Photo: NTNU Oceans ved Geir Mogen

Strategic Research Agenda of the EERA Joint Programme Hydropower

EERA
European Energy Research Alliance

Executive Summary

This document describes the Strategic Research Agenda (SRA) of the Joint Programme m (JP) on Hydropower within the framework of the European Energy Research Alliance (EERA).

The SRA represents the consensus of EERA JP Hydropower participants. It has been developed based upon an initial mapping of individual participating researchers' perception of the key challenges for hydropower technologies to contribute to the fullest extent towards meeting the climate targets of the European Union. After this mapping, the inputs were discussed in the individual Sub-Programmes (SPs) and the process of establishing the SRA was started as a bottom-up process, leading to the individual SP SRA contributions being merged with an overarching part anchored to the targets, frameworks, strategies and policies of the European Union and the European Commission.

The SPs were asked to present the most important focus areas from each SP to be included in this executive summary. Without prioritizing between them, the list presents the areas requiring focus and targeted research efforts for making hydropower a key enabling technology for making the green transition:

- Development of novel and innovative method for designing, engineering, constructing, installing and operating flexible hydroelectric units featuring high grade efficiency, reliability, safety and sustainability
- Using and further developing the latest technology regarding hydraulic scale models, numerical methods, and field investigations and by developing advanced hybrid modelling strategies combining laboratory, numerical and field studies to make full use of the advantages of the different modelling strategies to minimize associated uncertainties
- Value and operational requirements of hydropower in the future power system
- Open source hydropower data and models for energy system analysis
- Investigation of the impacts of climate change on water resources and subsequent impacts on power production and freshwater ecosystems
- Assessing and compensating environmental impacts, lost ecosystem services and biodiversity in reservoirs and downstream rivers
- Assessing factors promoting social acceptance, improved public engagement and increased uptake of hydropower in consumers` energy portfolios
- Investigating supportive and limiting effects of national and European policies, policy mixes and regulations on the environmental upgrading of existing hydropower infrastructure, new hydropower development and increased operational flexibility
- Transformation of hydropower asset maintenance from interval-based to prediction-based by use of new sensors and measurements
- Integration of cross-domain knowledge into new and established business processes in the hydropower sector


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Foreword

The launch of a new EERA Joint Programme on Hydropower is good news for energy system in Europe and beyond.

The clean energy transition is necessary, demanding and accelerating. Hydropower in Europe and worldwide represents a significant tool for achieving this change sustainably. Hydropower holds capabilities for energy supply, storage, and regulation that are unique. These characteristics are needed to deliver security of supply, stability in the grid, and for green growth. Increasing the flexibility of the hydropower fleet through innovation and modernisation is fundamental for these objectives.

Hydropower has a lot to offer. It can provide water management capabilities, mitigating damage from flood and drought events; it will provide clean energy and available capacity for stable and secure supplies; it will balance intermittent production from solar and wind, and it is capable of storing energy, both in short and long-term horizons. Hydropower rates very well in comparison to other renewable electricity production sources, including storage: energy-payback ratio, life-cycle assessment, greenhouse-gas emissions, water footprint, and more. Adding to that, hydropower has the highest energy-conversion efficiency and longest operating life. Without research, demonstration and investment, none of these roles will be optimised for the future.

Europe is instrumental in leading the way towards decarbonisation through competence building and innovation. And the Joint Programme on hydropower represents a renewed focus on new roles and priorities for hydropower; we can no longer rely only on the mature solutions and methods; we need to bring our existing knowledge further. What happens in a power plant that shall handle thirty starts and stops each day? How can we utilise rotating mass to provide instant regulation for the system? How will power peaking affect the watercourse, and how can we integrate water management solutions together with power production, recreation and navigation?

New challenges present new opportunities, but also new needs for research and innovation. The Joint Programme on Hydropower in EERA comprises a large group of excellent and dedicated R&D-communities in Europe. Our joint efforts will be a major hub for renewed research, supporting efforts to modernise the European fleet and assist the rest of the world, where the largest potential for new hydropower development lies. My hopes and expectations for this initiative is that it will expand globally and be a platform for research on topics related to hydropower in a world-wide perspective.

The need for this initiative is clear, and everyone involved should be very proud of the launch of this platform.

Richard Taylor
Former CEO, and executive advisor to
International Hydropower Association, IHA


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Content

Preface

This Strategic Research Agenda (SRA) is a result of the joint effort by all members of the Joint Programme on Hydropower of the European Energy Research Alliance (EERA). The Joint Programme was established in 2019, and as well as the Joint Programme, the content of a document such as this SRA is still in a phase of development. It is, however, important to launch it, and start to implement it as a working document, and this will lead to necessary revisions being clearer. The Joint Programme acknowledges this, and intends to revise the document after the launch. Even so, a strategy is only useful if it has taken into account all known uncertainties regarding future events that the future actually displays. In the energy system there are surprisingly many possibilities for disruptions, and because of this the SRA will have to be updated according to the developments of the energy sector. Such revisions will be initiated as and when needed, and not waiting for periodic revisions.

Part I of this document presents the framework of EU, EC, SET-Plan and EERA for the sake of anchoring the strategy to high level objectives, policies and frameworks. The readers familiar with this might jump directly to part II, which is specific to the EERA Joint Programme Hydropower. If the reader is also familiar with the Joint Programme Hydropower structure and the background for establishing the Joint Programme, jumping directly to Part III will describe the contributions from each Sub-Programme.

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Part I: The challenge and the EU framework for obtaining a solution

The climate change and mankind's need for energy

The need for energy, and the prosperous future foreseen by intensive energy use has historically driven most of mankind's endeavours. Exploiting the energy from the sun in different versions made it possible for mankind to travel the oceans, grow crops, heat buildings and develop technology for a better society. For some periods, it can be difficult to evaluate if society was better for all, or just for some, and to what extent there was an overall increase in wellbeing. But what really fuelled development of society towards being better for all, was the discovery of, and means to exploit, fossil fuels. It was a dream come true. But if something is too good to be true, it rarely is. This was also the case with fossil fuels. The dream is slowly turning into a nightmare, as evidence of climate change due to emissions of fossil fuels is mounting, and the long delay between emissions and global warming leaves little hope of avoiding severe implications on ecological systems and human lives. For the sake of future generations, we do not have the option of "keeping the band playing while the ship sinks" and people evacuate into the lifeboats, because there are no lifeboats! We must man all the pumping stations and do our best to keep the ship afloat. There is no plan B; there is no planet B.

Paradoxically there is no shortage of renewable energy in the world. Annually, the sun radiates more than 10.000 times the amount of human energy consumption to our planet! This energy fuels the atmospheric movements and weather systems, the water cycle, ocean currents, biomass increase, and so on. So, the energy is available as wind energy, bio energy, solar energy, potential energy from elevated water, tidal energy (not by light from the sun, but gravitational pull of the sun and moon), and wave energy. So why has mankind not abandoned fossil fuels already? There are many reasons. The major reason is high cost of renewables in a system demanding economic growth, even if long term cost of climate change by not abandoning fossil fuels has been calculated as much higher. The cost of something is dependent on many elements, and this is where the other reasons manifest themselves. Low efficiencies give low revenues on energy sales; design, construction and installation of many technologies are still far from optimal, giving large capital and operational expenses; environmental concerns and issues are (appropriately) given more focus; societal issues are also adding an element of public cost; technologies are not able to provide the instantaneous demand for energy, and so on. Until now, extraction of fossil fuels has been the path of least resistance for obtaining energy. This situation is starting to change, as people are starting to realise the consequences of the use of fossil fuels.

The challenge of "going green" is a substantial one, but at least the availability of sustainable energy is not the limiting factor. The challenge is viewed as a competition by some, but it is a competition where there will be no single winner in the end. There will be a winning solution, and this solution will be comprised of a mix of renewable energy technologies, energy storage technologies on a variety of time scales, centralised energy conversion units working together with distributed solutions and local sub-systems. In this winning solution all technologies must fulfil their potential and contribute what they are best suited for, at the most appropriate location. But fulfilling a technology's potential is not a one-time process leading to a static answer. Continuous development in all disciplines lead to limitations being pushed and removed, making further development possible. This development is dependent on research, and the importance of performing high quality cost-effective research within the renewable energy sector cannot be highlighted enough. The window for "going green" in time to limit the worst climate changes is closing fast. In order to get there, the world is in dire need of research on renewables and how to implement them.

EU energy Union and Climate change

The EU wants to become the first major economy to be climate neutral by 2050. This is an impressive goal, and the EU has put in place a political framework to ensure that they deliver on the Paris commitments. One of ten priorities of the European Commission is the so-called «Energy Union and Climate». It will help create an energy union that ensures Europe's energy supply is safe, viable, sustainable and accessible to all. One of the policy areas of this priority is «Research, Technology and Innovation». Within this, we find the Strategic Energy Technology Plan.

The SET-Plan

The Strategic Energy Technology (SET) Plan has been the research and innovation pillar of the EU's energy and climate policy since 2007. It was revised in 2015 to effectively line up with the EU's Energy Union research and innovation priorities. It coordinates low-carbon research and innovation activities in EU Member States and other participating countries (Iceland, Norway, Switzerland and Turkey).

The SET-Plan helps structuring European and national research programmes and triggers substantial investments on common priorities in low-carbon technologies. The aim of the SET-Plan is to accelerate the development and deployment of low-carbon technologies. Furthermore, it seeks to improve new technologies and bring down costs by coordinating national research efforts and helping to finance projects.

The SET-Plan key actions

To reach the aim, the SET-Plan statutes ten key actions:

1. ***Develop performant renewable technologies integrated in the energy system***
2. ***Reduce the cost of key renewable technologies***
3. ***Create new technologies and services for consumers***
4. ***Increase the resilience and security of the energy system***
5. Develop energy efficient materials and technologies for buildings
6. Improve energy efficiency for industry
7. Become competitive in the global battery sector (e-mobility)
8. Strengthen market take-up of renewable fuels
9. Drive ambition in carbon capture and storage/use deployment
10. Increase safety in the use of nuclear energy

The action marked with bold italic font are the ones regarded as relevant for hydropower technologies. In part III each SP section will make a reference to the actions relevant for the SP.

SET-Plan management

Apart from the SET-Plan Steering Group, the SET-plan is supported by three entities. One is the open-access SET-Plan Information system (SETIS) that provides up-to-date information on the SET-Plan activities covering all research and innovation priorities of the Energy Union. Another supporting organization is the European Technology and Innovation Platforms (ETIPs) representing the industry. The last organization supporting the SET-Plan is representing the research community, and is the European Energy Research Alliance, EERA. The first two supporting structures will not be explained any further in this document, and the interested reader may find information about this on the web pages of the SET-Plan. However, EERA will be explained in the following section.

EERA and its mission statement

Whereas the SET-Plan is the research and innovation pillar of the EU's energy and climate policy, EERA is the research pillar of the SET-Plan.

EERA's official mission is to catalyse European energy research for achieving the Paris Agreement target:

- Help streamline regional, national and European research efforts
- Deliver research results from basic research to the demonstration phase (TRLs 2 to 5) and ensure efficient transfer to industry and market

EERA was launched in 2008 and consisted originally of institutions from 11 countries. After its launch, several so-called thematic Joint Programmes (JPs) have been established, bringing together researchers aiming to find solutions to problems slowing down the development and deployment of low-carbon technologies. Currently, there are 17 active joint programmes, an overview can be seen in Figure 2. Their research fields range from Nano-scale structural and molecular materials

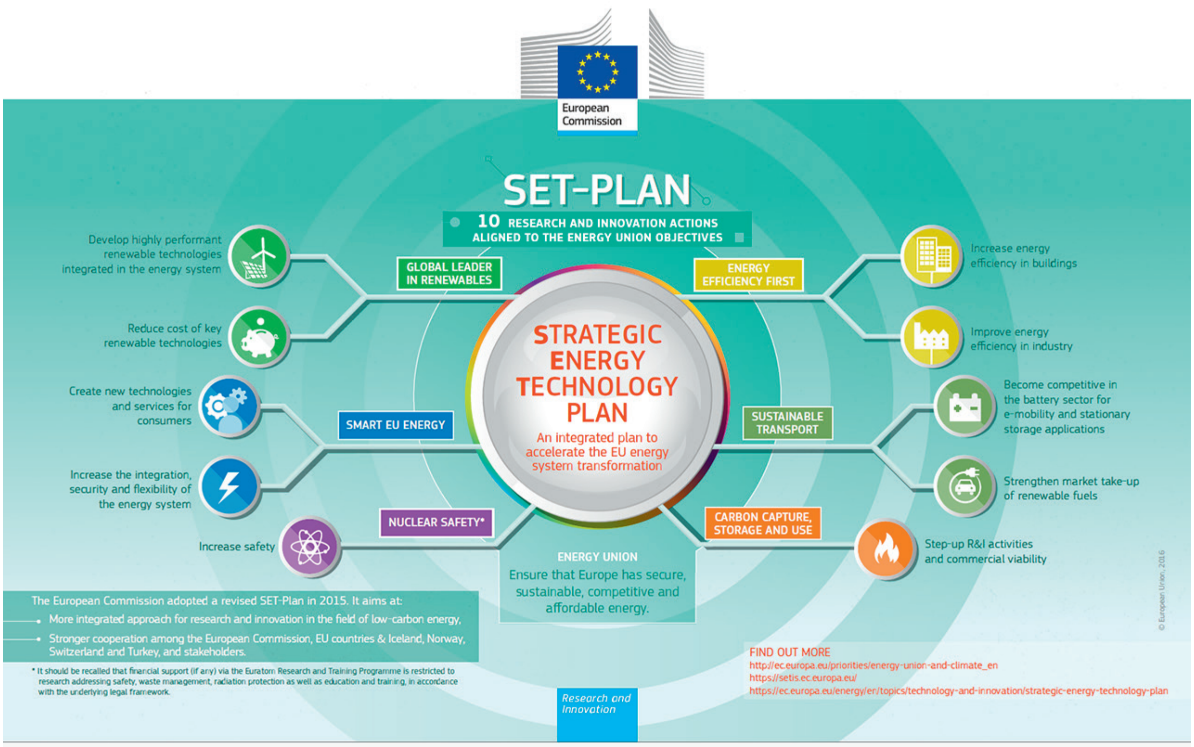

***Figure 1:** SET-Plan and the ten key actions*

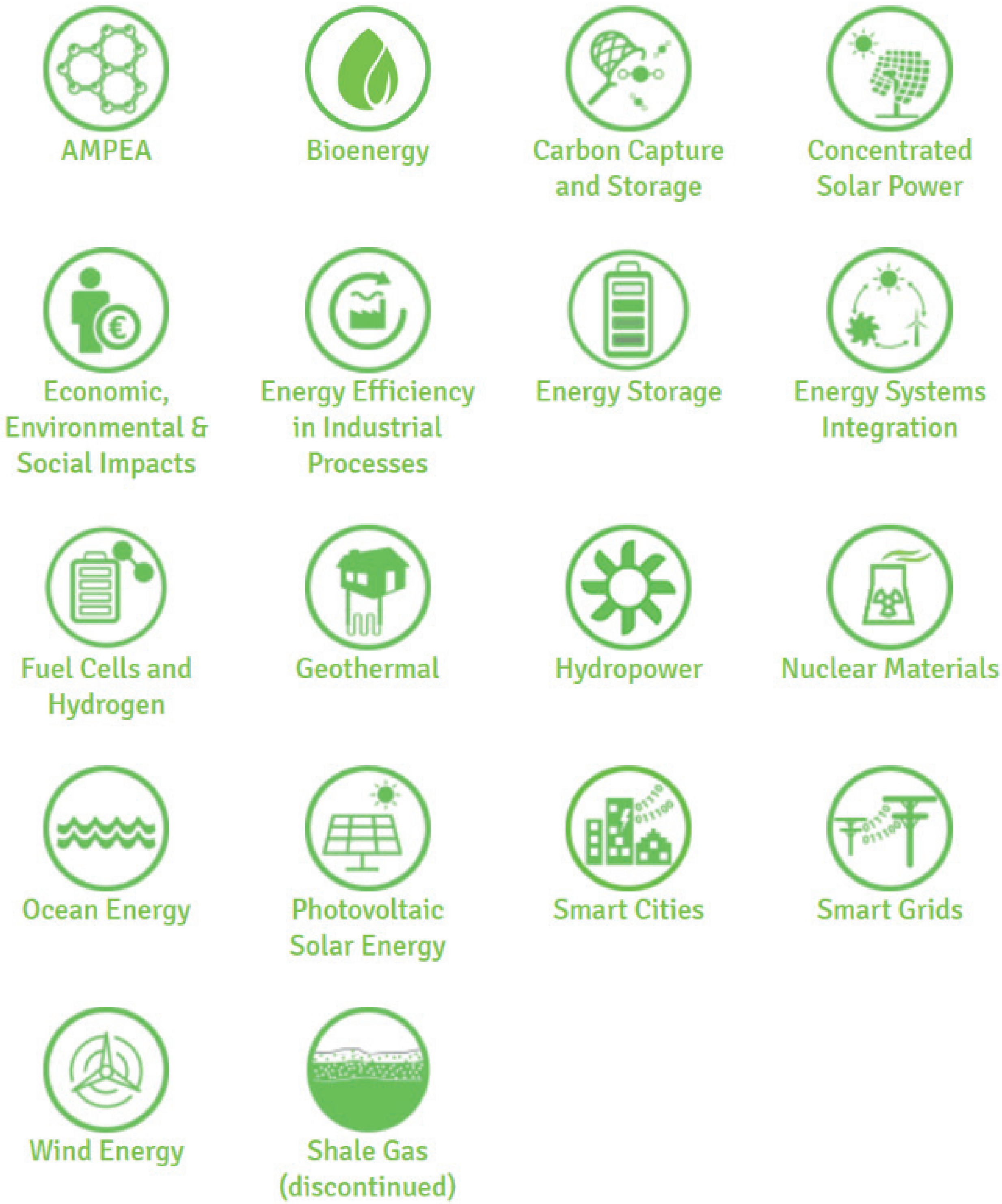

Figure 2: Current EERA JPs

science to social sciences and large-scale systems and integration. The more than 250 public research centres and universities that are membership organizations span 30 countries and more than 50000 experts. EERA aims to accelerate new energy technology development by cooperation on pan-European programmes.

EERA performs research covering all kinds of energies, both energy sources, carriers and systems. One of the most polluting sources of energy are fossil fuels. Fossil fuels are used for heating and cooking (furnaces and stoves), mobility (internal combustion engine vehicles) and for power generation (in coal and gas fired power plants). Power generation means that there is an energy conversion to the end-product electricity. New renewable energy sources are also converting to electricity as the end-product, as does hydropower. For this reason, the interesting energy system for hydropower applications is the electrical system. It will be described (very) briefly in the following section.

The current and future electrical energy system (the Power Sector)

The IPCC special report on global warning on 1.5°C [1] emphasises that it is crucial to keep the global temperature rise below 1.5 degrees to avoid the worst consequences. To reach this target, the power sector needs to become completely emission free. This means that fossil fuel-based technologies like coal and gas-fired thermal power plants must be abandoned. However, an electrical system must always be able to operate in a stable manner, otherwise black-outs will occur, and the reliability of the system is jeopardized. To achieve this, production and consumption of electrical energy must follow each other. However, the production of electrical power is not able to exactly follow the consumption, so temporary deviations are present. This is usually not a problem, because any discrepancy between production and consumption of electrical energy is provided by the stored rotational energy of all synchronous machines in the grid. This gives the production units a time window large enough so that they can match the consumption and obtain a new equilibrium. The size of this time window is proportional to the amount of synchronous rotating inertia in the grid, and systems with large amounts of rotation inertia will be much more stable subjected to imbalances between production and consumption than systems with little rotating inertia. The latter system will require electrical production units that are much faster to maintain the same stability of the electrical grid.

Currently, the large thermal units that must be abandoned due to burning fossil fuels not only provide energy, but also most of the synchronous rotating inertia providing stability to the European grid. These services are highly important for the grid, and when

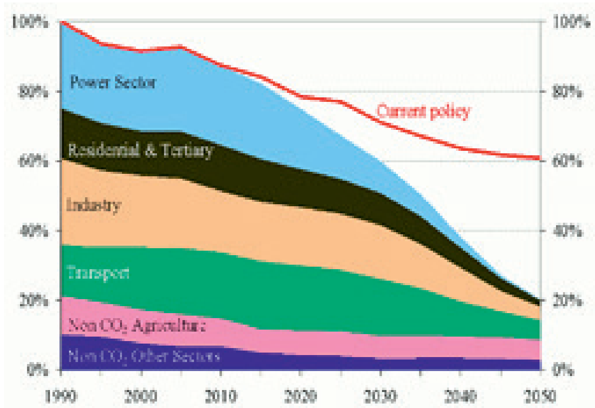

Figure 3 *Emissions trajectories for different sectors for an 80% reduction-by-2050 scenario https://ec.europa.eu/clima/policies/strategies/2050_en*

thermal units are shut down, the electrical system will be at a much more fragile state. Adding to this, the sources replacing the electrical energy from such thermal units are volatile Renewable Energy Sources (vRES), like wind and solar Photo-Voltaic (PV). This means that the imbalances between production and consumption of electrical energy come from both production side and consumption side. Solving the complex challenge of maintaining balance in the future electrical system is key to facilitate the transition needed for reaching the Paris agreement.

A new role for hydropower

Before describing the new role for hydropower, a reminder of the current role is appropriate.

Current capacity and change in the role of hydropower

Hydropower represents an important asset for renewable and emission free energy production. Hydropower has for many decades been producing the major share of renewable electricity in Europe and in EU 28 hydropower accounts for around 360 TWh produced annually[1], approximately 43% of the total renewable electricity production[2]. In all of continental Europe, hydropower provides approx. 200 TWh of storage[3] and more than 200 GW of power[4] in synchronous generators to stabilise the continental European electrical grid. Of this, approximately 155 GW is conventional hydropower and approx. 45 GW Pumped Storage Hydropower (PSH)[5]. Traditionally, run-of-river hydropower was operated as base load generation, together with large thermal units such as nuclear and coal fired plants. Storage hydropower and pumped storage hydropower performed the job of balancing the overall production with the consumption. The addition of production-side volatility though the new VRES penetration will put a lot of additional stress on the flexible generation units, such as hydropower units. Being designed and constructed for a different electrical system than the future one, it is obvious that the hydropower for the future system will look different from the hydropower from the past. Hydropower is considered a mature technology, but that is when considering the technological needs of yesterday's energy system. The role of hydropower will change, and the technology must be re-developed into the hydropower technology for the future. The research areas which we need to focus on in order to achieve this redevelopment of hydropower are described in this SRA document and detailed in the sections for each Sub-Programme of the JP Hydropower.

Evolution, advantages and climate adaption in a future scenario

The fact that hydropower is predictable, flexible and stores large amounts of renewable energy makes it an important part of any future energy scenario. Disruptive technologies imaginable on the generation side of the energy sector are likely to be characterized by baseload operation and balancing total generation to consumption

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1 [3] EU 28 2018 (363 TWh)

2 [3] Total renewable electricity generation is 856 TWh for EU 28 2018

3 EU 28 + Switzerland + Norway, Prof. Emerit. Å. Killingtveit NTNU, 2017,

4 [3], All Europe HP (251 GW) - Nordic countries HP (49,6 GW), including PSH

5 200 GW HP presented previously – ~45 GW of PHS in Europe [4]

must be provided by some other technologies. Hydropower and the projections on how hydropower can develop into an even more flexible technology firmly places hydropower as a strategic component in any future energy scenario. Water management will always be crucial for modern societies, and hydropower is an integral part of water management. European hydropower dams are already serving society with water management capabilities. However, to what degree the infrastructure related to hydropower is sufficient for future weather patterns with heavier rainfalls and more severe droughts is quite uncertain. Hence, re-developing a hydropower system that is flexible will need to consider possible trajectories for changes in weather patterns and the services, such as flood and drought control, which hydropower can provide. An optimization of hydropower units should also be considered in the light of climate adaptation.

Hydropower as a system enabler

All in all, hydropower is identified as a technology with a huge potential of becoming a much more important asset for the electrical system than is currently the case. The flexibility envisioned will be an enabler for the transitions needed to reach the goals of the Paris agreement. This flexibility will be available after overcoming some fundamental challenges related to technical, social, environmental and economic aspects. These challenges will be addressed by the EERA Joint Programme Hydropower.

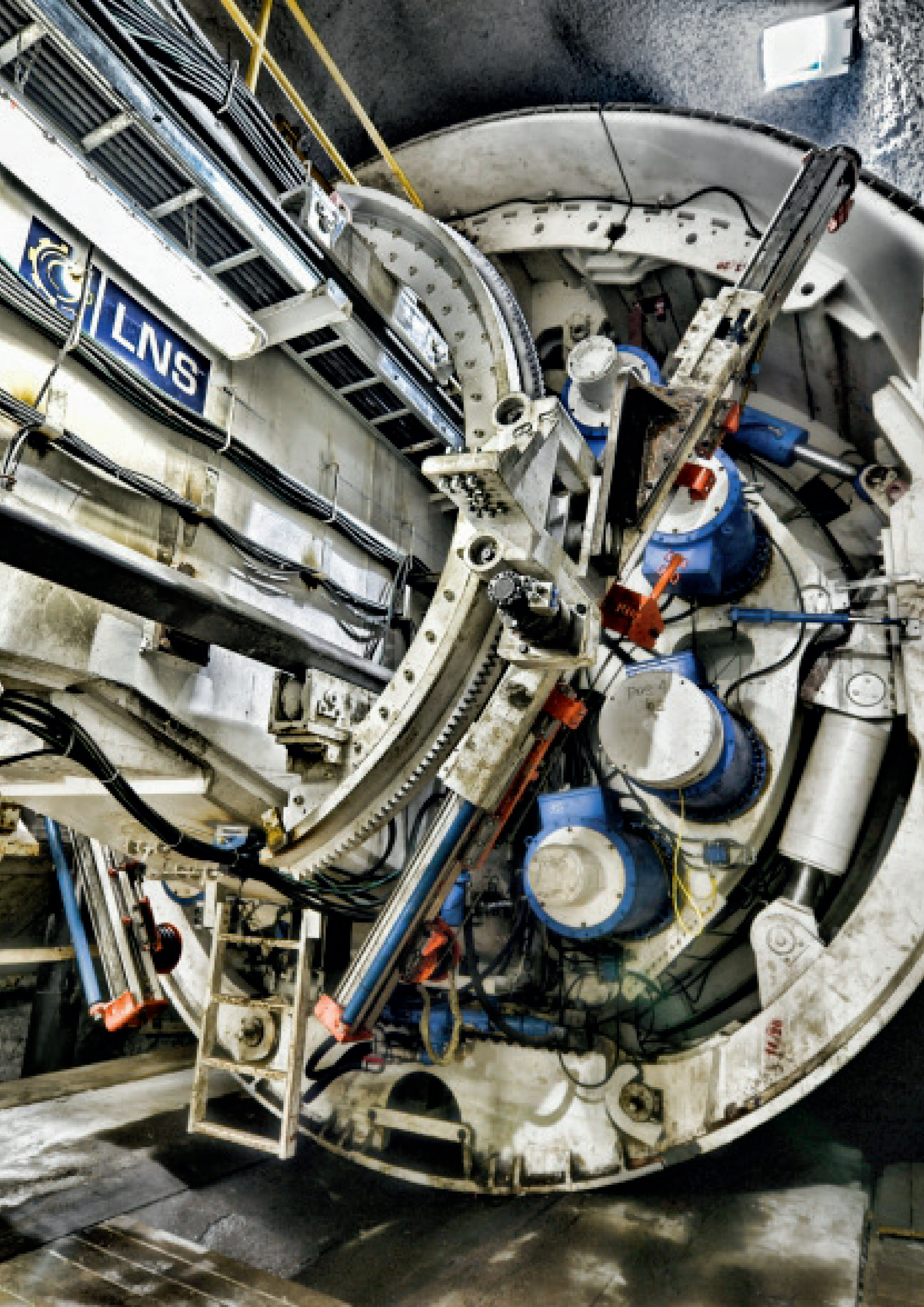
References (Part I)

[1] http://ipcc.ch/report/sr15/

[2] http://ipcc.ch/pdf/session48/pr_181008_P48_spm_en.pdf

[3] https://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_generation_statistics_%E2%80%93_first_results#Production_of_electricity

[4] https://setis.ec.europa.eu/publications/setis-magazine/power-storage/europe-experience-pumped-storage-boom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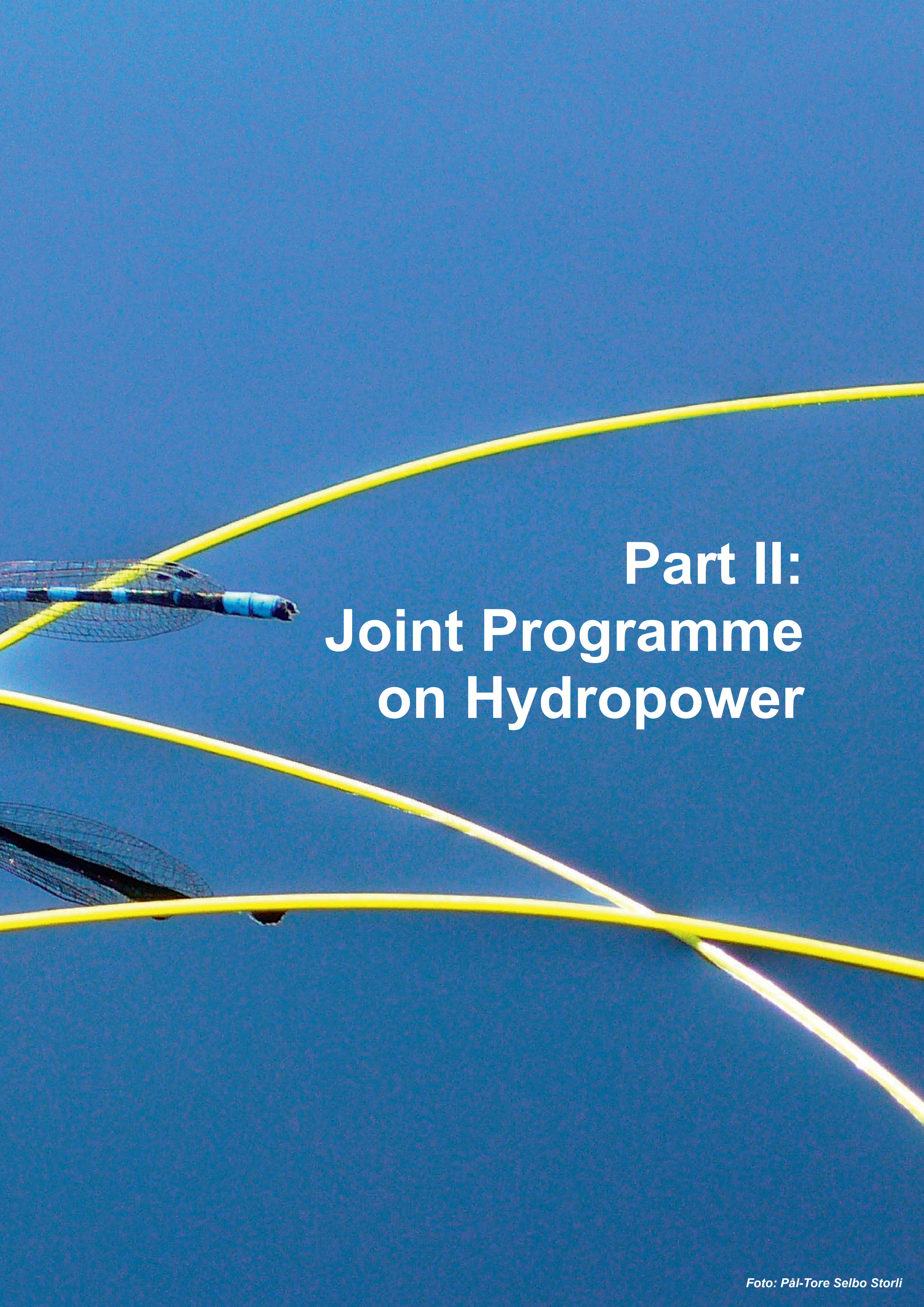


Part II: Joint Programme on Hydropower

Foto: Pål-Tore Selbo Storli

The EERA JP Hydropower

Background:

In 2019, JP Hydropower was launched. Thus, it took 11 years before this very important renewable electrical energy technology was included as a JP in EERA. After the Paris agreement, it became obvious that the role of hydropower had to change in order to contribute as much as possible to the green transition; given all its great properties, hydropower should be developed from the draught horse of the past to the thoroughbred needed for the future. In the initiation phase of JP HP, the members were asked to identify constraints currently limiting hydropower flexibility. The identified constraints were:

C 1. Limited and discontinuous operational range due to highly reduced lifetime of machines and plants because of dynamic flow phenomena, as well as low off-design efficiency

C 2. Thermic cycling in generator insulation reduces generator lifetime

C 3. Hydropower is a capital-intensive investment, suffering from uncertainty in electrical energy markets and increasing competition from other technologies

C 4. Hydropower production afflicts with water management and biodiversity

C 5. Social acceptance and growing concerns about environmental interventions

These constraints formed the basis for discussion on the structure of the Sub-Programmes of the JP, and eventually led to the different SPs being established, presented in the next section.

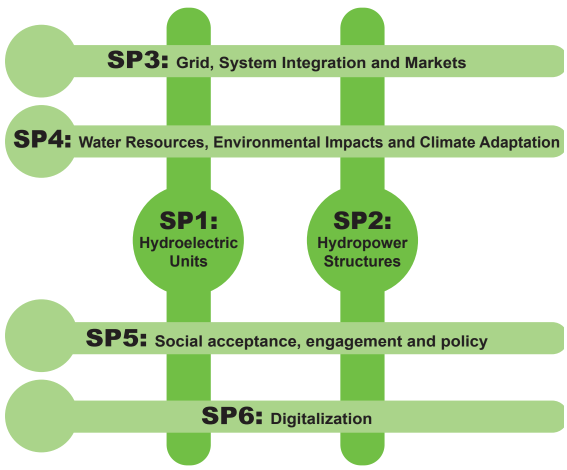
JP Hydropower Mission Statement & Key Objectives

The mission of EERA JP Hydropower is:

"The Joint Programme Hydropower aims to facilitate a new role for hydropower as an enabler for the renewable energy system by aligning and targeting research efforts in Europe"

To address the constraints listed above, the JP Hydropower will employ a broad, systemic, cross-disciplinary approach. Thematically, it spans the entire energy chain from water catchment to system integration, and includes cross-cutting elements such as energy markets and market design as well as environmental impacts, effects of climate change and policy and societal issues. This is reflected in the following structure of Sub-Programmes:

- SP1: Hydroelectric Units
- SP2: Hydropower Structures
- SP3: Grid, System Integration and Markets
- SP4: Water Resources, Environmental Impacts and Climate Adaptation
- SP5: Social acceptance, engagement and policy
- SP6: Digitalization



The JP Hydropower will emphasize cross-disciplinary cooperation between its Sub-Programmes, synergies with other EERA Joint Programmes and existing European and international projects, and actively engage with the industry in order to secure relevance and impact for the hydropower sector and the renewable energy system.

Aligning with EERA and JP Hydropower Mission Statements, the JP Hydropower key objectives are

1. Help streamline regional, national and European research efforts related to hydropower

2. Deliver research results on hydropower on technological, environmental and societal topics from basic research to the demonstration phase (TRLs 2 to 5) and ensure efficient transfer to industry and market

The actions implemented to achieve this are:

A. Ensure that members of EERA JP HP cover all European regions and most relevant countries.

B. Mapping of national efforts, and initiate research corporation among EERA JP HP members where this is possible.

C. Give input to funding agencies on call topics and on the importance of funding research being aligned with the SRA of JP HP for both Research and Innovation Actions (RIA) and Innovation Actions (IA).

D. Establish cooperation arenas with hydropower stakeholders within all elements of the value chain.

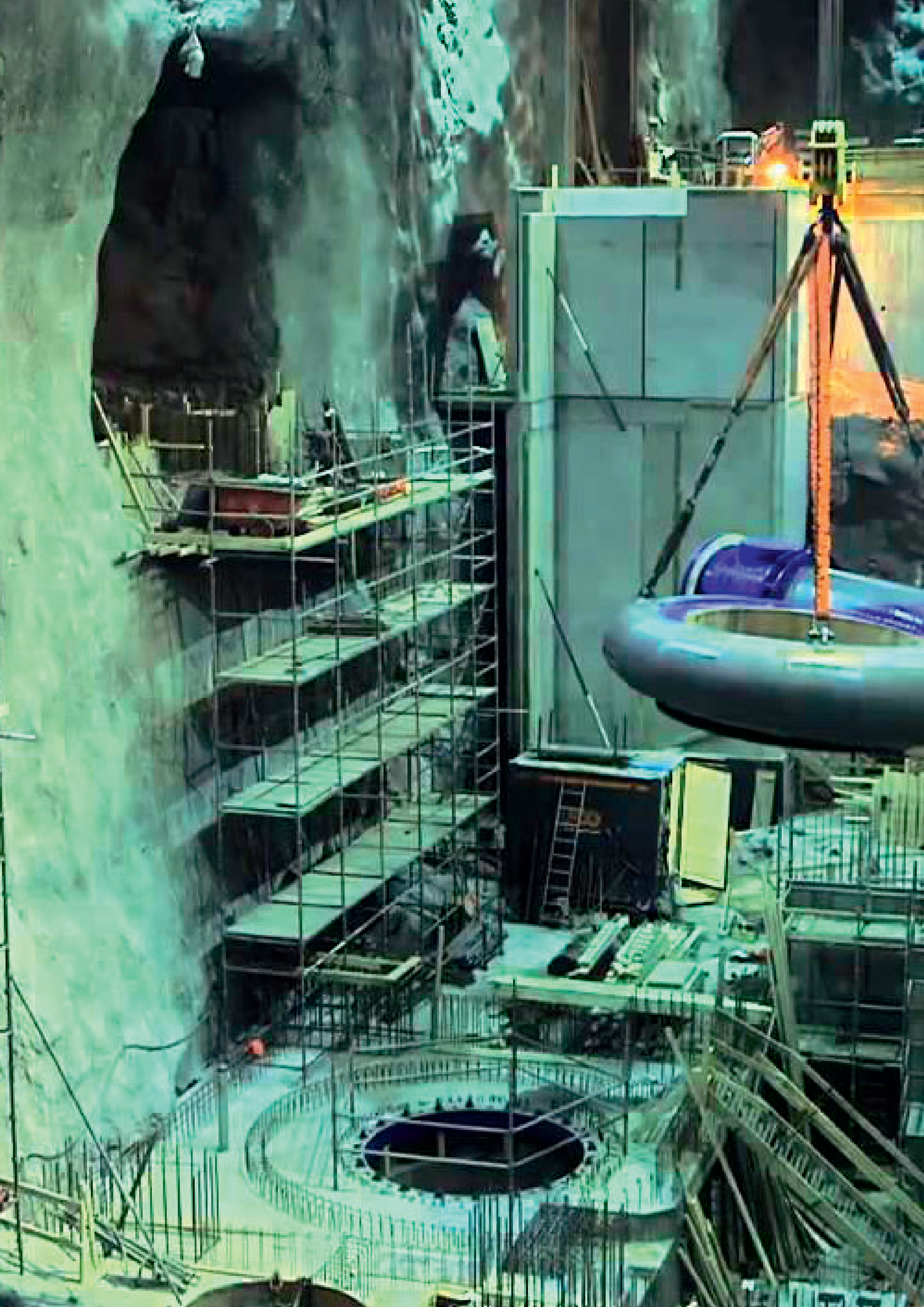
E. Form consortia to submit proposals in order to obtain funding for common projects.

Adding to this, the JP Hydropower will disseminate information on hydropower's current and potential capabilities as an enabling technology for transition of energy systems to policy makers and governments.

Facilitating a new role for hydropower

Hydropower is considered a mature technology. Its services are well established in existing electrical energy markets, and many power plants have returned investments while still capable of producing power without the need for reinvestments for decades to come. When research is performed on how hydropower can provide more flexibility, there is a gap between the Technological Readiness Level (TRL) associated with research (TRL 0-5) and what is needed for the technology to be commercially available (TRL 8-9). Not specific to hydropower research, this is commonly known as "the technological valley of death". Currently, there are few incentives to move technology from research that enables hydropower flexibility to a technology at higher TRL level, and into the investment-profit nexus. EERA JP Hydropower will be a key advocate in stating that new financial markets or mechanisms must be established in order to make the leap into commercially available and enabling technology for the green transition. On the technological aspect the EERA JP HP is confident that the aligning of research efforts by the EERA model will accelerate the development of more advanced hydropower technologies supporting the green transition. The strong societal and environmental focus of the JP HP will ensure an implementation of new technologies and solutions not only adding value for the electrical system, but for society by providing water management capabilities and increased ecological state of watersheds.

The interdisciplinary nature of hydropower makes it important to have a cross sectorial approach when considering the technology and its implementation. However, the disciplines themselves are best placed to evaluate the challenges and research needed to enable hydropower to become a technology capable of the new role in the future power system. For this reason, the JP HP SRA is organized in SP specific contributions, presented in the next part.



Part III: Sub-Programme descriptions

Photo: Pål-Tore Selbo Storli

Introduction

The process started in August 2018 when the initial meetings for establishing the new JP on Hydropower asked the participants to list all existing limitations preventing hydropower becoming a technology capable of even more flexible services to the electrical grid than the current situation. These inputs were used as the starting point for intra-SP discussions when the explicit work on creating the SRA was started. In the SP meetings held in connection with the JP HP kick-off event in Brussels in September 2019, the specific contributions from the SP to the SRA was one of the topics. The SPs were given a deadline for completing their drafts, and after this a merging of the documents was performed by JP HP management. Finally, an Editorial Workshop was held, where the participants were the coordinators and vice-coordinators (or proxies) of the different Sub-Programmes.

The subsequent sections present the individual Sub-Programme SRA contributions following a standardized structure:

- *Introduction*
  Describing the content and scope of the SP relative to the entire system and linking this to the key actions of the SET plan
- *Current status/state of knowledge and knowledge gaps*
  Describing the capabilities and properties of the SP content that is currently good, but can be improved, and what problems and challenges must be overcome for this improvement to be feasible
- *Research priorities/topics to be addressed*
  This is a condensed list of the problems and challenges from the above section that should be given priority when research is initiated, and provide a basis for policy makers and funding agencies to construct project calls aligned with the topics identified by the research community.
- *Objectives of SP*
  Objectives will, for most SPs, consist of alignment of existing research; form strong consortia for applying for funded projects and disseminate research results and knowledge to members in order to speed up local, regional and European research and results. The reason for not presenting more specific objectives is because there is no funding for research within the EERA organization, and the research relies on external funding. However, the SPs are encouraged to make specific objectives if they see that the coordination of research makes it possible to solve a specific problem or fill a knowledge gap.
- *Interaction with other JPs*
  Inter-disciplinary and inter-sectorial interactions are often accelerators in research. How others have solved similar problems or sharing unsolved problems and challenges etc. stimulate creativity and ingenuity is beneficial. Highlighting this is an important preparation for the SPs in order to establish these interactions.

The sections for each SP may be read individually without loss of continuity, but they do not provide any paragraphs containing high-level alignment to European policies and strategies other than the reference to the SP relevant SET-Plan key actions, as this alignment is found in Part I and II. If the reader is primarily interested in one of the SP topics, jumping directly to this section will give complete continuity from EU top level down to specific research priorities based on description of knowledge gaps identified as limitations for enabling more flexibility to the system by the members of each SP.

SP 1: Hydroelectric units

Introduction

At the heart of the hydroelectric generation are the power plant hydroelectric units. Water interacts with stationary and moving mechanical and electrical components, and energy is converted between hydraulic and electricity depending on the energy generation or storage needs of the power system. At the source of this energy conversion, hydroelectric units experience complex multi-physic phenomena related to the hydrodynamics, structural dynamics, material science and electrical fields. These multi-physical phenomena are harnessed to control the hydroelectric units for an efficient supply of safe and reliable electricity to the power system. Indeed, the power plant hydroelectric units need to match the power system characteristics which are nowadays facing the disruption of a high penetration in Europe of the volatile Renewable Energy Sources (vRES). This results in several scientific challenges and technology gaps to make the hydroelectric units more flexible to support the European power system with high penetration of vRES in relation to the EU low carbon energy/climate policy.

The SET-Plan key actions relevant for SP 1 are:

- Develop higher performance renewable technologies integrated in the energy system
  - Hydropower is already high-performance equipment, but research is aiming for improving the performance by addressing problems currently not overcome in a highly reliable, safe and sustainable way.
- Reduce the cost of key renewable technologies
  - By providing more stabilizing services to the grid, additional vRES installations can be made with as little additional grid stability cost as possible. Furthermore, the enhanced flexibility of hydroelectric power plants will add rotating inertia to the electric energy systems and thus mitigating the risk of voltage surge.
  - Increasing lifetime, resilience and reducing outage risk of hydropower units will reduce the cost.
- Increase the resilience and security of the energy system
  - Intrinsic to the points added above, the enhanced flexibility of hydropower plants will increase the resilience and security of the electrical energy system.

Current status/state of knowledge and knowledge gaps

Several topics or research areas are receiving attention due to a gap in knowledge or technical possibilities. Some topics/areas are based on a description of functionality, or sometimes a lack of functionality. Others are more related to specific phenomena that are not fully understood which have been identified as the root cause of problems, or for lack of functionality.

Operating range limitations and lifetime prediction

Ideally the hydroelectric unit may be operated from standstill to full load. For given operating conditions, the unit experiences physical phenomena such as hydrodynamic force excitation of both the waterways and the unit structure, cavitation and rotor-stator interactions which may cause unacceptable material erosion, wear and tear, and fatigue of the hydroelectric machinery components yielding unexpected outage. Therefore, these complex physical phenomena are preventing operation of the units to an extended operating range. Furthermore, those phenomena may give rise to operating instabilities or structural resonance phenomena challenging the unit operation, and even preventing it to be connected to the grid. In the case of power plant modernization, extending the operating range of existing hydroelectric units can be even more challenging by the lack of knowledge of the unit and waterways conditions, and by the high number of constraints.

Furthermore, harsh operating conditions in the extended operating range, usually combined with increased number of start-up and stop cycles, drastically reduce the expected lifetime of the units. Currently, the physics responsible for this reduction are not described in a way that allows this reduction to be quantified for a unit in a reliable way. Furthermore, the insulation of the electrical machines operated with large variations in loads is subjected to thermal cycling, and the amount of degradation is difficult to estimate, as well as predicting faults at an early stage. Consequently, inspections are imposed on a regular basis rather than on a basis of the condition of the unit. This poses a risk of failure, as well as requiring down-time on the unit, both expensive to the plant owner, and also reducing the online services to the grid. Therefore, accurate lifetime prediction is key for the reliability and security operation of the units, allowing more time on-line due to reduced inspection and reduced risk of failure. The empirical methods currently used for estimating the lifetime expectancy are not applicable to the units, but even if the methods are modified, they rely on experimental material property data collected several decades ago. This material property data needs to be updated for the current materials used for all the components of the hydroelectric unit, including both the hydraulic and electrical machines, and the power station electric systems.

Cavitation is a physical phenomenon that one seeks to avoid by appropriate design of units. Sometimes, local flow properties are still initiating cavitation, which in turn might lead to cavitation erosion. The risk of cavitation is increasing when operating far from the design conditions of the unit and will, in many cases, be a limitation on the operational range. Prediction of cavitation erosion will highlight the cost of extended operation range, and be important for increasing this range and reducing the risk associated with this operation.

Sediment erosion

At many locations the technical potential for hydropower coincides with large amounts of sediments in the water. Furthermore, restoring the sediment flow continuity through the hydropower plant is required to minimize the environmental impact. Therefore, the hydraulic machines will experience highly abrasive silt laden flow enduring severe erosion, putting at risk the economic feasibility of the plant, as well as its availability and flexibility due to shut down for inspection and maintenance. In addition, locations that have previously not experienced problems are now starting to experience silt laden flow because of the climate changes and the retracting glaciers. Therefore, turbine design and engineering suited for this highly abrasive silt laden flow are still a challenge to be addressed by research and innovation actions.

Fluid Structure Interactions (FSI)

The hydroelectric units, along with the waterways and the grid, make a complex system subject to coupled interactions and forced excitations, which may give rise to oscillation and resonance phenomena. Oscillations might cause structural fatigue and eventually rupture. Modelling Fluid Structure Interactions (FSI) for predicting the onset, the frequency, and the amplitude of the oscillation, is still challenging, and yet it is crucial to achieve before a unit is constructed. If the analysis has been flawed, units might exhibit unwanted characteristics, or even be deemed useless. Despite the current level of computational power available, industrial use of modelling tools is limited to simplified models due to limitations on computational cost and time. Brand new powerplants using high head Francis units have experienced damage despite receiving the state-of-art attention in the design phase. Until numerically resolved, the topic of FSI will continue to give large uncertainties with respect to structural soundness and integrity of units.

System dynamics, modelling and governing of turbines

The operation of units must be secure, safe and reliable. As already mentioned, the hydroelectric units are part of a complex system and both safe transient operation, as well as operation stability, are required. Water hammer and power surges must be controlled for safe operation. Therefore, accurate numerical simulation of the hydroelectric unit dynamics needs to be achieved, which relies on improved multi-scale modelling methodologies of both the physical phenomena and the system dynamics. These simulations are needed for control systems, ultimately assuring safe and stable operation in real time for a highly flexible and responsive future hydropower system. The challenges are to bring the knowledge gained on the unit dynamic behaviour into such «smart» control system by taking advantage of the availability of digital technologies.

Integrating new technology, inventions

Since the beginning, hydropower technology has constantly evolved, and new inventions are still emerging. Many of these inventions might have applications outside the original one, and presentation of such inventions for other researchers will help reveal this, and technologies might be migrated to other areas where they can be useful. One of the challenges is to integrate new inventions, such as digitalization, variable speed drive and/or generator, battery or compressed air storage hybridization, hydraulic short circuit, into existing hydropower plant, to make the power system more flexible in terms of regulation capability, fast frequency control, fast start/stop, fast generating to pumping modes transition, high ramping rate, inertia emulation, fault ride through capacity, etc.

Mitigating Environmental impact and integrating circular economy for enhanced sustainability

Enhancing the reliability, availability, maintainability, safety and sustainability of the hydroelectric units all along the manufacturing installation and operation process is a scientific challenge and represents a technology gap to be addressed. Specific solutions need to be developed for mitigating the environmental impact and integrating the circular economy of hydroelectric units, such as oil free lubrification, environmentally friendly materials and biotope friendly design and engineering of the units.

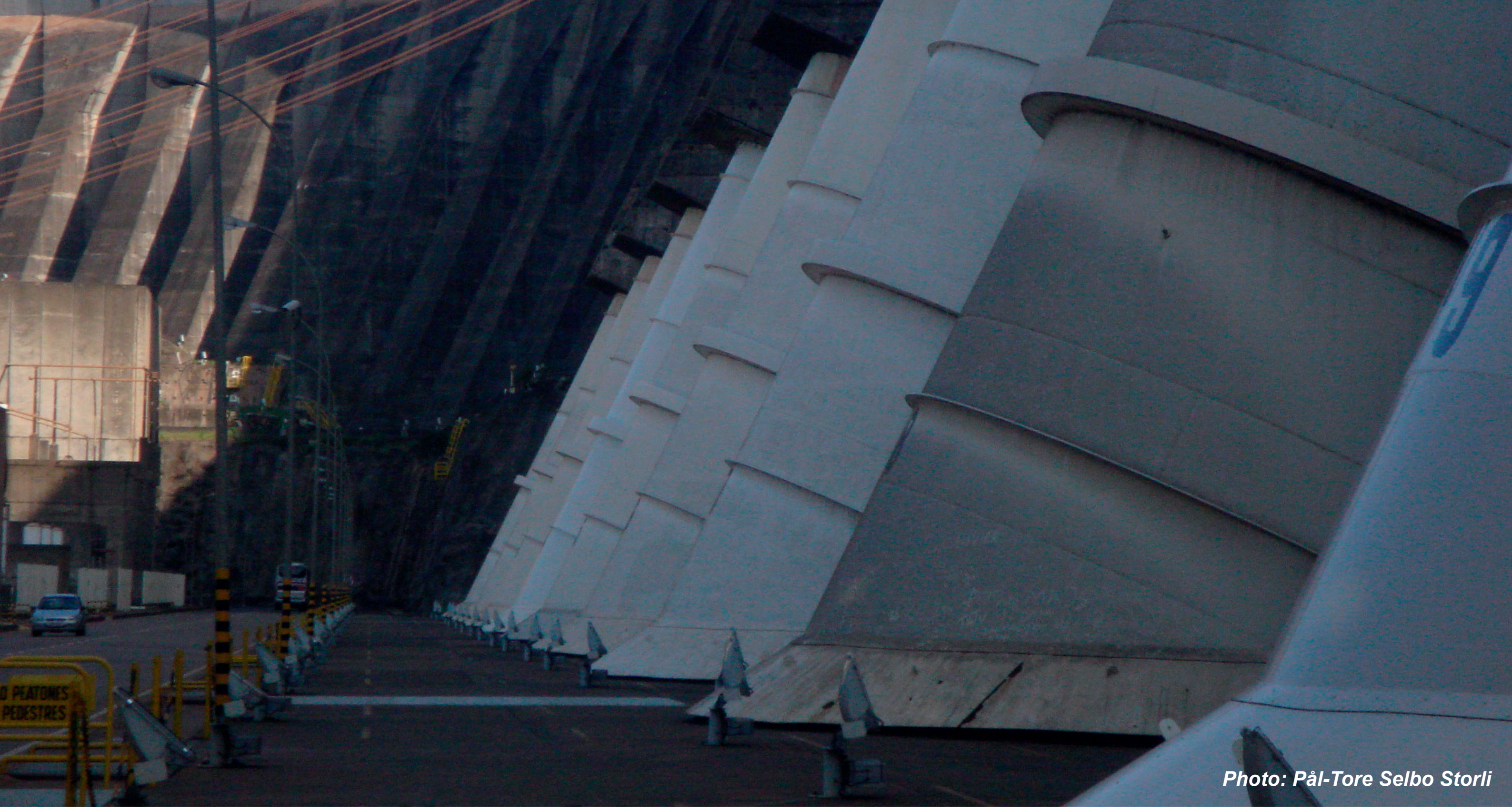


Photo: Pål-Tore Selbo Storli

Research priorities/topics to be addressed

Specific research priorities/topics identified by SP1 are:

Investigate, develop, validate, demonstrate and disseminate:

- Methods for accurate numerical simulation of hydro and structural dynamics of the hydraulic machine (FSI) over the full operating range and during transient operation;
- Digital model of the system dynamics for controlling the hydroelectric units;
- Methods for accurate prediction and mitigation of hydraulic machine component erosion by silt laden flow and/or cavitation;
- New methodology for lifetime assessment, and advanced material law properties of the components of both the hydraulic and the electric machines;
- Advanced design, engineering and manufacturing methodologies for every single component of the hydroelectric units integrating reliability, availability, maintainability, safety and sustainability constraints;
- New technology/inventions giving increased flexibility to the power system, and to enhance hydroelectric unit sustainability by mitigating environmental impact and integrating circular economy.

Objectives of SP1

Aligning with the scope of EERA, the scope of SP1 is to coordinate and align national, regional and European research efforts. By doing so, SP1 is confident that breakthroughs will occur in the fields within the scope of SP1. Specifically, the topics of FSI, new methodology for lifetime assessment and advanced design has a widespread interest amongst the members of SP1.

Interaction with other JPs

JP Energy Storage SP4 Mechanical Storage: This SP include researchers working on Pumped Storage Power plants, a key technology for electrical energy storage, with many similarities and challenges shared with hydropower technologies.

JP Energy Storage SP6 Techno-economics & sustainability: Once more linked to Pumped Storage Power Plants technology.

SP 2: Hydropower Structures

Introduction

Hydropower structures represent all the physical parts of a hydropower plant such as dams, weirs, spillways, intakes, tunnel systems, power waterways, penstocks, power station, and outlets from the waterways. In other words, hydropower structures are essentially composed of hydraulic structures which are submerged, or partially submerged structures built in the aquatic environment. They are designed to store and divert water (e.g. dams, weirs), to deliver water to the powerhouse and turbines (e.g. intakes, canals, penstocks and tunnels), to guarantee the safe conveyance of floods (e.g. spillways, stilling basins), and to mitigate environmental consequences (e.g. fish-passage, supply of environmental flows), amongst others. The diversity of hydropower or hydraulic structures becomes even more widespread when the different classes of hydropower plants are considered such as storage plants, run-of-the-river plants, with and without impoundment, and pumped storage. In fact, hydropower infrastructure often requires specific and tailor-made structural parts, which depend on local boundary conditions.

Hydraulic structures can be regarded as the backbone for the generation of hydroelectricity and their adequate design is important for the reliability, efficiency, safety, and environmental compatibility of hydropower plants. The reliability is determined by both water availability and the functionality of structural parts. Hydropower structures such as dams, weirs, and reservoirs are typical water retaining structures to control the water flow and make water available for both power generation and environmental flows. Pumped storage schemes, on the other hand, are almost independent of hydrological boundary conditions and can be used to increase the reliability of hydropower systems by increasing the flexibility and security of electric energy supply in the power grid.

The reliability of hydropower infrastructure also depends on the functionality of structural parts, which in turn is affected by mechanical (e.g. flexibility of turbine units in short and long-term timescales), geological (e.g. stability of tunnels, penstocks and dam foundations), hydraulic (e.g., hydraulic pressure, and flow transients in pipes, tunnels, and open channels), and climatic boundary conditions (e.g. ice, floods and draughts). The efficiency of hydropower plants depends on the functionality (i.e. reliability) and operation of the different structural parts of hydropower systems. This includes the design and operation principles of the headworks (e.g. water intakes and water diversions, flow regulation), head losses (e.g. friction losses along the water conveying system as well as so called minor or local losses caused by trash racks, valves, pumps, etc.), flexibility (e.g. surge tanks that allow rapid load changes), maintenance optimization (e.g. sandtrap flushings and backflushing of trash racks to avoid unnecessary outage), and the efficiency of the turbine units (see also SP1).

The public safety of hydropower infrastructure is directly linked to essential hydraulic structures. Spillways need to be designed so that the excess water during (extreme) flood events can be conveyed downstream without threatening the stability of dams or weirs. The flood wave associated with the failure of a dam or a weir can cause casualties, damage critical infrastructure and may result in large economic losses. Moreover, the reservoir environment such as valley flanks and shoreline, is critical for dam safety, as mass movements from landslides, debris flows and avalanches can occur in steep mountainous areas, potentially triggering tsunami-like impulse-waves. These may impose a risk for dam safety and the downstream river reaches if they overtop the dam. In fact, flood waves due to overtopping of a dam can cause many fatalities and threaten the infrastructure and environment in downstream areas - a well-known example is the Vajont catastrophe in Italy on October 9, 1963.

The environmental friendliness of hydro-power structures is mainly tackled by SP4 but concerns also hydraulic structures. An example is the longitudinal connectivity across reservoirs and weirs for both biota (plant and animal life of a region) and sediments, for which the optimization of the design and operation principles of hydraulic structures is necessary to obtain satisfactory hydraulic conditions. A further issue concerns the regulation of the water temperature in downstream areas, as the water temperature in regulated reservoirs differs from the water temperature in unregulated streams.

The list of issues that need to be tackled could be further enhanced by, for example, considering different spatial scales (e.g. single power plants vs. cascades), the multifunctionality of reservoirs (e.g. drinking water, irrigation, navigation, recreation, flood protection, etc.) and the digitalization of our society (e.g. remote control of weirs, dam monitoring, sediment management, all based on real-time data). Thus, the problems and phenomena that need to be addressed regarding hydropower structures are manifold, and the scope of SP2 is to find solutions and answers related to different problems and phenomena in structural parts of the hydropower system.

The SET-Plan key actions most relevant for SP 2 are:

- Reduce the cost of key renewable technologies
  - The development of novel innovative methods to estimate the lifetime of hydraulic structures, to upgrade technologically outdated hydropower structures, and to determine head losses in waterways will be helpful for an improved evaluation of the cost-efficiency of hydropower plants.
  - The development of new designs and rules of operation together with uncertainty analyses, will be beneficial for the evaluation of the performance of hydropower structures.
- Increase the resilience and security of the energy system
  - The development of efficient and innovative ways to design new, or to upgrade, as well as to monitor, dams and spillways is an important aspect regarding the security of hydropower schemes.
  - Novel strategies for the management of floating debris and sediments in waterways and reservoirs will increase the resilience of hydropower plants against hydro-abrasion and reservoir sedimentation.

Current status/state of knowledge and knowledge gaps

Reliability

The reliability of hydropower infrastructure depends on the design, operation and maintenance, and thus on the lifetime and the monitoring of the structural integrity, of mechanical and hydraulic structures. The assessment of the reliability over longer time periods requires adequate methods for the analysis and modelling of the performance of hydropower structures, as well as adequate monitoring strategies. Examples are strength tests regarding the residual lifetime of penstocks, the design of open channels and pressurized conduits aimed at increasing strength and lifetime parameters, while guaranteeing small energy losses, and the development of innovative monitoring techniques of the technical condition and performance of hydropower structures. A more specific aspect is the optimization of hydro-abrasive resistant materials for use at hydropower structures to extend their lifetime, and the optimization of de-sanding facilities to reduce turbine wear by hydro-abrasion.

Many hydropower plants, especially the ones at the most preferable locations, have been in operation for a long time. Ageing of their components requires refurbishment and upgrades (e.g. remediation of alkali aggregate reaction), so that current safety and reliability criteria are met. The upgrade of existing hydropower infrastructure to today's technical standards will increase the efficiency of hydropower plants. An economic and sustainable way to upgrade hydropower infrastructure may be the modernization and reuse of already used equipment so that it complies with future needs. Today, hydropower plants are challenged more and more by the need of increased flexibility to guarantee a stable energy grid considering the renewable energy mix (wind and solar energy). This in turn means that many hydropower structures are exposed to rapid load changes, and the development of new designs and rules of operation will aid to increase the efficiency and reliability of hydropower plants.

Safety

Climate change imposes a threat to the safe operation of hydropower infrastructure not only through an altered hydrological scheme, which may result in more extreme hydrological events such as floods and droughts, but also due to the increased risk of mass movements like landslides in the alpine environment. Sufficient spillway capacity is required to encounter future extreme flood events, and many existing spillways will have to be upgraded in the future to guarantee the safe conveyance of excess water. Moreover, spillways also require maintenance on a regular basis to guarantee their reliability. A recent example is the failure of the spillway at the Oroville dam in the US in 2017. Thus, there is the need to develop efficient and innovative ways to design new, as well as to monitor and eventually upgrade existing, spillways to guarantee their conveyance capacity for future extreme events. This includes considerations on how to deal with floating debris in waterways and reservoirs, as wooden logs and debris can block intakes and hence enhance the risk of the malfunctioning of spillways. Moreover, high-velocity flows that occur on spillways and in low-level outlets are typically aerated, and there exist many open questions regarding the characteristics and aeration requirements of two-phase air-water flow at these structures.

Sediments

Hazards related to mass movements into reservoirs require detailed investigations on how they interact with the reservoir water body as well as the hydrodynamics and dimensions of potentially triggered tsunami-like impulse waves. Recent research on this topic has advanced the available knowledge, but there remain many open questions, such as the load on dams and the height of the impulse wave dependent on slide characteristics and reservoir bathymetry. Although modern dams are considered as safe, there is still a residual risk of dam breaks due to various natural (e.g. extreme loads, earthquakes) and anthropogenic (terrorism, maloperation or malfunctioning of spillways) reasons. Thus, there is the need for the development of improved methods for dam break analyses to create hazard maps and hence to enhance the safety of the downstream areas.

The sedimentation of reservoirs is currently a "hot" topic around the globe, as the world-wide reservoir capacity decreases at a yearly rate of approx. 1% due to sediment deposition. Novel reservoir management strategies are therefore required to counter reservoir sedimentation, also in the light of climate change effects. Examples are the construction of sediment bypasses, venting of fines via power waterways or environmentally friendly strategies for the flushing of reservoirs.

Environment

An aspect closely related to the objectives of SP2 is the improved design of fish migration structures to provide connectivity of aquatic systems in hydropower systems. Hydraulic structures are an anthropogenic barrier within aquatic systems affecting the connectivity in both the up- and downstream direction, and novel solutions are required to comply with the current EU water legislation (Water Framework Directive), while optimizing the use of required water to guarantee the findability of the migration facilities and their passage. The quality of habitat in the vicinity of hydropower structures depends also on water temperature, which may be altered by the release of reservoir water (thermal radiation). Such issues may be resolved by designing adequate hydraulic intake structures over the depth of reservoirs to account for the temperature stratification of water bodies. Another issue related to the release of stored water is hydropeaking, i.e. a sudden up- and down-ramping of the flow downstream of a storage hydropower plant outlet. These anthropogenic transients may cause sudden drift of benthic species and stranding of fish, requiring for counter measures such as compensation basins to dampen both the peak discharge and the ramping rates delivered to the receiving streams.

Research priorities/topics to be addressed

Specific research priorities/topics identified by SP2 are:

- Development of novel and innovative methods to estimate the lifetime of hydraulic structures and for the determination of their performance using numerical and physical models.
- Development of improved approaches to determine head losses in waterways.
- Optimization of hydro-abrasive resistant materials and of de-sanding facilities to encounter turbine wear by hydro-abrasion.
- Development of new designs and rules of operation, including real-time monitoring driven operation, for hydropower structures to increase the efficiency and reliability of hydropower plants, also considering cascade hydropower plants.
- Development of efficient and innovative ways to design new, or to upgrade, and to monitor existing spillways; this includes the optimization of physical and numerical modelling techniques for the determination of cost-efficient possibilities to enhance existing spillway capacities.
- Uncertainty analyses to evaluate the performance of the different modelling strategies and to address

uncertainties in the design of hydropower structures.

- Development of strategies for the management of floating debris in waterways and reservoirs.
- Development of a better understanding of the characteristics of two-phase air-water flows and of aeration requirements to counter gate vibration and cavitation risk.
- Improved methods for the analysis of dam break scenarios, particularly for the progressive erosion of embankment and fill dams.
- Quantification of hazards for hydraulic structures arising from mass movements such as landslides and avalanches in steep mountainous areas.
- Development of strategies, methods and operation rules of hydraulic structures and reservoirs to minimize reservoir sedimentation.
- Improvement and development of hydraulic structures used to guarantee the connectivity of aquatic systems.

Objectives of SP2

Considering the aforementioned knowledge gaps and research priorities, the objective of SP2 is to develop and provide novel and innovative solutions for improving the reliability, efficiency, safety, and environmental friendliness of hydropower infrastructure. This will be achieved by using the latest technology regarding hydraulic scale models, numerical methods, and field investigations. Another important objective is the further development of hybrid modelling strategies, i.e. the combined application of hydraulic scale models, numerical models and field investigations to make full use of the advantages of the different modelling strategies in order to minimize the uncertainties associated with the different modelling strategies.

Interaction with other JPs

JP Advanced Materials and Processes for Energy Application (AMPEA): The work in this JP is relevant for the development of hydro-abrasive materials and considerations of lifetime of hydraulic structures.

JP Economic, Environmental and Social Impacts (JP e3s): Hydropower and hydraulic structures have a significant impact on the environment and society, topics which are addressed in this JP.

JP Energy storage, particularly SP4 Mechanical Storage: This is an obvious JP to interact with, as hydropower and pumped hydro are specifically addressed in this JP.

JP Ocean Energy: There is an interaction through the medium water with this JP.

JP Wind: There is a possibility to interact with this JP regarding the load on structures through moving fluids.

Photo: Juliet Landrø

SP 3: Grid, System Integration and Markets

Introduction

In the course of ambitious climate targets, the European power system is subject to substantial structural changes significantly affecting hydropower. In this transformation, hydropower will continue to constitute a backbone of the power system with its unique capability of generating and storing energy in a large scale without emitting greenhouse gas. However, the upcoming shift from dispatchable fossil-fuelled generation to intermittent renewable feed-in poses challenges also for hydropower largely based on mature technology and proven principles, and for another role in the power system. Refurbishing hydraulic units with new technology solutions and operational possibilities maximizing the flexibility, hydropower will be able to cover a large share of the European need for flexibility in a power system shaped by renewables. SP3 shall, thus, support coordination of research activities for the grid and system integration of hydropower incarnating the link to the other SPs of JP Hydro towards the electrical power system of the future.

The scope of SP3, thus, is to enable the alignment of supply and demand for flexibility in the European electrical energy system and market. Consumption and production need to be balanced at all timescales, along with keeping the state of the synchronous electrical grid within acceptable stability and security levels. Therefore, the previously mentioned challenges must be considered, and particularly addressed, in future research projects. Consequently, the analysis of hydropower in the system as a whole, along with the interaction of other technologies, gains in importance. Understanding the interoperability of the different technologies and the role of the different flexibility and storage providers (e.g., batteries, CAES, H2, CCS, and demand elasticity), and how they supplement each other will be important to understand when stakeholders on all levels are making decisions regarding the power system.

Hydraulic power plants have been a renewable energy source for decades. The previously mentioned transformation of the European power system poses challenges for hydropower largely constructed on mature technology and proven principles. Updating hydraulic power plants with new technology solutions could maximize their flexibility and turn them to higher performance renewable technologies. Hydraulic power plants are able to provide flexibility in various ways to balance consumption and production in the electricity system from short-term to long-term. Analysing and evaluating the operation of hydropower in the future European power system will lead to findings that will contribute to increasing the resilience and security of the energy systems.

The SET-Plan key actions most relevant for SP 3 are:

- Develop higher performance renewable technologies integrated in the energy system
  - The identification of the operational requirements hydropower plants will have to meet in future power systems, as well as valuation of their potential profit, will help orient the development of high performance technology solutions for hydropower.
  - Variable speed operation will contribute to enhancing the performance of hydropower in the future power system and

to increasing the integration of variable renewable generation.

- Increase the resilience and security of the energy system
  - The consideration of climate change effects in hydropower planning and operation will increase the resilience and security of the energy system.
  - The coordination between hydropower and other flexibility providers (e.g. batteries) will help increase the power system's security.
  - Adequate use of the extra flexibility provided by innovation e.g. new turbine designs, will improve the security of the energy system.

Current status/state of knowledge and knowledge gaps

The role of hydropower in the future power system

Hydraulic power plants have been a renewable energy source for decades. Their storage capability enables them to provide flexibility in various ways to balance consumption and production in the electricity system. The transition of the European power system from fossil-fuelled generation to an intermittent renewable feed-in poses challenges to the system. Due to the volatility and forecast errors of PV and wind power, the future demand for flexibility and grid stability providers will increase significantly. At the same time, mothballing of thermal power plants leads to a decreasing number of currently used flexibility options. The question arises what the macroeconomic and technical benefit of hydraulic power plants in the future power system will be. Hydraulic power plants are largely constructed based on mature technology and proven principles. They are usually operated with few start-stop cycles and low ramping-rates in order to maximize lifetime. Technology solutions, such as those in the field of turbine design, could increase the value of hydropower through increased flexibility. For this purpose, it is relevant to evaluate the operational requirements hydraulic power plants must meet in the future European power system. And derived from that, what could be the financial benefit of increasing the flexibility of hydraulic power plants?

Energy system modelling and the need for open source data and models

Climate change effects how hydro power plants will operate in the future. The inflow to the mountain reservoirs due to snow melting will be earlier, the glacier runoff will decline as glaciers recede and precipitation and evaporation patterns will change. In order to evaluate the services provided and operation of hydro in the future, climate change effects have to be taken into account. Presently, there is a lack of European wide, open source, inflow data for hydro reservoirs and rivers based on climate simulations.

The European Commission strives for the development of a harmonized European competitive electricity market. In this context, balancing the volatile renewables is conducted via the transmission grid on a European scale. For system analysis, a sufficiently detailed European hydropower model is needed. Simulation of hydro power generation is complex, since many plants are interlinked and the outflow from one plant is influencing the production and operation of the next downstream reservoir or river power plant. Due to the complexity and the huge data requirements European hydro models tend to be much more simplified than national models. Huge synergies can be created by transforming know-how and data existing on national level into a sufficiently detailed open source European hydropower model and inflow data set. This will provide benefits for all European energy system simulation projects.

Coordination and/or competition with other flexibility providers

Evaluating flexibility from a systemic perspective always means considering all available flexibility options. In the past, thermal and hydraulic power plants have provided the flexibility to ensure the equilibrium of generation and demand in the power system. Today, new technologies such as sector-coupling elements (P2X, electric vehicles) or storage (batteries, etc.), capable of providing flexibility as well, are increasingly integrated into the system. Several questions arise: how will these flexibility providers will interact with each other and which market design will allow to make use of these manifold options in an optimal way?

Flexible hydropower operation

New technologies, such as variable speed operation, are increasingly investigated for new installations and are also an option for upgrading existing plants. They can contribute to enlarge the flexibility of hydropower. However, issues concerning the grid connection, and operation of variable speed hydro units is not completely investigated. The integration of such units in the current and future power grid needs to be studied in more detail.

Research priorities/topics to be addressed

Specific research priorities/topics identified by SP3 are:

- Macroeconomic and technical benefit of hydraulic power plants in the future power system.
- Operational requirements of hydro power plants in the future power system.
- Develop open source European wide reservoir and river inflow data set based on up to date climate simulations.
- Develop sufficiently detailed open source European hydro power model and data set for energy system modelling.
- Interaction between different flexibility providers considering new market designs.
- Grid connection and operation of variable speed hydro units.

Objectives of SP3

The main objective of SP3 is to reveal the benefit of hydropower in terms of flexibility, system adequacy and system stability. Furthermore, the derivation of future technical requirements for the design of hydropower units, as well as concepts for modernization of existing plants in order to meet new demands, is to be investigated.

Interaction with other JPs

JP Energy Storage, SP6 Techno economics: The work in this SP could serve as input data for the cost perspective and the economic viability of energy storages.

JP Energy Systems Integration: Synergies could be utilized in the cross-sector modelling of energy systems.

JP Smart Grids: The achieved findings in particular network operation and network planning simulation could be a benefit.

Photo: Bjørn Barlup/Uni Miljø

JP Wind Energy, SP5 Systems integration/ SP8 Planning & Deployment, social, environmental and economic issues: The research in wind power units' system integration and the knowledge about cost parameters could be beneficial.

JP Photovoltaic Solar Energy, SP5 PV Systems/SP6 PV durability and reliability: The work in these SPs could serve as input data regarding the cost perspective and the economic viability of PV systems.

JP Ocean Energy: The grid connection issues concerning tidal power is very much related to those of variable speed hydro.

Photo: Pål-Tore Selbo Storli

SP 4: Water Resources, Environmental Impacts and Climate Adaptation

Introduction

Increasing the production of low carbon energy from hydropower plays an important role in the European effort to reduce greenhouse gas emissions. This production must, however, be balanced with the potential negative impacts on the local environment, local communities and other business sectors. Hence, this subprogram will focus on how hydropower can be produced cost-efficiently without jeopardizing natural resources and hampering crucial ecosystem services for the society, ranging from recreation through fishing, flood protection, irrigation, biodiversity protection to climate change resilience.

Water is an essential part of the environment including its influence on ecology and how water is used for many different purposes by mankind. Hence, sustainable water management is crucial for the society. The EU Water Framework Directive (WFD) provides a framework for sustainable water management legislation. The goal of the WFD is to achieve good ecological and chemical status for all rivers and lakes in the EU. In particular hydrological connectivity within and between rivers, lakes and floodplains should be maintained, to ensure both spatial and temporal distribution of nutrients, energy and matter, which determine biological activity. In this context and regarding quantity and chemical status also vertical connectivity between the river and the ground water body is of importance.

Water resources are essential for any hydropower plant. Accordingly, it is essential to estimate the water resources available in watersheds to estimate the power potential for hydropower infrastructure. With a changing climate, new opportunities for hydropower infrastructure may emerge (e.g. glacial lagoons below retreating glaciers, enhanced snow melt due to warmer temperatures). Nevertheless, climatic change can also be a threat to existing infrastructure, as heavy precipitation event, landslides and also drought might jeopardise hydropower production at existing facilities.

Hydropower is an energy source that can react within minutes to drastically changing energy demands. In particular, large reservoirs and pump-storage systems can be used to balance a dynamic energy market with emerging new energy demands. With the emerging renewable energy sources, such as wind and solar, which depends on environmental factors, and energy intensive electricity demands for mobility, a smart usage of large water reservoirs and pump storage systems may play crucial roles in securing the stability of the supply.

Thus, developing solutions for the management of water resources will be an important task to establish guidelines for the operation of hydropower installation to generate minimal negative impact on the environment, taking also future climate scenarios into account. Loss of habitat and habitat degradation are regarded as major threats to biodiversity worldwide, and the recent report from IPBES (the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services) states that loss of biodiversity is as large a threat to humanity as climate change. Consequently, a major challenge is to develop guidelines for hydropower operations with the objective to minimise negative impact on the biosphere.

Hydropower production is directly impacted by climate change. Glaciers are disappearing, precipitation events become more intense, droughts become longer, and sediment erosion rates are increasing with an intensifying climate. Accordingly, adaptation of hydropower infrastructure should account for projected climatic impacts, and hydropower operational guidelines should anticipate adequate manage of water masses, accounting for flood and drought risks. The operational regime of regulated watershed provides the possibility to produce hydropower, secure landscapes and biodiversity and protect the society from flood and draught. Finding the optimal trade-offs are challenging, but recent research has shown that the technology exists.

SP4 will focus on the assessment of water resources, the mitigation of environmental impacts and the adaptation to future climate change impacts. Additionally, the SP will investigate a reduction of the overall cost and create new technologies and services for consumers.

The SET-Plan key actions most relevant for SP 4 are:

- Develop high performance renewable technologies integrated in the energy system
    - The research performed in SP4 will facilitate hydropower to be a high performance technology in a dynamic energy system by, for instance, development of new technologies, guidelines and tools that can be used to mitigate an increased regulation of the river, facilitate fauna passage and enable a smart usage and storage of the water.
- Reduce the cost of key renewable technologies
    - Costs related to local loss of biota and biodiversity and changes in landscape will be considered and mitigated.
    - A smart water management of hydropower represents a benefit (negative cost) which can be increased, both quantified using monetary numbers but also in a qualitative way.
- Increase the resilience and security of the energy system
    - Effect of changes in water resources due to climate change will be considered by accounting for the loss of glacial ice melt, intensified precipitation events and expected droughts as well as changes in the vertical connectivity between the river and the ground water body.

Current status/state of knowledge and knowledge gaps

Biodiversity

Hydropower operations/regulation can cause severe environmental problems, including decreased habitat quality and quantity, in rivers as well as reservoirs. By altering water flow, water flow patterns and temperature aquatic ecosystems are likely to be heavily influenced and disrupted (biodiversity). Freshwaters provide important aesthetic, cultural, economic and provisioning ecosystem services and these systems are experiencing declines in biodiversity far greater than most other ecosystems worldwide. The most common impacts of hydropower on the environment are disruption of hydrological connectivity, changes in the natural discharge dynamics, changes in suspended solid and nutrients dynamics, flooding of areas for water storage and disruption of the biosphere especially during the construction phase of the plant. The methods for assessing these impacts should be improved and adapted to the new regime of future hydropower operation and climate.

Water resources and climate adaption

An essential part for hydropower production is the available water resources. New and existing power plants require an estimation of water availability and better process-based definitions of environmental flow requirements in order to optimize infrastructure to the available resources.

Furthermore, recent climate change projections reveal massive changes in the natural hydrologic cycle: dry periods are expected to become longer and high precipitation events more intense. Both factors are crucial for hydropower production and might call for an adaptation of infrastructure to meet future conditions.

A better assessment of the advantages of storage infrastructure to use water resources in an efficient way and stabilizing the electricity grid through smart usage of large reservoirs and pump storage operations will lead to solutions on how hydropower can efficiently produce electricity with minimal negative impact on the environment including effects from climate change and alterations in the energy market. Ideally, the operational regime of regulated watershed gives the possibility to simultaneously produce hydropower, secure landscapes and biodiversity and protect the society from flood and draught. Finding the optimal trade-offs are not straight forward and are thus a major challenge for this SP. This will require interdisciplinary research, especially regarding biology, technology and social sciences. Particular topics that need to be addressed are, for example, the longitudinal connectivity of river systems for biota (e.g., fish, macroinvertebrates, beavers) and sediments, hydro-morphological development of regulated rivers, habitat conditions for flora and fauna (up- and downstream of the barrier), reservoir sedimentation, ecological effects of hydropeaking, required dynamics of ecological flows to guarantee some natural dynamics in the river system (e.g. by using a hydrograph over the year instead of a constant discharge) etc. These issues should be considered additionally in light of: i) changing climate conditions (e.g., will the available amount of water change in future due to changing precipitation patterns?); ii) different climatic zones and regarding different spatial scales; iii) alteration of the energy market.

Research priorities/topics to be addressed

- Water resources availability under changing conditions.
- Guidelines to include environmental constraints in hydropower operation and scheduling models.
- Climate adaption of production planning and regulation.
- Optimization of existing hydropower infrastructure to changing climatic conditions due to climate change.
- To develop two-way fish passages for multiple species.
- Transparent dams, weirs and intake structures (combine by-passages for fish and sediments).
- Development of tools for estimating and compensating lost ecosystem services and biodiversity in rivers and reservoirs.
- Mitigation measures in reservoirs and rivers with flexible operational regimes.
- Circulation in land area use (overall impact).

- Investigation of the interplay between climate change and environmental impact in regulated rivers.
- Optimization of storage of water resources (pumps storage technology, large reservoirs, discharge fluctuation mitigation installations, etc) in the frame of a changing energy market.
- Transport of chemicals in the rivers and to the ground water under changing conditions, increased regulation and climate change.

Objectives of SP4

The main objective is to assure environmentally accepted power production under a changing climate, optimize the use of water resources to adopt to a changing electricity market, find the optimal trade-offs between the operational regime of regulated watershed to produce hydropower, secure landscapes and biodiversity and protect the society from flood and draught.

Interaction with other JPs

JP Energy Storage SP4 Mechanical Storage: This sub-programme includes hydropower and the potential for interactions is high.

JP Economic, Environmental and Social Impacts (e3s) SP1 Public perception and engagement: Especially related to hydropower regarding the local environmental impacts.

SP5: Social acceptance, engagement and policy

Introduction

Facing the challenge of climate change, the required energy transition towards "going green" gives hydropower a new, increasingly important role as a system enabler by providing flexibility to the envisaged system. This transition requires new forms of governance and policies that include environmental and socio-economic perspectives and valuation of costs and benefits on different temporal and spatial scales, and it depends on public support and citizen engagement. The need and challenge to balance environmental, economic, and social concerns becomes even more important for hydropower in this new role.

SP5 aims to find solutions and answers related to sustainable policymaking, effective cross-border regulation, social acceptance and stakeholder engagement, with regard to this new role of hydropower in the European renewable energy transition. To maximize the benefits of hydropower in a low carbon energy system, policymakers require a better understanding of possible ways and methods to balance the environmental, economic, and social concerns of hydropower production. It is therefore an objective of this SP to improve the knowledge base for policymakers, project developers, hydropower companies and the public concerning planning, deployment and social acceptance of hydropower infrastructure.

SP5 research on social acceptance, public engagement and policy will distinguish between 1) existing hydropower infrastructure and related concession licenses requiring environmental mitigation measures and 2) new hydropower infrastructure and related requirements for a more or less extensive impact assessment, on one hand. On the other hand, SP5 aims to give a differentiated view on different types of hydropower production facilities (including e.g. reservoirs, run-of-river or pumped-storage), as well as on small, medium and large hydropower plants.

The SET-Plan key actions most relevant for SP 5 and its respective contributions are:

- Reduce the cost of key renewable technologies
    - Costs due to conflicts and potential foregone new hydropower development can be minimized through research on factors of (lacking) acceptance and public engagement.
- Increase the reliance and security of the energy system.
    - Finding innovative ways and valuation methods to balance social, environmental and economic concerns can support decision making in order to secure the role of hydropower for a resilient and secure energy system.
    - Research on factors affecting acceptance of hydropower and uptake by consumers is key for a successful transition towards increased share of hydropower in the renewable mix.
    - Research on the role environmental mitigation measures play in improving the perception of existing and new hydropower can facilitate social acceptance on all societal levels and hence strengthen the role of hydropower in the energy system.

Current status/state of knowledge and knowledge gaps

Transitions toward low-carbon energy system, public acceptance and engagement.

Although industry leaders often identify social acceptance as a major challenge for hydropower development, research on this topic in the fields of Social Science and Humanities (SSH) is strongly underrepresented and surprisingly absent from the recent academic literature. Compared to other energy technologies, there has, in general, only been little SSH research on hydropower. This is possibly due to the long history of hydropower in Europe and its role in the nation building process in Scandinavia and the Alpine regions. There is some research on lack of acceptance and conflicts regarding earlier hydropower infrastructure installation. Since there are relatively few new installations, there are probably fewer recent case studies on public protest. There is no research reported on changes in acceptance for hydropower that will be equipped with new designs and rules of operation for meeting the challenge of providing the required flexibility services in an increasingly renewable energy production mix with a high penetration of vRES.

A meta-analysis of studies on the economic valuation of hydropower externalities identified a significant public aversion towards deteriorations in landscape, vegetation, and wildlife caused by hydropower. However, pure aesthetic considerations seem to play a less important role for hydropower compared to its significant role in the public acceptance of wind turbines and solar power). A few studies have paid attention to balancing environmental goals with renewable energy targets in the context of hydropower. For example, a number of studies quantified the willingness to pay for environmentally friendly hydropower in single countries. Only one study examines in addition the role of procedural justice (in terms of public participation), and distributional justice, related to social acceptance of hydropower projects. More research on the role that trade-offs between clean and renewable energy production, flexibility and environmental conditions play for public acceptance will therefore be highly beneficial.

Several studies emphasize the importance of environmental justice in hydropower development and implementation and establish a link between social acceptance on the one hand, and procedural justice (fair, democratic and inclusive participation in decision-making), and distributional justice (fair distribution of benefits and disadvantages), on the other hand. This is in line with research on other energy technologies. There is an indication that ensuring the participation of relevant groups of the public in decision-making will enable access to local knowledge, enhance the chances for public support, and improve the quality of decisions. However, studies so far have almost exclusively been based on case studies in countries from the Global South. More research is thus needed for the European context. Furthermore, previous research has mostly studied the development of new power plants, while there are only few studies related to changing the operation of existing plants to a more flexible operation. Moreover, more research is needed to focus on how citizens can become more active participants in energy transitions.

Policy and regulation

Although some aspects of policy and regulation related to hydropower have been addressed by previous research, existing studies highlight the need for more systematic research on the position of hydropower at the interface of climate, energy and environmental governance, as well as on its role as a major component in the renewable energy transition. There is also a need for research on a more encompassing valuation of the costs and benefits of social, environmental, economic and cumulative impacts of both large, medium and small hydropower across local, regional, national and transnational scales, as well as its valuation in comparison to the other renewable energy sources. More research would therefor be particularly beneficial from the aspect of social sciences, interdisciplinary research teams and the field of policy studies.

Research priorities/topics to be addressed

Transitions and public acceptance:

The transition towards low-carbon energy system is complex, involves many different actors, and requires substantial public support. As hydropower represents a systems enabler through its provision of flexibility, a better understanding of the required extensive societal changes/ transition processes is key. An important field of research relates, for example, to factors promoting social acceptance of new hydropower development, related to small, medium and large hydropower plants, as well as the uptake of hydropower energy by consumers (e.g. the role of eco-labels). It will also be important to gain further insight into the role environmental improvements of existing hydropower plants (of different kinds and sizes) play in terms of social acceptance and uptake.

Policy and regulation

It is relevant to study the effects of particular policies, policy mixes and regulations and their contribution to hydropower development. Given the EU objectives to achieve good ecological status according to the WFD, scenarios could be developed where the potential of the hydropower sector to take mitigation measures (across Europe) in order to reach a certain percentage of water bodies at a good level (e.g. by 2027 and beyond) is explored. The supportive and limiting factors at EU and national policy level for the different scenarios would be investigated. Policy and regulation can have a strong impact on the operational flexibility of hydropower and therefore effect the system benefits and economy of project development. Finding solutions to combine local environmental protection with the role of hydropower to enable green transition in the energy system is a key aspect of SP5. Furthermore, practices of policymaking, e.g. in constructing publics (perception and categorization of groups of the public, such as lay people, users or stakeholders due to their attitudes, roles, behaviour, practices by policy makers or experts (such as industrial and policy actors and scientists)) and its influence on technology and policy development and implementation, should be addressed.

Planning and public engagement

The comprehensive and demanding transition towards low-carbon energy systems requires substantial public support. Hence, planning and deployment of hydropower developments is another relevant topic to cover. Thus, public engagement of local communities with hydropower developments is important. This includes understanding public knowledge, attitudes, perceptions and responses related to hydropower. Related to this, a specific focus will be turned towards:

- Issues of place, notably how attachment and meaning associated with particular landscapes are implicated in public responses to hydropower.

- Impacts on tourism and recreation.

- Issues of trust and justice (distributional justice, environmental justice) in order to develop good strategies for public engagement.

- The potential and pitfalls associated with community benefits funds, community finance, financial participation models.

Research on this topic includes strategies for public and stakeholder participation, participatory and integrated planning and management (e.g. River Contracts, Round Tables) including using innovative technology such as 3D visualization and scenario co-development with stakeholders. The rationales, methods and practices of developers' engagement with the public generally, and local communities in particular (here, for example, also their constructions of publics works departments), are important to understand in order to develop effective strategies for participation.

Objectives of SP5

- To identify potential members for SP5 and recruit them
- To work strategically towards EC and in particular Horizon Europe to emphasize the importance of including SSH perspectives in calls
- To find funding sources and develop proposals related to the topics listed above
- To find suitable opportunities and fora to discuss issues and initiate research on the interfaces and in collaboration with the other SPs of JP Hydropower
- To describe the state of the art of hydropower SSH research
- To work on science-policy interface tools (also in cooperation with the other SPs).

Interaction with other JPs

We see common interests, synergies and cross-cutting research and collaboration needs with several other EERA Joint Programmes. Many of the JPs have SPs that are focusing on issues related to their specific technologies in the same way SP5 focuses on issues related to hydropower. The knowledge and skills found in these SPs might be transferrable and applicable to hydropower technologies. A description of the specific relevance of all identified SPs within EERA to JP Hydropower SP5 is considered too detailed for the SRA, but a list of the identified SPs sharing focus with JP Hydropower SP5 is presented below.

JP Economic, Environmental and Social Impacts of Energy Policies and Technologies (JP "e3s") SP1 Public perception and engagement.

JP Wind Energy SP8: Planning & Deployment, social, environmental and economic issues.

JP Bioenergy SP5 Sustainability/Techno-Economic Analysis/Public Acceptance.

JP Energy Systems Integration SP4 Consumer; SP5 Finance & regulation.

JP Geothermal SP7 Sustainability, Environment and Regulatory Framework.

JP Ocean Energy Research Theme Environmental and Socio-economic impacts.

JP Smart Grids SP4 Consumer and Prosumer Engagement through Digitalization and ICT.

SP 6: Digitalization

Introduction

The scope of SP6 is to find solutions and answers related to digitalization of business processes in hydropower. The SP may cover the whole value chain including planning, building and renewal, maintenance and asset management, production planning, marked analysis and environmental monitoring. Digitalization provides new opportunities in many sectors, and hydropower is no exception. The overall aim is to reduce costs and increase the income for the entire lifespan of hydropower assets. This is done by optimizing business operation with improved business processes and models. Digitalization goes beyond automatization, digitization (converting analogue to digital data) and using digital tools. Thus, digitalization will change the way how a utility runs the business.

The SET-Plan key actions most relevant for SP 6 are:

- Reduce the cost of key renewable technologies
  - Coordinated scheduling of maintenance and operation will save costs on the long term.
  - Avoid scrapping of useful equipment by predictive maintenance.
  - Balance increased income and increased wear and maintenance cost from new operating patterns.
- Develop higher performance renewable technologies integrated in the energy system
  - Increase the share of system services from small-scale hydropower.
  - Installation of small pumped storage as an enabler for the integration of more renewable energy into the distribution grid level of the energy system.
- Increase the resilience and security of the energy system
  - Increased awareness of the condition of the hydropower plants in the energy system.
  - Facilitate the integration of small-scale hydropower (web-of-cells).
  - Virtual power plants supporting ancillary services.
  - Additional flexibility from hybrid power stations with hydropower and batteries.

Current status/state of knowledge and knowledge gaps

As digitalization in the hydropower sector is still very young, the experience and knowledge are limited. Operators are now actively developing strategies to digitalize their business. Digitalization builds a cross-sectional function between traditional areas such as turbine engineering, and new areas such as data handling and visualization. From this perspective, one of the biggest challenges is how to integrate the expertise of professionals from different disciplines. The focus in SP6 will be on testing of existing methodologies and concepts and methodologies and applying them to relevant hydropower applications rather than on development of new basic/fundamental IT and data analysis methodologies and technologies. Thus, identification of good use cases and conduction of pilot and concept studies both in the lab and the field are of major interest for this SP. The aim is to bring together the domain knowledge of hydropower with the domain knowledge of IT and data science. By connecting cross-domain competence with real-world use cases, SP6 can identify the need for research in both domains and act as a catalyst for development and application of new methodology and technologies.

Predictive Maintenance

One important topic to be addressed is the relation between operation, loads, degradation and lifetime. Operational changes, such as more frequent load changes and faster power regulation, increase the loads on the components and thus may increase degradation and reduce lifetime. Digitalization will help to get better knowledge about these relations, for example, through better access to relevant data, more and smarter sensors, and better methods for data interpretation. Identifying typical fault patterns in both, old and new sensor data with different quality is a big challenge. Accordingly, taking advantage of the new technology such as calculated sensorics with edge computing, can increase the efficiency of the data exploration process.

To realize the potential for value creation from digitalization, the hydropower producers must build processes that can utilize information from parallel business areas. An example is maintenance of power plants, where we can expect that digitalization will change traditional maintenance processes from regular manual inspections, to monitoring and surveillance of components resulting in a shift from time-based and scheduled maintenance to condition-based and predictive maintenance. By integrating this optimized maintenance with optimization for production planning there is an even larger potential for value creation.

Flexibility

In today's market, the flexible power offered by hydropower is restricted by conservative limitations set to the operating range of the generating units. This is in place to safeguard long service life of these units. By allowing more versatile exploitation of the generating units, more flexible power can be offered. The versatility comes at a cost that needs to be known if this strategy is to be employed. A key question here is if digital twins of generator units can lead to a breakthrough in calculations of the reduced remaining life of new operating patterns?

One of the goals of the Energy Union is free flow of energy without technical or regulatory barriers between countries. At the same time, hydropower has the potential to become an enabler for integration volatile renewable resources into the power system on a local level. Will new digital market platforms open up for more flexibility from hydropower on both local level and across countries? Which new business models will develop on such platforms?

Security

Industrial IT systems have witnessed an increasing number of cyber-attacks in the past two decades. The technical reasons for this are twofold: First, there is a trend in industrial control systems (ICS) to replace proprietary protocols, operating systems and hardware by standardized and off-the-shelf products. As a consequence, many vulnerabilities of general-purpose ICT systems now also appear in ICS. Second, more and more ICS are connected to the company network or even the Internet in order to simplify their management (e.g. by providing remote access to engineers) or to allow business departments to access production data and influence production in real time. Not surprisingly, there are also attacks against critical infrastructures, such as electricity generation and distribution systems. In fact, they are of special interest for attackers because a successful attack can cause widespread disruptions. For example, the cyber-attack against the Ukraine power grid in 2015 left about 230,000 people without electricity for up to 6 hours.

Concerns over cyber-attacks against hydropower plants have increased in recent years. IT systems in hydropower plants are less regulated than, for example, their counterparts in nuclear power plants. An intruder could do significant damage by manipulating the plant's dam gates. There has been a study of a hypothetical scenario where an attacker opens all gates of a hydroelectric dam and causes rapid and massive flooding downriver as week as damage to the turbines and power station.

It can be expected that many best practices in industrial IT system security can be also applied to hydropower. Those practices include the separation of industrial control systems from other networks and the usage of data diodes where connections between networks cannot be avoided. They also include the application of the principle of defence in depth, for example by deploying multiple intrusion detection and prevention systems that operate on different levels (network level, application level). However, hydropower also has unique properties that could lead to new types of attacks and that must be addressed by researcher. For example, if several plants are located at the same river, an attack against a plant could trigger a chain reaction on plants downriver.

Digital transformation

Digitalization shows also opportunities in field of social aspects. Digital workforce management and especially Know-How management in terms of maintenance and operation are a crucial topic today. Knowledge based databases and virtual realities could act as a pathfinder in this direction. In collaboration with SP5, research could contribute with research on topics such as organizational culture, institutional learning, and industry acceptance. To realize the potential for value creation form digitalisation, industry must have willingness to accept and trust new technology such as machine learning and big data analysis tools, that may replace former manual processes. Is it equally interesting investigate how to limit the complexity level for users, while the complexity inside the expert tools is growing?

Research priorities/topics to be addressed

Digitalization in hydropower is not an established and traditional research topic. The topic merges two quite different fields. Thus, the research priorities and topics to be addressed must be identified in the first stage of SP6. The priorities and topics depend also on the SP members' interests and competences. Since the hydropower business is in the beginning of the digital transformation, establishing an overview of national initiatives and status for different SP partners within the field of digitalization is a relevant initial activity.

Specific research priorities/topics identified by SP6 are:

Machine-level technological aspects

- Installation and management of monitoring systems.
- Quality assurance and harmonization of data.
- Digital twin of turbine and generator.

System-level technological aspects

- Virtual power plants supporting ancillary services.
- Security and prevention of cyber-attacks.
- Benchmarking of methods for big data.
- Interface towards other digitalization initiatives.

Economic aspects

- Cost-effective operation and maintenance.
- New business models from digital platforms.

Environmental aspects

- Improving inflow models from new available data.
- Digital twin of river from scanning of riverbeds.
- Model verification based on satellite monitoring of flow.
- Image processing for identifying fish behaviour and effect of fish ladders.

Social aspects

- Acceptance of existing and new technology.
- Mitigation of increased complexity from cross-discipline collaboration.
- Know-How Management in terms of maintenance and operation.

Objectives of SP6

The objective of SP6 are:

- To identify and describe the state of the art within the fields of SP6.
- To identify relevant use cases for digitalization in hydropower.
- To provide an overview of national and international research initiatives within digitalization in hydropower.
- To contribute to better understanding of the relations between operation, loads, degradation and lifetime.
- To identify future challenges, such as, security with more data-based decision making.
- Act as a hub for digitalization initiatives and projects between scientists and industry.

Interaction with other JPs

Collaboration with other SPs in JP Hydropower and other JPs in EERA must be identified and defined. There are many common interests and synergies between hydropower, other types of power production, and other industries and sectors. Thus, exchange of experience and knowledge with other sectors, as well as collaboration with other sectors, is of major interest for the work in this SP. The most relevant already established EERA JPs for collaboration and exchange of experience are:

JP Energy Storage: The results of this SP could serve as input for an optimization on a system level. Other SP's are interesting on a technological level to combine them with hydropower and optimize the "hybrid approach".

JP Wind Energy, SP 3 Wind conditions and climatic effects; SP 5 System integration; SP 8 Planning and deployment, social, environmental and economic issues: Environmental aspects, economic issues and system integration of the wind sources are definitely a connection point to this SP.

JP Photovoltaic Solar Energy, SP 5 PV systems: PV Systems play a vital role in the electrical grid and are therefore a good connecting point for a system approach.

JP Geothermal. SP 6 Operation of Geothermal Systems; SP 8 Computing and Data Management: Operation, Computing and Data Management are key roles in terms of digitalization. In a future world, where more and more utilities are connected, these SP's are prioritized for collaboration.

JP Smart Cities: Distributing energy in cities will need digitalization and hydropower could act as energy supplier. Therefore, any experience exchange will lead to a better understanding of needs and requirements.

JP Smart Grids: Flexible distribution of energy and electricity in Smart Grids plays a vital role in the future. JP Hydropower, SP 6 could collaborate very closely in terms of a system approach.

JP Energy Systems: Hydropower plays a role in electricity production and is therefore part of the energy system mix. The best way to cooperate is on a system level with digitalization as the linkage.