropower
Norwegian Research Centre for Hydropower Technology	Ongoing research focused on: <ul style="list-style-type: none"> <li>- Sediment handling</li> </ul>

#### 3.4.4 Innovative techniques for enhancement of useful life of concrete structures

Activity Leader	Description
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University Stuttgart	R&I activities on improving data accuracy/model (spatial, temporal resolution) in cooperation with Hydropower Companies and Universities
<b>3.4.5 Innovative techniques for enhancement of overtopping safety of embankment and rockfill structures</b>	
Activity Leader	Description
EDF Hydro Engineering Centre (EDF-CIH)	Experimental tests in the lab and in the field to better understand physics <ul style="list-style-type: none"> <li>- European partners (Spain and UK)</li> <li>- university and consulting engineers</li> <li>- Budget: approx. €100k/year</li> </ul>
DPST Consulting	Use of lime and mineral binders in earthworks and hydraulic works <ul style="list-style-type: none"> <li>- Budget €70k/year</li> <li>- Partners: research centres, owners, engineers, contractors, designers</li> </ul>
<b>3.5.1 Development of innovative storage and pumped storage power plants</b>	
Activity Leader	Description
University of Innsbruck <b>Partners: other universities (architecture, fluid machinery, thermodynamics), construction and pump companies, energy companies</b>	Model tests, calculations, numerical simulations, examination of the functionality, optimisations of the design to develop new storage system, optimisation and reduction of the costs <ul style="list-style-type: none"> <li>- Budget: range of €100.000 to €200.000 per project</li> </ul>
Delft University of Technology	MSc students involved in analysing this topic since 2018 (no funding for further research yet)
Technical University of Madrid	Development of optimisation models for the short- and medium-term generation scheduling of power plants and systems (with special emphasis on hydropower and pumped storage plants or systems), in both centralized and decentralized markets, and their application to perform diverse techno-economic analyses; <ul style="list-style-type: none"> <li>- The team is composed by 5 full-time PhD professors a variable number of PhD and MSc students and participates both in research projects funded under national and international calls and research projects for public and private companies</li> </ul> Approximate budget €80k/year
Romande Energie SA	Demonstration project with a floating PV powerplant for a high altitude storage in the Alps (lac des Toules). Verifying the technical and financial feasibility of the large floating solar parks.

	- The project is supported by the Swiss federal office of Energy
<b>3.5.2 Marine energy</b>	
<b>Activity Leader</b>	<b>Description</b>
TIDETEC	Developing a rotating turret turbine to turn the turbine, to enable optimal bi-directional functionality including capability to generate energy in both flow directions, “basin to sea” and “sea to basin”
<b>3.5.3 Hybrid &amp; Virtual Power Plants</b>	
<b>Activity Leader</b>	<b>Description</b>
Kleinwasserkraft Österreich	Smart Hydro Mobility project seeks to determine technical/economic potential of small hydropower plants for providing 100% renewable electricity for emission-free electromobility. According to the project, by installing e-filling stations at small hydropower plants, the existing network infrastructure can be used, network losses can be minimised, and an efficient provision of 100% green electricity can be guaranteed
<b>3.6.1 Flow regime management, assessment of environmental flow release, innovative connectivity solution for fish and biodiversity protection and improvement of stored water quality in reservoir</b>	
<b>Activity Leader</b>	<b>Description</b>
EDF/IRSTEA partnership	Long term monitoring of trout population in rivers submitted to hydropeaking
University of Innsbruck	River surveys all over Europe and processing new big data volumes, numerical modelling
SINTEF Energy Research	Environmental impacts from hydropower, mitigation of impacts and environmental design of hydropower
Reykjavik University	Public perception of new hydropower plants in Iceland and Switzerland
Uniper	Producing models and tools to maximise the effect of environmental measures
Technical University of Munich (TUM)	Development of the shaft hydropower concept offering fish and sediment bypass. Lab experiments with live fish. Realization of the idea in a real hydropower plant in Bavaria. Monitoring and further improvement
EDF R&D together with Ecogea and GHAAPPE partners	Downstream passage devices assessment
University of Innsbruck; Albatros Engineering; IUS Weibel	Development and testing of the FishProtector <ul style="list-style-type: none"> <li>- The main goal is to provide a cost-effective and reliable solution for fish protection at medium and large scale HPPs</li> <li>- Budget: €860,000; duration: 5 years</li> </ul>

HydroFlex (H2020) (Coordinator: NTNU)	(Increasing the value of Hydropower through increased Flexibility) is a research and innovation action with a budget of €5,7M funded under the EU Horizon 2020 programme  How will a more flexible Hydropower effect the environment and can an uneven flow rate from the turbines be dampened out?
FIThydro (H2020) (Coordinator: <b>Technical University Munich</b> )	(Fishfriendly Innovative Technologies for hydropower) is a research and innovation action with a budget of EUR 7,1 M; duration 4 years
Joint Research Centre (JRC)	Fluid dynamic simulations for the optimization of fish passages and for sturgeon fish passages
<b>3.6.2 Assessment of general impact and contribution of hydropower to biodiversity and identification of innovative approaches and guidelines to support more sustainable hydropower development</b>	
<b>3.7.1 Innovative concepts of hydropower infrastructure adaptation and tapping hidden hydropower</b>	
No reported on-going R&I activities	
Activity leader	Description
Politecnico di Torino	Optimisation of Water Wheels and their Efficiency (ORME)
(Framework 7 Programme) <b>Southampton University – SOTON C</b>	Hylow is a research project which has the aim to develop novel hydropower converters for very low head differences or pressure differences
Joint Research Centre (JRC)	<ul style="list-style-type: none"> <li>- Research on the optimisation of overshot water wheels aimed at improving the efficiency at higher rotational speeds, with implications on the reduction of power take off costs</li> <li>- Research to quantify design parameters of water wheels, in order to find design equations for practical applications (in cooperation with some companies that provide data)</li> </ul>
IHA	<ul style="list-style-type: none"> <li>- Allocation methodology to different uses in multipurpose reservoirs</li> <li>- Creation of future plants database and potential for retrofitting</li> </ul>
IEA Technology Collaboration Programme	<p>Hydropower technology research and innovation in the context of hidden hydropower opportunities. Objectives<sup>26</sup>:</p> <ul style="list-style-type: none"> <li>- Understanding the potential for sustainable “Hidden Hydro” that has not been addressed through traditional approaches to hydropower development planning.</li> <li>- Identifying processes to prepare inventories of the potential for sustainable “Hidden Hydro”</li> </ul>

<sup>26</sup> IEA Hydropower, 2020.

	<ul style="list-style-type: none"><li>- Studying approaches to identify “Hidden Hydro” opportunities through improvements in data gathering, technology innovations, changes in regulation policies and deployment measures</li><li>- Formulating needs for further technology development to maximize the future use of the potential of sustainable hidden hydropower and develop a research and innovation agenda</li></ul>
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## Appendix C - Actors to involve

### Increasing flexibility

Actors to involve	Topic			
	Innovation in flexibility storage design and operations	Innovative design of turbines including reversible pump-turbines and generators	New models and simulation tools for harsher operation conditions	Development and application of a business model for flexibility
R&D centres and academia	✓	✓	✓	✓
HPP and PSP operators	✓	✓	✓	✓
Manufacturers	✓	✓	✓	✓
Investors	✓			✓
DSOs/TSOs	✓	✓	✓	✓
Utility	✓		✓	✓
Engineering & construction companies	✓			✓
ICT companies (software)			✓	✓
Regulators	✓			✓
Decision-makers and EU citizens	✓		✓	✓

Figure 7-2 Actors to involve in topics under theme Increasing flexibility

### Optimisation of operations and maintenance

Actors to involve	Topic	
	Digitalisation and AI to advance instrumentation and controls	Monitoring systems for predictive maintenance and optimised maintenance intervals
R&D centres and academia	✓	✓
HPP and PSP operators	✓	✓
Equipment manufacturers	✓	✓
Investors	✓	
Water management OS developers	✓	
Control system and instrumentation providers	✓	
Utility	✓	
Engineering & construction companies	✓	
Hydraulic modelers	✓	
Software developers	✓	✓
ICT companies	✓	
Forecasting model developers	✓	

Figure 7-3 Actors to involve in topics under theme Optimisation of operations and maintenance

## Resilience of electromechanical equipment

	Topic
Actors to involve	New materials for the increased resistance and efficiency of equipment
R&D centres and academia	✓
HPP and PSP operators	✓
Equipment manufacturers	✓
Material producers	✓
Material-testing laboratories	✓
Engineering consulting companies	✓
Chemical industry	✓
Engineering & construction companies	✓

Figure 7-4 Actors to involve in topics under theme Resilience of electromechanical equipment

## Resilience of hydropower infrastructure and operation

Actors to involve	Topic				
	New materials and structures for increased performance and resilience of infrastructures	Databases of incidents and extreme events, integrated structural risk-analysis models and innovative solutions for multi-hazard risk analysis	Innovative sediment management technologies for sustainable reservoir capacity and river morphology restoration	Innovative techniques for enhancing the working life of concrete structures	Innovative techniques for the enhancement of overtopping safety of embankment and rockfill structures
R&D centres and academia	✓	✓	✓	✓	✓
HPP and PSP operators	✓	✓	✓	✓	✓
Equipment manufacturers	✓	✓	✓	✓	
Professional associations		✓			
Utility			✓		
Material producers	✓				
Material testing laboratories	✓				
Dredging industries			✓		
Engineering consulting companies	✓	✓	✓		✓
Software developers		✓			
Engineering & construction companies	✓	✓	✓	✓	✓
Chemical industry	✓				
Public authorities			✓	✓	✓
Experts in lime and mineral binders					✓

Figure 7-5 Actors to involve in topics under theme Resilience of infrastructures and operations

## Developing new emerging concepts

Actors to involve	Topic		
	Development of innovative storage and pumped-storage power plants (e.g. multipurpose PSH, sea water PSH, etc.)	Marine energy	Hybrid & virtual power plants
R&D centres and academia	✓	✓	✓
HPP and PSP operators	✓		✓
Power electronics converter manufacturers	✓		✓
Manufacturers of emerging electrical energy storage technologies			✓
Turbine manufacturers		✓	
Coastal engineering and environment specialists		✓	
DSOs/TSOs	✓		
Utility	✓		✓
SWRO technology developers & suppliers	✓		
Marine and civil works companies		✓	
Automation and control industry			✓
Fishing industry			✓
Public authorities	✓	✓	
Legislators			✓
Broad public	✓		

Figure 7-6 Actors to involve in topics under theme Developing new emerging concepts

## Environmentally compatible solutions

	Topic	
Actors to involve	Flow regime management, assessment of environmental flow release, innovative connectivity solutions for fish and biodiversity protection and improvement of stored water quality in reservoirs	Assessment of the general impact and contribution of hydropower to biodiversity and the identification of innovative approaches and guidelines to support more sustainable hydropower
R&D centres and academia	✓	✓
HPP and PSP operators	✓	✓
Equipment manufacturers	✓	✓
Utility	✓	✓
Purification plants, sewage treatment	✓	✓
Agricultural sector	✓	✓
Engineering consulting companies	✓	✓
Fishing industry	✓	✓
Engineering & construction companies	✓	✓
Environmental and organisations	✓	✓
Public authorities	✓	✓

Figure 7-7 Actors to involve in topics under theme environmentally compatible solutions

## Mitigating the impact of global warming

	Topic
Actors to involve	Innovative concepts of hydropower infrastructure adaptation and tapping hidden hydro
R&D centres and academia	✓
Micro-hydropower companies	✓
Mill owners / carpentry companies	✓
Engineering consultant companies	✓
Engineering & construction companies	✓
Public authorities	✓

Figure 7-8 Actors to involve in topics under theme Mitigating impact of global warming