



POWERING EUROPE IN A SUSTAINABLE WAY



RESEARCH & INNOVATION AGENDA  
EXTENDED EXECUTIVE SUMMARY BROCHURE  
NOVEMBER 2021



The HYDROPOWER EUROPE project is built on the ambition to achieve a research and innovation agenda and a technology roadmap for the hydropower sector, based on the synthesis of technical and transparent public debates through a forum that gathers all relevant stakeholders of the hydropower sector.

The present brochure is an extended executive summary of the Research and Innovation Agenda. The full report of some 120 pages can be found on:

[www.hydropower-europe.eu](http://www.hydropower-europe.eu)

## Contact us:


✉ [contact@hydropower-europe.eu](mailto:contact@hydropower-europe.eu)

🐦 [@euhydropower](https://twitter.com/euhydropower)

🌐 [/company/hydropower-europe/](https://www.linkedin.com/company/hydropower-europe/)

## Disclaimer

This document reflects only the authors' views and not those of the European Union. This work may rely on data from sources external to the HYDROPOWER EUROPE project Consortium. Members of the Consortium do not accept liability for loss or damage suffered by any third party as a result of errors or inaccuracies in such data. The information in this document is provided "as is" and no guarantee or warranty is given that the information is fit for any particular purpose. The user thereof uses the information at its sole risk and neither the European Union nor any member of the HYDROPOWER EUROPE Consortium is liable for any use that may be made of the information.

 The HYDROPOWER EUROPE Forum is supported by a project that has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 826010



# Contents

1. Introduction – Vision of hydropower in Europe	4
2. The process of building the RIA	5
3. Overview of the research themes	6
4. Short description of the suggested research themes having high to very high priority and their respective topics	7
4.1. Increasing Flexibility	7
4.2. Optimisation of operations and maintenance	11
4.3. Resilience of electromechanical equipment and infrastructures	13
4.4. Developing new emerging concepts	16
4.5. Environmentally-compatible solutions	18
4.6. Mitigating impact of global warming	20
5. Comparison of identified research themes with Green Deal Goals and Hydro Equipment Technology Roadmap	21
6. Comparison of the research theme priorities with the results of the complex system analysis	21
7. Outlook & closing remarks	23
References	24

## List of Figures

Figure 1 - Approach to increasing hydropower production to complement renewable energy production	4
Figure 2 - Research themes as obtained by Hydropower Europe through a wide stakeholder consultation with indication of priority levels, time perspective, needed budget and desired TRL level	6
Figure 3 - Hydropower in Europe in a complex environment: Network of factors representing the sectors Hydropower (blue), Energy and economy policy (pink), Electricity market (orange), Environment and public society (green), Research and development (yellow), Legal framework (red) and Climate change (black)	22



# 1. Introduction – Vision of hydropower in Europe

The ambitious plan for European energy transition towards becoming carbon-neutral by 2050 is the greatest endeavour of our generation. The uptake of renewable sources, 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 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 an untapped potential, which allows hydropower to perform this role. However, this will require a more flexible, efficient, environmentally and socially acceptable approach to increasing hydropower production to complement other renewable energy production.

<p>Increasing hydropower production through the implementation of new environmental friendly, multipurpose hydropower schemes and by using hidden potential in existing infrastructures</p>	<p>Increasing the flexibility of generation from existing hydropower plants by adaptation and optimization of infrastructure and equipment combined with innovative solutions for the mitigation of environmental impacts</p>	<p>Increasing storage by the heightening of existing dams and the construction of new reservoirs, which have to ensure not only flexible energy supply, but which also support food and water supply and thus contribute to the WEF NEXUS and achievement of the SDGs of the United Nations</p>	<p>Strengthening the contribution of flexibility from pumped-storage power plants by developing and building innovative arrangements in combination with existing water infrastructure</p>
---	---	---	--

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

One of the main objectives of the Hydropower Europe Forum has been developing a Research and Innovation Agenda (RIA) and a Strategic Industry Roadmap (SIR) for the hydropower sector. This brochure presents the main results of the Research & Innovation Agenda (RIA). The goal is to provide recommendations on the R&I priorities for hydropower to EU institutions and national

authorities, stimulate and steer shaping of public spending for R&I as well as to provide a useful reference for the entire hydropower community.



## 2. The process of building the RIA

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. The scope of the R&I Agenda consultation was to collect relevant feedback from hydropower stakeholders on the relevant R&I themes and topics, the rationale behind them and their expected outcome. These themes and topics covering the whole hydropower value chain were clustered into the following 8 thematic groups addressing the challenges which European hydropower sector 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

All themes and topics were included in the on-line consultation, allowing respondents to choose only the themes and topics they deemed relevant. The consultation process was accompanied and validated by the Consultation Expert Panel (CEP) within the total of four workshop and consequent consolidation. The final consultations produced priority levels for each research theme and respective topics; their time perspective and needed budget as well as desired TRL levels.

Furthermore, based on the recommendation of the Consultation Expert Panel (CEP), two research themes identified during the elaboration and consultation of the Strategic Industry Roadmap (SIR) were transferred to Research and Innovation Agenda (RIA), which resulted in the final 18 research themes and in total some 80 detailed topics.

### 3. Overview of the research themes

The 18 research themes are summarized in Figure 2 indicating also the priority levels, time perspective, needed budget and desired TRL

level. The themes are numbered according to the chapters in the full report of the RIA (HPE, 2021a).

Consultation Feedback				
Challenges	Research Themes	Priorities	Recommended Call	Recommended Funding Scheme
Increasing flexibility	3.1.1. Innovation in flexibility, storage design and operations	Very High	before 2025	€ 26-35 million
	3.1.2. Innovative design of turbines including reversible pump-turbines and generators	High	before 2030	€ 16-20 million
	3.1.3. New models and simulation tools for harsher operation 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 operation and maintenance	3.2.1. Digitalisation and artificial Intelligence to advance instrumentation and controls	High	before 2030	€ 16-20 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 and infrastructures	3.3.1. New materials for increased resistance and increased efficiency of equipment	Medium High to High	before 2030	€ 8-15 million
	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 enhancement of 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
Environmental-compatible solutions and mitigation of the impact of global warming	3.6.1. Flow regime management, assessment of environmental flow release, innovative connectivity solution for fish and biodiversity protection and the improvement of stored water quality in reservoir	Very High	before 2025	€ 16-25 million
	3.6.2. Assessment of the general impact and contribution of hydropower to biodiversity and identification of innovative approaches and guidelines to support more sustainable hydropower development	Very High	before 2025	€ 8-15 million
	3.7.1. Innovative concepts of hydropower infrastructure adaptation and tapping hidden hydro	Very High	before 2030	€ 16-25 million

Figure 2 - Research themes as obtained by Hydropower Europe through a wide stakeholder consultation with indication of priority levels, time perspective, needed budget and desired TRL level



## 4. Short description of the suggested research themes having high to very high priority and their respective topics

### 4.1. Increasing Flexibility

---

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, while maintaining a secure power system (IEA, 2014; EURELECTRIC, 2011). A general conclusion in these reports is that hydropower, due to its quick response and good ramping capabilities, represents an important asset for the system operator. Improving the ability of hydropower installations to provide system services 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 turbines' flexibility will increase the value of hydropower in a future energy system (IEA, 2012, NREL, 2019; HEA, 2013). 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.

Besides these equipment adaptations a significant increase of flexibility at existing hydropower schemes can be achieved above all by increasing the installed capacity in the powerhouses by adding a new waterway system parallel to the existing one and by increasing the storage capacity for example by heightening of dams.

## Innovation in flexibility, storage design and operations

Priority: Very High

Recommended call: initiate research before 2025

Recommended funding scheme: € 26-35 million

### Background and challenges

Today, pumped-storage hydro (PSH) and reservoir hydro is currently the cheapest and most mature large-scale technology for energy storage and balancing the electricity network. In addition, it has a long lifetime, offers attractive grid services (e.g. black start availability, 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 the European hydropower reservoirs is exceeding 185 TWh. Thus, being the largest battery available, and an energy storage system for other renewables. Storage capacity is huge and available from a technical point of view and there is still a considerable untapped potential in Europe. A significant potential exists uprating of existing storage hydropower 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 electrical energy storage (i.e. storing electricity flowing through the network) 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.

The massive and fast penetration of solar PV and wind generation will undoubtedly place enormous pressure on grid stability and balancing requirement. By consequence, this means creation of market and/or regulatory mechanisms to stimulate entry of storage and flexibility providers is a high priority. In this context, hydropower advantages as a well understood technology with low lifecycle costs 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.

### SUGGESTED RESEARCH TOPICS with high to very high priority

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

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

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

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

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

Expected TRL: 4-5 Budget range: €1-3M

Improving feasibility and cost-efficiency of seawater PSH

Expected TRL: 6-7 Budget range: €4-6M

Further improving the efficiency and operation range of variable speed pump turbines

Expected TRL: 8-9 Budget range: €4-6M

Developing suitable equipment for low-head PSH

Expected TRL: 4-5 Budget range: €4-6M





## 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 hydro was in competition with fossil fired thermal plants. Since, the decarbonisation policy has led to decommissioning of fossil fired plants. A new energy system, where renewable energies sources (solar, wind, water) will only be developed, needs a new appropriate market model.

The revised Renewable Energy Directive (RED III) increases the overall Union target for renewable energy in 2030 to 40%. The RED III proposals, however, fall short in terms of supporting energy storage deployment to fa-

ilitate renewable energy sources (RES) integration. More precisely, the main challenge for Hydropower is the limited payoff in today's markets of flexibility, although hydropower is unique in its ability for providing system flexibility across all timescales. To demonstrate the solution and to give an accurate price to the flexibility, a market design must be built on an economic model taking account the wide portfolio of renewable energy sources, the interconnection and the liquid power markets.

### SUGGESTED RESEARCH TOPICS with high to very high priority

Development and application of a business model for flexibility to decarbonise the energy sector  
Expected TRL: 6-7 Budget range: €8-15M



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

Priority: High

Recommended call: initiate research before 2030

Recommended funding scheme: €16-20M

### 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 to 20-30. Similar performances are expected from pure-generation hydropower plants. Among the components that can fail are the generator's high voltage insulation system, which is damaged by thermal cycling and the higher temperatures associated with power converter technology. Stops and 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 hydro 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

### SUGGESTED RESEARCH TOPICS with high to very high priority

Analysing the relation between flexible operation and lifetime reduction  
Expected TRL: 6-7 Budget range: €4-6M

Improvement of operation at minimum load  
Expected TRL: 6-7 Budget range: €4-6M

Developing reversible Pump-Turbines fit for purpose in seawater environment  
Expected TRL: 6-7 Budget range: €4-6M

Cost reduction of variable speed turbines and ternary set systems  
Expected TRL: 6-7 Budget range: €4-6M

Developing robust designs of hydro plant components  
Expected TRL: 6-7 Budget range: €4-6M

## New models and simulation tools for harsher operation 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 operation conditions (increased number of start/stops, cavitation, fatigue strength). Most of the present machine sets -primarily- are not 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, at 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 the management of floods as well as drought situations.

In the future, the changing conditions on 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 future operating regimes.

### SUGGESTED RESEARCH TOPICS with high to very high priority

New simulation tools (also for power system level modelling) for new harsher operation conditions in conjunction with the material properties of the machine sets

Expected TRL: 6-7 Budget range: €4-6M

Understanding and numerically predicting the power plant performance at off-design operating conditions

Expected TRL: 4-5 Budget range: €1-3M

Demonstration of an integrated approach to solve extreme natural events in a harmless and optimised way involving universities, authorities, operators, insurance companies and manufactures

Expected TRL: 6-7 Budget range: €1-3M



## 4.2. Optimisation of operations and maintenance

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). In order to carry out predictive maintenance of

hydraulic installations, a 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.

### 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

High availability of hydropower plants, as of 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 in the hydro plants, detect early failure mechanisms or postpone unnecessary maintenance actions, i.e., avoid unplanned outages (failures), limit planned outages, thereby providing high overall plant availability. Moreover, additional investigations are required to develop a strategic asset management in hydro plants based on the exploitation of predictive maintenance software, facilitating the design of optimal predictive maintenance strategies for optimising HPP machinery maintenance management also in combination with sediment management.

#### SUGGESTED RESEARCH TOPICS with high to very high priority

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

Developing new online monitoring and diagnostic systems with intelligent sensors that predict the optimal maintenance interval based on the method of operation  
Expected TRL: 6-7 Budget range: €4-6M



## 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.

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 efficiencies of HP 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 need to better exploit sensor data to reliably track failure patterns and make use of big data as basis for predictive maintenance.

The further automatization and digitization of hydraulic power plants will allow to accelerate their competitiveness, flexibility and safety of operation. Furthermore, weather forecasts should be used for water management more frequently. Better forecasts enable more sustainable, profitable and secure operation of reservoirs. Remote data from satellites are promising for advanced precipitation and inflow forecasting.

### SUGGESTED RESEARCH TOPICS with high to very high priority

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

Expected TRL: 6-7 Budget range: €4-6M

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

Expected TRL: 6-7 Budget range: €4-6M

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 power-plant monitoring data including incidences

Expected TRL: 4-5 Budget range: €1-3M

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

Expected TRL: 6-7 Budget range: €1-3M

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 Budget range: €1-3M



## 4.3. Resilience of electromechanical equipment and infrastructures

The resilience of hydropower equipment structures means the capacity and adaptability to operate in adverse situations, which may be extreme events or slightly different changes in hydrological patterns from those for which the power plant and related infrastructures have been primarily designed (including a civil, hydro-mechanical, and electrical system). Extreme adverse situations for hydropower plants and infrastructures' 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 infrastructures against these

threats. Another source of risk is the ageing of infrastructures, which causes a decrease or variation in structural materials' strength properties. In the coming decades, more and more infrastructures are going to reach the end of the project's expected life span (100 years) and most of them will need retrofitting. Through regular monitoring and risk assessment, infrastructures' owners can keep risks from natural events under control. 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), multiplying threats for hydropower infrastructures in the future.

### 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. Its main reason is the sediment yield transported by rivers as suspended fine material or bed load into the reservoirs. Anthropogenic activities such as deforestation and overgrazing, combined with climate change effects exacerbate the soil erosion and deposition. Reservoir sedimentation is one of the most serious problems endangering the sustainable use of the vital worldwide reservoir capacity. The effects of climate change, especially glacier retreat and droughts in Europe, will in future increase the sediment yield entering the reservoirs during floods.

Over the last decades, many technical and operational mitigation measures against reservoir sedimentation have been developed. Unfortunately, there is not and will not be a magic solution which is successful for all reservoirs. Nevertheless, the wide and rich portfolio of confirmed measures allows finding tailor-made solutions for each reservoir. Still, finding the best solution requires high 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.

#### SUGGESTED RESEARCH TOPICS with high to very high priority

Development of innovative resistant coat for turbines for turbid waters during suspended sediment release  
Expected TRL: 6-7 Budget range: €4-6M

Developing innovative and sustainable sedimentation management methods and solutions enabling sediment continuity at dams and weirs  
Expected TRL: 6-7 Budget range: €4-6M

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

Estimation and analysis of increased sediment yield into reservoirs due to climate change and impact on hydropower generation  
Expected TRL: 4-5 Budget range: €4-6M



## 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: civil engineering structures, electro-mechanical equipment, data acquisition systems (SCADA – Supervisory Control and data acquisition/ADAS – Automated Data Acquisition system) applied to safety structural monitoring, maintenance teams, hydrological forecast systems, human organisation etc. Consequently, a systemic functional approach based on risk analysis is a necessary tool to address the main risks and improve dam resilience and dam operation.

However, while taking into account the ageing of dams and the associated structures, the modernisation and optimisation of their monitoring devices and plans should be carried out, envisaging structural resilience. Automated data acquisition systems with trigger alerts should be implemented, incorporating new monitoring devices based on the development of recent technologies.

Today more accurate hydrological data are available, and the climate change's effects can be better foreseen. 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 interventions' prioritisa-

tion. There is also the need to have a larger number of dams equipped with seismic monitoring systems (preferably automatic) to increase the knowledge about the actual seismic dam behaviour and above all under medium-strong earthquakes.

### SUGGESTED RESEARCH TOPICS with high to very high priority

Collecting and/or updating international data regarding structures dynamic behaviour, the seismic accidents and behaviour of hydraulic systems, structures and mechanical equipment (gates etc.) during earthquakes  
Expected TRL: 6-7 Budget range: €1-3M

New probabilistic design and risk analysis approaches  
Expected TRL: 4-5 Budget range: €1-3M

Collecting, update and interpretation of international data on large and extreme floods in Europe  
Expected TRL: 4-5 Budget range: €1-3M

Management of concrete swelling in dams and HPP structures  
Expected TRL: 6-7 Budget range: €1-3M

## Innovative techniques for 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 (especially of earth fill) dam failures.

Many dams were designed decades ago and the existing hydrologic data is much completed and more 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. Innovative solutions are focused on crest and downstream protection (i.e. mainly for embankment

dams). Besides, more satisfactory and simplified technologies for sealing restoration are required during the operation of dams and impounding of those whose reservoirs cannot be emptied.

### SUGGESTED RESEARCH TOPICS with high to very high priority

Innovative techniques for enhancement of over-topping safety of embankment and cemented structures  
Expected TRL: 4-5 Budget range: €4-6M



## New materials for increased resistance and increased 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 on electromechanical equipment as many hydro plants have not been designed to provide balancing power continuously. Among the components that can fail is the generators' high voltage insulation system, which is 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 caused by flexible operation 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 occurs..

### SUGGESTED RESEARCH TOPICS with high to very high priority

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



## 4.4. Developing new emerging concepts

While 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 hydro 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 hydro projects are already tapped, the hydro equip-

ment industry increasingly needs to provide innovative equipment capable of adapting and performing well under more challenging design constraints. **For greenfield development** multi-purpose schemes have become a must since they allow to achieve a win-win situation for all stakeholders involved and the best synergy between all purposes. This is difficult task and confirmed methodologies including evaluation of non-monetary goals and cost-sharing approaches are still missing.

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

Priority: High to Very High

Recommended call: initiate research before 2030

Recommended funding scheme: €8-15 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 appropriate water management, including water supply, flood and drought management, irrigation, navigation, fisheries, environmental services and recreational activities. Dams have been built most often to serve only one of the above-mentioned purposes. However, due to the increasing demand for the various provided services, their spatial and temporal overlaps, the increasing threat posed by climate change and national and international sustainability goals, construction and/or retrofitting multipurpose uses of dams has been favoured in recent years as they can fulfil several purposes with a single facility. Multi-purpose water infrastructure encompasses all constructed water systems, including dams, dykes, reservoirs and associated irrigation canals and water supply networks.

Through these uses, the profitability of storage and pumped storage plants can be improved, while 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.

#### SUGGESTED RESEARCH TOPICS with high to very high priority

Integrating storage and pumped storage in hybrid and virtual power plants  
Expected TRL: 6-7 Budget range: €4-6M

Transforming a storage power plant into a Pumped Storage Plant  
Expected TRL: 6-7 Budget range: €4-6M

Development of a new type of heat storage in underground reservoirs of PSH  
Expected TRL: 4-5 Budget range: €1-3M

Developing and optimising Integrated Sea Water PSH and Desalination Plant (SWRO) schemes  
Expected TRL: 6-7 Budget range: €4-6M  
Estimation and analysis of increased sediment yield into reservoirs due to climate change and impact on hydropower generation  
Expected TRL: 4-5 Budget range: €4-6M





## 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 the Hybrid Power Plant's 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 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).

In hybrid power plants, combining hydropower with solar or wind power to increase the stability and reliability of electricity generation is possible. Furthermore, adding emerging electrical energy storage technologies to the VPP would help further mitigate the adverse effects of variable renewable generation on the power system and its integration. Batteries are well suited for electrical en-

ergy 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 a very limited electrical energy storage capacity. Hydropower and pumped hydro 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 with high to very high priority

Pilot projects integrating hydropower with other RE sources and energy storage systems  
Expected TRL: 6-7 Budget range: €7-10M



## 4.5. Environmentally-compatible solutions

Hydropower is an excellent way of producing electricity from renewable energy. 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 its improvement in regulated rivers on a “case by case” basis, to better adapt a solution to the specific locations/hydropower site.

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 perception and social acceptance 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.

### 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

Recommended call: initiate research before 2025

Recommended funding scheme: €16-25 million

#### Background and challenges

Multipurpose schemes refer to the use of reservoirs to reduce the negative impact of hydropower plants on the environment, R&I activities 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 the environmental flows that mimic the natural water flow whilst maintaining the necessary climate protection (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 that fits all (e.g. concerning the Water Framework Directive). More research should also be undertaken on ecological flows within Mediterranean contexts as well as for high altitude alpine contexts 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) are not taken into account. The protection of fish populations by reducing mortality at power plants is another key issue and

there is still a need for development and finding solutions for downstream fish migration devices and guiding fish to such downstream bypass systems. All mitigation measures have to be defined by taking into account the future needs of a carbon neutral energy system.

#### SUGGESTED RESEARCH TOPICS with high to very high priority

Measures and approaches to protect biodiversity  
Expected TRL: 6-7 Budget range: €4-6M

Development and testing of solutions for improved biodiversity and fish protection  
Expected TRL: 6-7 Budget range: €4-6M

Investigating linked effects on biological community's resilience population dynamics and diversity through analysing different ecological flows in various geographical contexts  
Expected TRL: 4-5 Budget range: €4-6M

Evaluate, study and propose improvement of river ecology and fish habitat  
Expected TRL: 6-7 Budget range: €4-6M

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

Priority: High to Very High

Recommended call: initiate research before 2030

Recommended funding scheme: €8-15 million

## Background and challenges

The Global Assessment Report on Biodiversity and Ecosystem Services (IPBES, 2019) 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 among decision-makers and other stakeholders at all levels. Such technical measure can include, for example side channel reconnection, removal of bank protections 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. 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?

## SUGGESTED RESEARCH TOPICS with high to very high priority

Assessment of the general impact and contribution of hydropower to the biodiversity

Expected TRL: NA Budget range: €7-10M

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

Expected TRL: NA Budget range: €4-6M



## 4.6. Mitigating impact of global warming

Exploring the theme of 'Water and Climate Change', UN Water's annual report on World Water Day (2020) 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>) (IHA, 2018) 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.

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

Priority: High to Very High

Recommended call: initiate research before 2030

Recommended funding scheme: € 2-7 million

#### Background and challenges

Europe has a lot of sites with low head potential, where hydraulic structures like small barriers are already present, and for example, used for irrigation purposes or old mill sites. 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 with high to very high priority

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

Pilot projects validating and exploiting innovative solutions for hidden hydro at existing water infrastructures  
Expected TRL: 6-7 Budget range: €7-10M

Research on allocation methodologies and future GHG emissions savings for the uses in multipurpose reservoirs  
Expected TRL: 4-5 Budget range: €1-3M

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





## 5. Comparison of identified research themes with Green Deal Goals and Hydro Equipment Technology Roadmap

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 evolution compared to the previous attempt to formulate R&I priorities for 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. Moreover, they are not limited only to technological issues, but also include environmental, social and economic issues in view of sustainable development.



## 6. Comparison of the research theme priorities with the results of the complex system analysis

Based on the feedback received from the wider stakeholder consultation of the first draft of the Strategic Industrial Roadmap (SIR) and the Research and Innovation Agenda (RIA), a list of 103 factors have been identified which are considered relevant for the system analysis (HPE, 2020). With these factors a network of the hydropower market in Europe has been built which presented as a whole in Figure 3.

With matrix analysis of the interconnection of all factors in the network their activity and reactivity could be determined. Regarding the active or critical factors, it has to be distinguished between two important categories: those that can be controlled directly by an action and those who are not controllable. The controllable factors can be used as a lever and are therefore important for the prioritisation of any actions.

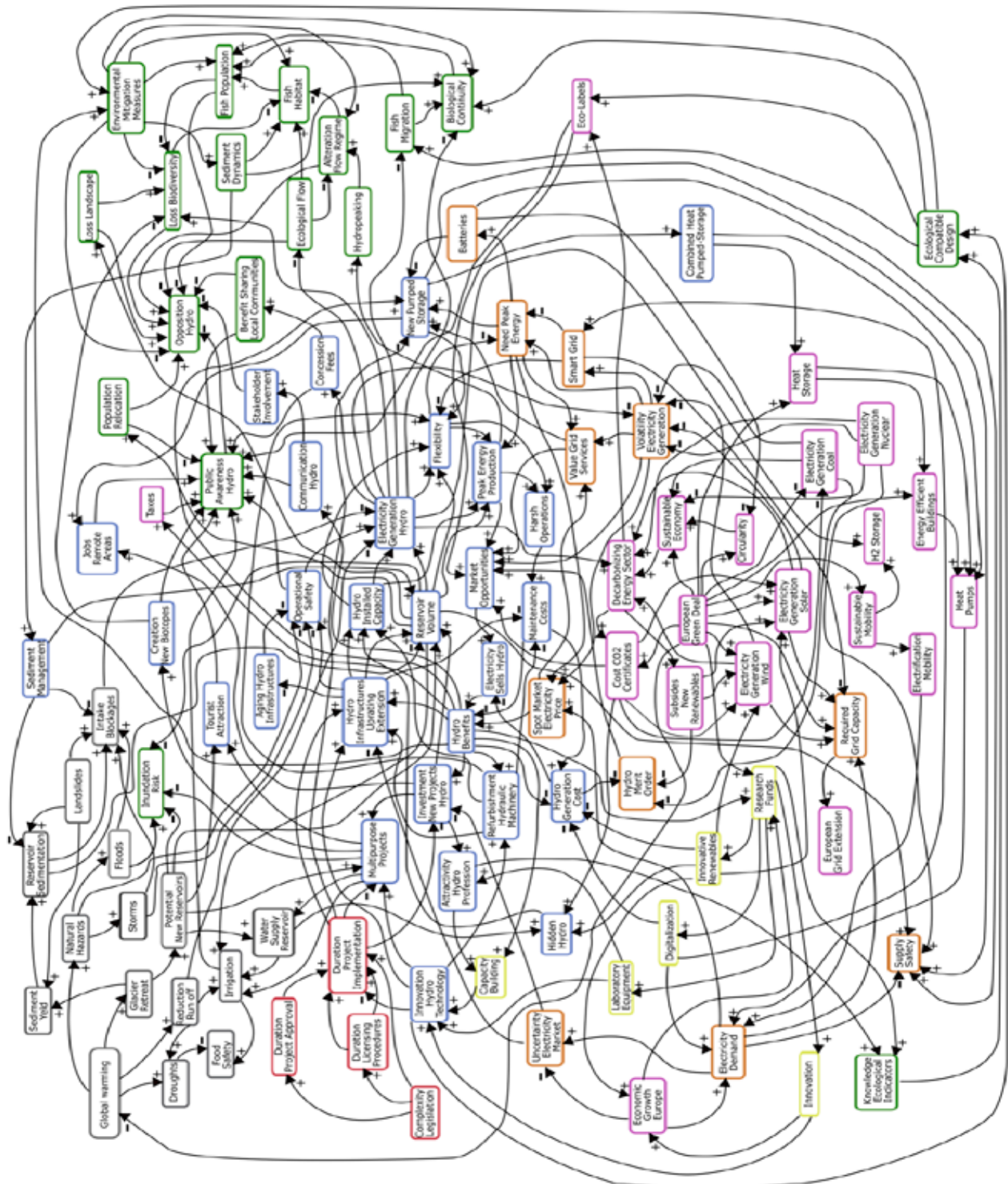


Figure 3 - Hydropower in Europe in a complex environment: Network of factors representing the sectors Hydropower (blue), Energy and economy policy (pink), Electricity market (orange), Environment and public society (green), Research and development (yellow), Legal framework (red) and Climate change (black)

The priority categories of the research themes obtained from the feedback of the Consultation Expert Panel could be validated by the results of the complex system analysis, when comparing them with the controllable, active factors having a high impact level on the network describing the hydropower system in Europe. Nevertheless, it could be also noted that important active

factors as Communication Hydro 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 (HPE, 2021b) and the required strategic actions are recommended.



## 7. Outlook & closing remarks

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 among other renewable energy sources as the world's largest source of renewable electricity generation.

Climate change will play a decisive role in the development of hydropower energy due to its threat to the entire hydrologic 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 it 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 mitigation of climate effects

as draughts and floods. There is a significant potential in 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 development avenue 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.

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 hydro revenues. Frequent alteration of regulations is indeed a factor that impacts negatively on the decision-making process for new hydro projects, since it increases the risk of uncertainty, in a sector that is already capital intensive and facing long project investment pay-back times.

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).

## References

EURELECTRIC (2011), “Flexible Generation: Backing up Renewables”. EURELECTRIC.

EUROSTAT (2019), <https://ec.europa.eu/eurostat/fr/home>

Hydro Equipment Association - HEA (2013), “Hydro Equipment Technology Roadmap”. Brussels: Hydro Equipment Association.

Hydropower Europe Forum (HPE, 2021a), “Research and Innovation Agenda (RIA)”, [www.hydropower-europe.eu](http://www.hydropower-europe.eu)

Hydropower Europe Forum (HPE, 2021b), “Strategic Industry Roadmap (SIR)”, [www.hydropower-europe.eu](http://www.hydropower-europe.eu)

Hydropower Europe Forum (HPE, 2020), Hydropower in Europe in a complex world - A global system analysis approach, Hydropower Europe Technical Report WP2-DIRp-47, June 2020.[www.hydropower-europe.eu](http://www.hydropower-europe.eu)

International Energy Agency -IEA (2014), “The Power of Transformation: Wind, Sun and the Economics of Flexible Power Systems”. Paris: IEA.

International Energy Agency -IEA (2012), “Technology Roadmap: Hydropower”. Paris: IEA.

IPBES (2019), “The Global Assessment Report on Biodiversity and Ecosystem Services”, Summary for policymakers

Norwegian Research Centre for Hydropower Technology - NREL (2019), [www.hydrocen.no](http://www.hydrocen.no)