European
Commission

LOW CARBON ENERGY OBSERVATORY

HYDROPOWER
Technology development report

Joint
Research
Centre

EUR 29912 EN

Contact Information
Name: Ioannis KOUGIAS
Address: European Commission, Joint Research Centre, Ispra, Italy
E-mail: Ioannis.KOUGIAS@ec.europa.eu
Tel.: +39 0332 785681

Name: Thomas SCHLEKER
Address: European Commission, Directorate General for Research and Innovation, Brussels, Belgium
E-mail: Thomas.SCHLEKER@ec.europa.eu
Tel.: +32 229 88652

EU Science Hub
https://ec.europa.eu/jrc

JRC 118316

EUR 29912 EN

PDF	ISBN 978-92-76-12437-5	ISSN 2600-0466 / 1831-9424 (online collection)	doi:10.2760/49932
Print	ISBN 978-92-76-12436-8	ISSN 2600-0458 / 1018-5593 (print collection)	doi:10.2760/957325

Luxembourg: Publications Office of the European Union, 2019

How to cite this report: Kougias I., Hydropower Technology Development Report 2018, EUR 29912 EN, European Commission, Luxemburg, 2019, ISBN 978-92-76-12437-5, doi:10.2760/49932, JRC 118316.

Contents

Acknowledgements

Nigel Taylor (JRC, C2) provided guidance, suggestions, science- and technology-related comments supporting the present analysis. He also reviewed the final version of the report. Katalin Bódis (JRC, C2) and Johan Carlsson (JRC, C7) reviewed draft versions of the manuscript, provided their insight and ideas helping to improve its overall quality.

Thomas Schleker (DG RTD, D1) provided insight and expertise that greatly assisted the analysis. He also reviewed the final version of the manuscript and provided detailed recommendations.

Foreword on the Low Carbon Energy Observatory

The LCEO is an internal European Commission Administrative Arrangement being executed by the Joint Research Centre for Directorate General Research and Innovation. It aims to provide top-class data, analysis and intelligence on developments in low carbon energy supply technologies. Its reports give a neutral assessment on the state of the art, identification of development trends and market barriers, as well as best practices regarding use private and public funds and policy measures. The LCEO started in April 2015 and runs to 2020.

Which technologies are covered?

- Wind Energy
- Photovoltaics
- Solar thermal electricity
- Solar thermal heating and cooling
- Ocean energy
- Geothermal energy
- Hydropower
- Heat and power from biomass
- Carbon Capture, utilisation and storage
- Sustainable advanced biofuels
- Battery storage
- Advanced alternative fuels

How is the analysis done?

JRC experts use a broad range of sources to ensure a robust analysis. This includes data and results from EU-funded projects, from selected international, national and regional projects and from patents filings. External experts may also be contacted on specific topics. The project also uses the JRC-EU-TIMES energy system model to explore the impact of technology and market developments on future scenarios up to 2050.

What are the main outputs?

The project produces the following generic reports:

- Technology Development Reports for each technology sector
- Technology Market Reports for each technology sector
- Future and Emerging Technology Reports (as well as the FET Database).

How to access the reports?

Commission staff can access all the internal LCEO reports on the Connected LCEO page. Public reports are available from the Publications Office, the EU Science Hub and the SETIS website.

Executive summary

The present report collects the technological developments of hydropower. It is a deliverable of the Low Carbon Energy Observatory (LCEO) project, a European Commission (EC) project that assesses the technological progress of clean energy sources. It is a follow-up the previous (internal – EC only) LCEO assessment (Kougias, 2016a) and presents important research activities that have taken place in EU and abroad related to hydropower. Since the operation of hydroelectric facilities involves different sectors and scientific fields, efforts of the present report focused on monitoring research and development (R&D) activities that cover the involved sectors. Thus, apart from the purely technological projects, the report covers studies that aim to enable better simulations of hydrological cycle, climate change and its relation to hydropower operation as well as the water-energy-food (WEF) nexus interactions.

In addition to projects funded under the Horizon 2020 (H2020), the present exercise screened Knowledge and Innovation Community (KIC)-Innoenergy, InnovFin and the European Fund for Strategic Investments (EFSI) schemes for relevant projects. Moreover, national research councils of countries with a strong tradition in hydropower were analysed and R&D projects supported by national research organisations were identified. This included the U.S. Department of Energy (DoE), the hydropower research organizations of Norway and China and the national research councils of Switzerland and Japan.

The identified activities fall into four main categories. Projects on hydraulic design and hydropower mechanical equipment aim at advancing the construction and operational characteristics of hydro stations. This includes advanced materials and computational models to minimise machinery wear. Efforts for increased range of operation and flexibility of hydropower have been consistent for some time now and were identified in both the present and the previous report (Kougias, 2016a). The exploitation of the generally untapped low-head hydropower potential is coupled by advancing the technical characteristics of hydrokinetic turbines. The environmental and ecological characteristics of hydropower plants have been the objective of projects with a special focus on fish population, fish-friendly turbines and the important challenge of securing the required environmental flows that allow ecological conservation. The topics of the remaining large-scale projects are the integrated water resources management, the WEF nexus, hydro-powered solutions for irrigation and advanced climate simulations. Most of these projects have additional aims to hydropower technological advancement; however, their implementation promotes a more efficient and sustainable operation of hydroelectric stations.

1 Introduction

Hydropower technology has provided clean energy for more than a century and is, thus, regarded as the most mature low carbon energy technology. Accordingly, technological progress and R&D have focused on improving the operation of existing and future hydro facilities rather than transforming the hydropower technology per se. This is the main difference between hydropower and some of the renewable energy sources (RES) when referring to technological advances: While there is still room for significant developments in some RES (e.g. the commercialization of Perovskite solar cells), hydropower technology mainly offers room for marginal improvements. The technological maturity of hydropower has been achieved through its commercial application since the late 19^{th} century. Presently, approximately 160 countries use hydropower for energy production and more than 1270 GW of hydro capacity is installed, globally (Whiteman et al., 2018). Accordingly, hydro facilities have been operational for a long time. The majority of systems and components have reached the highest level of technological maturity (technology readiness level (TRL) equal to 9) and hydro systems are ready for deployment at the market-induced rate.

An additional particularity of hydropower is that, apart from energy production, it also provides other services. Hydro reservoirs are used for irrigation, drinking water provision, flood risk mitigation and recreation, among other uses. This creates interactions and allows synergies among different scientific disciplines i.e. the natural sciences and the applied sciences. It also creates challenges and trade-offs that require a wider spectrum of research.

The third particularity of hydropower technology is its large variability in scale. Hydropower stations range from the "pico" scale stations with a nominal power capacity of few kilowatt (kW) to projects of huge scale and several gigawatt (GW) power capacity. Although the principles among the very different in scale stations are similar or even identical, the technological and market maturity is not the same. Some technologies like small-scale hydropower (SHP), run-of-the-river (RoR) and low-head hydropower are not as commercially advanced as large hydro (CanmetENERGY, 2007) and this is also indicated by the efforts of corporate R&D.

Hydropower technology is also particular for an additional reason: each hydropower station is unique in terms of design. Reservoir hydropower stations involve dam construction, with each dam being unique in design. This necessity for tailored-made, ad hoc solutions is common in several hydropower components. Thus, R&D in the hydropower technology solution is often different from efforts in other renewable energy technologies, because it does not aim at developing final solutions with universal application. Contrary to that, RES such as solar or wind can be deployed in different –suitable– settings with relatively little adaptation. Efforts to design and create modular hydropower stations are still at a relatively early stage of commercialization and refer to stations of the small ($<$10 MW) and –mainly– the mini scale ($<$1 MW).

EU and associated European countries host world-leading hydropower R&D activities. New practices and technological advancements would facilitate the utilisation of EU's untapped sustainable hydroelectricity potential. The latter is estimated to be up to 80% higher than the current output, if new greenfield installations, refurbishment of existing stations and utilisation of unconventional sites are fully developed (SET-Plan, 2014). Moreover, non-EU countries of the Western Balkan region host the largest unexploited hydropower technical potential of Europe that is estimated at 80,000 GWh/year. Bosnia and Herzegovina, Montenegro and Albania have significant potential which could support the countries' transition towards low-carbon power systems, if developed in accordance with environmental standards.

EC's latest Strategic Energy Technology Plan (SET-Plan) has highlighted the need to develop the next generation of flexible hydro-plants aiming at increasing the resilience and security of power systems (SET-Plan, 2018). Recognising the central balancing role of hydropower capacities the SET-Plan prioritises the design and development of technologies to rehabilitate and upgrade hydro-stations, enabling advanced functionalities. Equally important it underlines the need for smarter compatibility with environmental restrictions with the timeline being 2018–2023.

The present technology development report analyses recent technological advances of hydropower, in the described frame that characterises hydropower technology. Its main focus is EU-funded projects that have been either recently completed or are at an ongoing phase. This includes analysis of approved projects, but it also aims to identify the general R&D tendencies and needs of the hydropower technology. Its scope is complemented by another LCEO output, the journal publication on emerging technological tendencies in hydropower (Kougias et al., 2019).

2 Technology state of the art and development trends

It is important to note that the present report distinguishes research in scientific hubs over corporate R&D activities because the latter are closely related to market developments-growth rather than technological advancement. In the European context, the majority (≃75%) of the technical hydropower potential has already been utilised (Edenhofer et al., 2012). Moreover, the Water Framework Directive 2000/60/EC (WFD) has set specific and strict rules in new dam construction. Thus, opportunities for the construction of new large-scale hydropower stations in the European rivers are limited. Accordingly, the technology development efforts are directed at upgrading existing stations, increasing their efficiency and prolonging their lifetime through refurbishments. Naturally, this is also related to cost-reduction approaches and optimal operation to increase the output. It also aims at extending the flexibility of operation of hydro machinery. Flexibility involves operation in a wide range of conditions and adaptation in a dynamic electricity market environment, where variable electricity production (mainly from RES) gets an increasing share.

An additional area of development is the design of a hydropower technology that is tailored designed for complex and dynamic environmental conditions. Large-scale hydropower deployment has encountered social and scientific opposition due to its ecological impact on the environment, water availability and population relocation. The present report also analyses the latest research progresses in assessing and addressing the ecological and social impact of hydropower as well as the pathways to mitigate, reduce the negative consequences and increase its positive contribution. The environmental science field is also related to hydropower due to climate variabilities. Hydro infrastructure needs to become more adaptive to climate change. It is thus required to further improve simulation and modelling approaches to estimate future water inflows and whether they allow hydropower to operate in a safe, continuous and economically viable manner. Hydro infrastructure is closely related to climate change and particularly flood/drought mitigation strategies. Enhancing its operation and safety capabilities (e.g. through digitalisation) is clearly a priority.

The present analysis performed a thorough screening of EU-funded projects.Eleven large-scale projects were identified and are listed in the next lines. Their budget ranges between EUR 1.5 million and EUR 8 million while a number of additional projects with a relatively smaller budget were also identified and presented in a separate section (§4).

CaFE: Development and experimental validation of computational models for cavitating flows, surface erosion damage and material loss;

HydroFlex: Increasing the value of Hydropower through increased Flexibility;

ECO-DRILLING: Environmentally efficient full profile drilling solution;

Hydrolowhead: Profitable low head hydropower;

DP Renewables: A range of economically viable, innovative & proven hydrokinetic turbines that will enable to exploit the huge potential of clean, predictable energy in the world's rivers, canals and estuaries;

FIThydro: Fishfriendly Innovative Technologies for Hydropower;

EUROFLOW:	A EUROpean training and research network for environmental FLOW management in river basins;
BINGO:	Bringing INnovation to onGOing water management – A better future under climate change;
DAFNE:	Use of a Decision-Analytic Framework to explore the water energy food NExus in complex and trans-boundary water resources systems of fast growing developing countries;
HyPump:	Enabling Sustainable Irrigation through Hydro-Powered Pumps for Canals;
IMPREX:	IMproving PRedictions and management of hydrological EXtremes.

Table 1 provides some basic information on the analysed projects. This includes the number of participating institutions per project, the EU programme that has funded the project, the overall project budget and the percentage of the budget covered by EU funds. It is important to note that several of the analysed projects were still ongoing when this report was written.

Table 1: Basic information of the analysed projects

Project acronym	# of partners	H2020 call	Budget	EU share
CaFE	8	MSC Innov. Train. Net.	EUR 3 939 999	100%
Hydroflex	16	Comp. low-carbon energy	EUR 5 716 989	95%
ECO-DRILLING	1	SME instrument #2	EUR 2 811 875	70%
Hydrolowhead	2	SME instrument #2	EUR 1 512 893	70%
DP Renewables	1	SME instrument #2	EUR 2 877 033	67%
FIThydro	26	Comp. low-carbon energy	EUR 7 171 550	82%
EUROFLOW	10	MSC Innov. Train. Net.	EUR 3 923 989	100%
BINGO	20	Water Innovation	EUR 7 822 423	100%
DAFNE	14	Water Innovation	EUR 5 420 223	63%
HyPump	1	SME instrument #2	EUR 2 545 390	70%
IMPREX	23	Water Innovation	EUR 7 996 848	100%

A deeper analysis of the participants shows that their total number is 112 (see listing in Annex), which is smaller than the number identified in the 2016 exercise. Indeed, the previous technology development report (Kougias, 2016a) identified 164 universities, research organizations, R&D departments of multinational companies, local authorities and small-medium enterprises (SMEs) as participants in hydropower-related projects. The vast majority of institutions and companies participate in a single project. The exception is few hubs of hydropower R&D that participate in more than one projects. These are the Norwegian University of Science and Technology (NTNU) that participates in three projects, the Chalmers University of Technology (Sweden - 2 participations), ETH Zürich (Switzerland - 2), the Politecnico di Milano (Italy - 2), the Technical University of Munich (Germany - 2) and the Forschungsverbund Berlin (Germany - 2). As far as corporate R&D is concerned only two Norway-based companies participate in more than one project. This includes Statkraft (2) the hydropower company owned by the Norwegian state and Sintef Energy an energy research company.

The reduction in the number of participating institutions (by $\simeq$32%) is also shown in the lower overall budget directed to hydropower research. Indeed, the previous screening showed that the total budget of hydro-related projects was EUR 54.6 million, while the one covered by the latest H2020 projects is EUR 41.4 million[1]. This shows an overall reduction of the allocated funding by $\simeq$24%.

It is interesting to note that some of the projects do not have an exclusively hydro-related objective. BINGO, DAFNE, HyPump and IMPREX projects (with a total budget of EUR 23.75 million) have a wider scope related to water resources. This includes developing integrated strategies for water resources management under climate change (BINGO), the WEF nexus in developing countries (DAFNE), RES-powered irrigation pumps and advanced hydrological simulation and modelling techniques for weather extremes (IMPREX). Hydropower technology development is directly related to these projects as it can definitely benefit from them. Indeed, a better simulation of river water discharge (e.g. as a result of the IMPREX project) may enable better design and operation of hydropower stations and increased resilience and efficiency. However, it is clear that a significant part of the work in such projects will also cover aspects that are not directly related to hydropower.

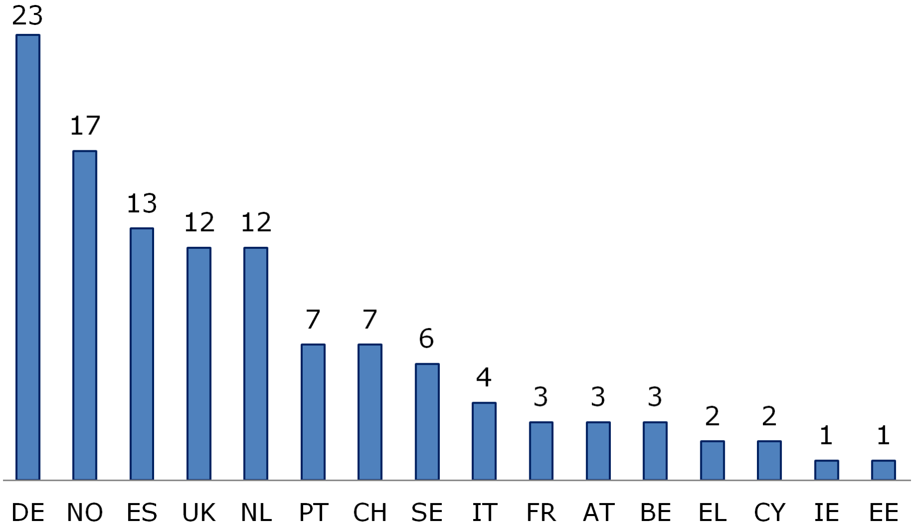

Figure 1: Number of research project participants per country. Source: Author's compilation

Leading countries in hydropower technology developments are –traditionally– Germany, Norway, Sweden, Austria and Switzerland. Figure 1 illustrates an analysis of the project partners in terms of their host country. Institutions based in Germany participate 23 times as partners in the analysed projects, where Norwegian appear 17 times. Spanish, UK-based and Dutch institutions are also very active. Portugal-, Switzerland, and Sweden-based partners also appear in several occasions, indicating the active hydropower R&D in these countries.

---

[1] This figure does not take into account the EUR 7.8 million of the "BINGO" project. The latter was already approved and initiated in mid 2015 and, thus, included in an earlier study (Kougias, 2016a).

It is interesting to note that the DAFNE project also includes four African universities as partner institutions. Compared to the previous analyses, this is a development that shows EU's commitment in partnering with Africa and expanding the scope of hydropower R&D in the African region. Naturally, the scope of DAFNE project is much wider than hydro and covers the WEF interactions, as it will be presented in the following text.

2.1 Assessment of the state of the art per sub-technology

Each of the identified projects has different scope and targets specific advancement on the way hydropower is developed and operates. However, it is possible to group the projects by distinguishing the core of their approach. While some projects mainly have a technical objective, meaning advancing a specific component, others analyse the hydropower from a bigger perspective. This includes the environmental implications of hydropower or water resources management and their interactions with energy production. Accordingly, the identified projects can be categorised into four main groups[2]:

2.1.1 Hydraulic design and mechanical equipment

The first group includes those projects that aim to address specific technical challenges mainly on the machinery level of hydropower. It includes developing materials and computational model to address important hydraulic challenges such as erosion and cavitation (CaFE project). It also includes the development of techniques to support a wide range of operation of hydraulic turbines (HydroFlex project). Turbines' flexibility is generally related to both conventional hydropower plants as well as pumped hydropower storage (PHS).

2.1.2 Low-head hydropower and hydrokinetic technologies

The second group of projects includes new turbine design to enable better utilization of untapped hydro resources, mainly of the small scale (SHP). This includes developing low-head turbines suitable to locations with a small (<10 m) hydraulic head (Hydrolowhead project). This group also embeds research activities on hydrokinetic turbines for river currents (DP Renewables project).

2.1.3 Environmental-friendly hydropower

The third cluster contains projects that aim at improving the ecological characteristics of hydropower. This includes developing advanced fish passing technologies and generally creating a fish-friendly hydropower (FIThydro project). It also extends to another long-debated challenge i.e. the residual ecological flows of dams. This issue, also known as environmental flow, is the topic of a training and research network activity (EUROFLOW project).

---

[2] The four groups are separated in Table 1 by horizontal lines.

2.1.4 Water resources management and hydropower interactions

The fourth cluster includes projects that deal with water resources in general. Energy production is one of the studied aspects of these projects as they aim at addressing needs and challenges that are indirectly connected to energy production. Accordingly, a new approach to water resources management is the topic of one project (BINGO project). Naturally, a better understanding-simulation of the hydrological processes can cross-fertilise research among the various hydropower services. Accordingly, projects that improve the predictability of hydrological extremes (i.e. flood, draught) enable developing better strategies for hydropower production (IMPREX project). The recognition of the need to address the different aspects of water reservoir management in an integrated manner has resulted in the development of WEF approaches. Indeed, DAFNE project analyses decision making and hydropower development in trans-boundary river basins in developing countries. Moreover, HyPump project advances the technology of a hydro-powered pump to irrigate agricultural areas from rivers and canals in a sustainable and cost-efficient manner.

2.2 Indicators

The present report adopts some indicators to evaluate technological developments related to hydropower. Conventional hydropower systems are technologically mature and well-established having provided electricity to power systems for over a century, globally. However, hydropower components and new designs are still under development. Such advances generally refer to the categories presented in sections 2.1.1–2.1.4 and their status of development are quantified by the technology readiness level (TRL) index. Hydropower's TRL definitions are specifically presented in a guidance document prepared by Directorate-General for Research and Innovation (DG RTD) in 2017, in collaboration with the EC Joint Research Centre (JRC). These definitions have been included in the recent LCEO report on hydropower emerging technologies (Kougias, I. and Moro, A. (eds.), 2018).

The parameter of the cost is taken into account using capital expenditure (CAPEX) and operation expenses (OPEX) figures. A combination of the two is provided by the levelised cost of energy (LCOE) index that shows the net present value of the unit cost of electricity (e.g. kWh) over the assumed lifetime of a hydropower station. The present report includes such values as documented by the project developers. It is important to note that the comparatively longer lifetime of hydropower plants affects the LCOE values; depending on the component, hydro lifetime ranges between 30 and 80 years with several plants operating for more than 100 years without major overhaul (IRENA, 2012).

The operation of hydropower does not include direct greenhouse gas (GHG) emissions. Still, the construction of the civil works of hydropower schemes involves such emissions. Moreover, there is an increasing concern of GHG emissions on hydro reservoirs resulting from the decomposition of the submerged organic material. Scientific evidence identifies this issue predominantly in tropical regions (Fearnside, 2015, Fearnside, 2016), underlining its possible under-estimation in the global climate targets.

In a similar manner, the water that hydropower stations use to drive their turbines is returned to the river systems and is not consumed. However, the water evaporated from the artificial reservoirs to produce electricity is significant and according to (Mekonnen and Hoekstra, 2012) equivalent to the 10% of the blue footprint of global crop production.

The research projects that the present report identified do not focus on the development of new “greenfield” hydropower stations on locations that were not previously developed. The projects either relate to the operation of existing stations or the development of SHP with minimal environmental and visual impact. Accordingly, the relation of the new technologies with additional GHG emissions and/or water losses is generally assumed to be low.

3 R&D overview and impact assessment

3.1 CaFE project

The full title of CaFE project is *Development and experimental validation of computational models for cavitating flows, surface erosion damage and material loss*. It started on 1/1/2015 and with a total duration of 48 months, it was completed at the end of 2018. Its overall budget is $\simeq$ EUR 4 million, all covered by EU sources. CaFE deals with an important hydraulic phenomenon, cavitation.

Cavitation includes the formation of vapour/gas bubbles of a flowing liquid in those parts of the liquid where the pressure falls below its vapour pressure. Such bubbles may collapse suddenly on the metallic surface of the various components and lead to high local stresses, vibration and damage. The phenomenon and its appearance in a Francis-type hydropower turbine are shown in Figure 2. Cavitation results in an erosive wear of the turbines that decrease their operational lifetime and involves significant operation and maintenance (O&M) costs or even full replacement. Cavitation takes place in reaction turbines (Francis and Kaplan turbines type) and mainly affects the runners and draft tube cone.

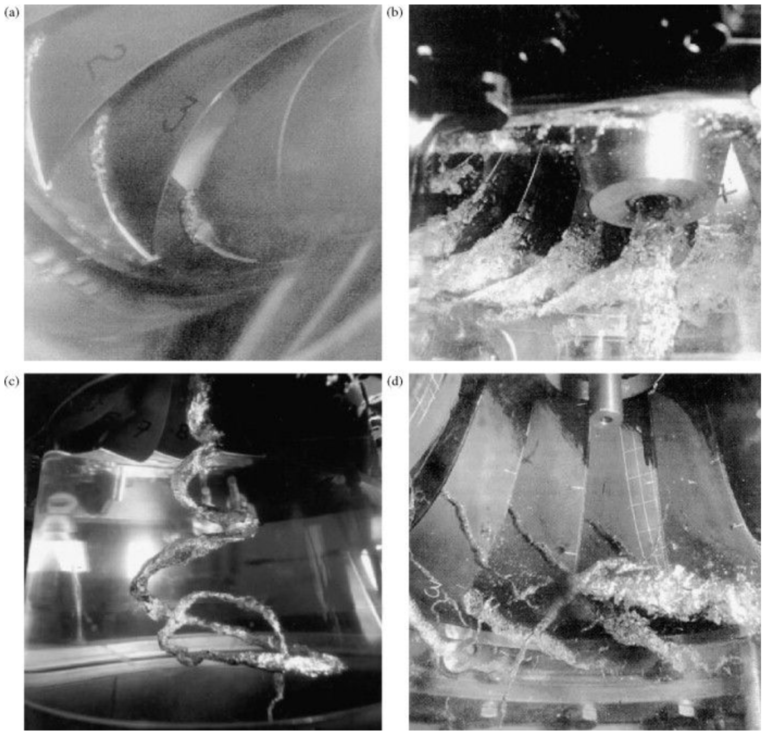

Figure 2: Different types of cavitation in Francis turbines. Source: (Kumar and Saini, 2010)

Francis turbines are particularly prone to cavitation, which limits their operating range. This reduces the flexibility of both conventional hydropower stations that run Francis turbines as well as storage PHS stations that typically host Francis (Kougias and Szabó, 2017). CaFE has aimed at attaining a better understanding of the dynamics of the phenomenon that leads to the formation of cavitation erosion. To achieve that, simulation processes have been planned along with the design of novel test rigs. The developed models have been validated using existing and new experimental data, in order to fine-tune them and reach higher levels of accuracy.

The validated model's application in real cases allows a higher degree of understanding of cavitation erosion, which is valuable not only to hydropower machinery but also to other mechanical components affected by cavitation.

The implementation of the CaFE project can be divided into four main objectives. Firstly, a simulation exercise aimed at improving knowledge on the fluid-structure interaction that leads to surface erosion. Subsequently, quantitative flow measurements in cavitating flows provides the required data for the validation of the numerical tools. In a third step, specific methodologies would be developed to indicate potential locations of surface erosion. Finally, the validated models were be applied to cases of industrial interest in the first step of making them design tools to industrial practice (TRL-6).

CaFE has, thus, not only focused on fundamental work and basic research but has also moved towards industry-oriented technological development. This includes the development of computational fluid dynamics (CFD) tools able to predict cavitation in real-world facilities. This is also shown by the participation of six non-academic partners in the consortium.

3.2 HydroFlex project

The full title of the HydroFlex project is: *Increasing the value of Hydropower through increased Flexibilty*. It is a very recent project, as it started on 1/5/2018. It has a total duration of 48 months and it is expected to end by 30/4/2020. Its overall budget is $\simeq$ EUR 5.7 million, with the vast majority ($\simeq$ EUR 5.4 million) covered by EU funds. The objective of HydroFlex is to further increase the operational flexibility of hydropower stations. This topic is high in the research and policy agenda; hydropower being the most flexible energy source it has a crucial role in power system balancing. It is important to reach even higher levels of flexibility of hydropower, due to the expected increasing shares of variable RES coupled with decreasing capacities of gas turbine power plants[3].

The HydroFlex project identifies the operating conditions of hydropower plants in the future energy system. It focuses on a well-documented issue related to the flexible operation of Francis turbines. This includes the operating range of turbines and hydraulic phenomena that hinder the wide range operation of Francis turbines. Accordingly, when operated either under part load conditions ($<$ 30% of the rated value) or over the nominal conditions, Francis turbines experience vibrations and large pressure fluctuations. This causes heavy dynamic stress on the mechanical equipment, reducing the life expectancy of the machine. Considering that Francis turbines are used practically in most PHS stations, this problem affects both conventional and pumped hydro storage stations.

Future power systems are expected to force hydropower stations to higher ramping rates and frequent start-stop cycles. Accordingly, the occurrence of non-favourable conditions is expected to affect the lifetime of Francis turbines, increase their O&M costs and increase safety-related risks. The objective of HydroFlex is to achieve technological breakthroughs that enable very flexible hydropower opera-

---

[3] Apart from hydroelectric, open cycle gas turbine (OCGT) stations are the main source of power systems' flexibility. They have a low start-up time and high ramp-rate that allows them to provide peaking power (Gonzalez-Salazar et al., 2017).

tion, utilising the power and storage capability. This will be implemented in three phases. Firstly, the role of hydropower in the future power systems will be assessed. This will provide estimations on the dynamic loads that hydropower machinery will experience as a result of high ramping rates and frequent start-stop cycles. This allows to develop a new hydraulic design of Francis turbine and construct a model that allows high ramping rates and 30 start-stops per day, without significant impact on the operating life (TRL–4). Analyses have also studied the use of new materials, CFD simulations, and extending testing. Subsequently, the electrical layout of the novel power station will be developed, including generator component and control. The latter will allow testing the prototype system in an environment close to real conditions and, thus, reach a maturity TRL–5.

An additional characteristic of the HydroFlex project is that it also analyses the environmental impact of hydropower, particularly if operated under increased flexibility conditions. Frequent start-stops involve variations and disruptions of the water releases with a possible impact on the ecology of the river downstream the power station. Disrupted water releases may also influence fish migration and flora-fauna. Accordingly, HydroFlex will develop and test innovative methods to mitigate the environmental impacts.

In the recent years, the extension of the operating range of Francis turbines has been the subject of a few other projects such as the nationally-funded projects of the Norwegian University of Science and Technology[4] (e.g. Francis-99 and HiFrancis projects), research activities in Switzerland (e.g. FlexSTOR project), and research work of the Romanian Academy in collaboration with the Timisoara University.

The important topic of hydropower's flexible operations was also studied in terms of the Hyperbole FP7 project. The scope of Hyperbole is linked to that of Hydroflex and shows the chain of research and technology development. Hyperbole was monitored in an earlier LCEO report (Kougias, 2016a) when it was still ongoing; for this reason an update of its findings is presented in the following text[5].

The full title of the Hyperbole project is *Increasing the value of hydropower through increased flexibility*. It started on 1/9/2013 and had a total duration of 42 months. Its overall budget was $\simeq$ EUR 6.3 million, with a significant part ($\simeq$ EUR 4.3 million) covered by EU funds. The beneficiaries included global leading companies (Alstom[6], Andritz, Voith) as well as universities and research organisations. Hyperbole was the only project supported under the topic "optimisation of water turbines for integration of renewables into the grid" (call: ENERGY.2013.2.7.1).

Hyperbole, similarly to Hydroflex, studied the flow instabilities of Francis turbines when their operation exceeds their rated range. The project conducted an extensive series of testing and experiments to analyse such phenomena. A 1-D model that simulates-analyse the flow and the instability phenomena was developed and validated in reduced-scale models (TRL–4), in both conventional and reversible Francis turbines. This enabled the development of a methodology for predicting and assessing hydros' dynamic behaviour. The methodology was then tested on full-scale Francis turbine units of a PHS plant in Spain (Aldeadávila II) and on a conventional hydropower plant in Canada (Mica) reaching higher technological maturity levels (from TRL–5 to TRL–7).

---

[4] NTNU: Coordinator of HydroFlex project

[5] Hyperbole's basic information was not included in §2, to avoid duplication with (Kougias, 2016a)

[6] In late 2015, General Electric completed the acquisition of Alstom's power and grid businesses.

3.3 Eco-Drilling project

The full title of the Eco-Drilling project is *Environmentally efficient full profile drilling solution*. It started on 1/9/2017 and with a total duration of 30 months it will end on 29/2/2020. Its overall budget is $\simeq$ EUR 2.8 million, with the main part ($\simeq$ EUR 2 million) covered by EU funds. It is funded under the Small and Medium-sized Enterprises instrument (H2020-SMEINST) and the beneficiary is a single company, Norhard AS. Norhard is a Norwegian company specialised in hard rock drilling.

The aim of the project is to develop an environmentally friendly full profile directional drilling technology for the hydropower sector. This includes the development of a prototype, a pilot application and eventually achieving a commercial cost-effective final product reaching TRL–8 to TRL–9.

Hydropower development often includes drilling and tunnelling activities, especially in large-scale stations. This is because tunnels are occasionally a better option to convey water than e.g. a canal around a hill. This is particularly the case for underground hydropower projects, where powerhouses are located deep inside the ground. Thus, the construction of the power-plant requires an underground waterway system that conveys the water to the powerhouse. The system is known as the head-race system and is a combination of tunnels, pressure shafts, surge tank, air cushion chamber etcetera. Over the years developments of tunnelling methods and geology have favoured tunnelling over above ground solutions (e.g. steel penstock pipes) (Bråtveit et al., 2016). Thus, while early solutions for plants with a high hydraulic head included a penstock attached to the ground, tunnelling was widely adopted after the mid-1970s (see Figure 3).

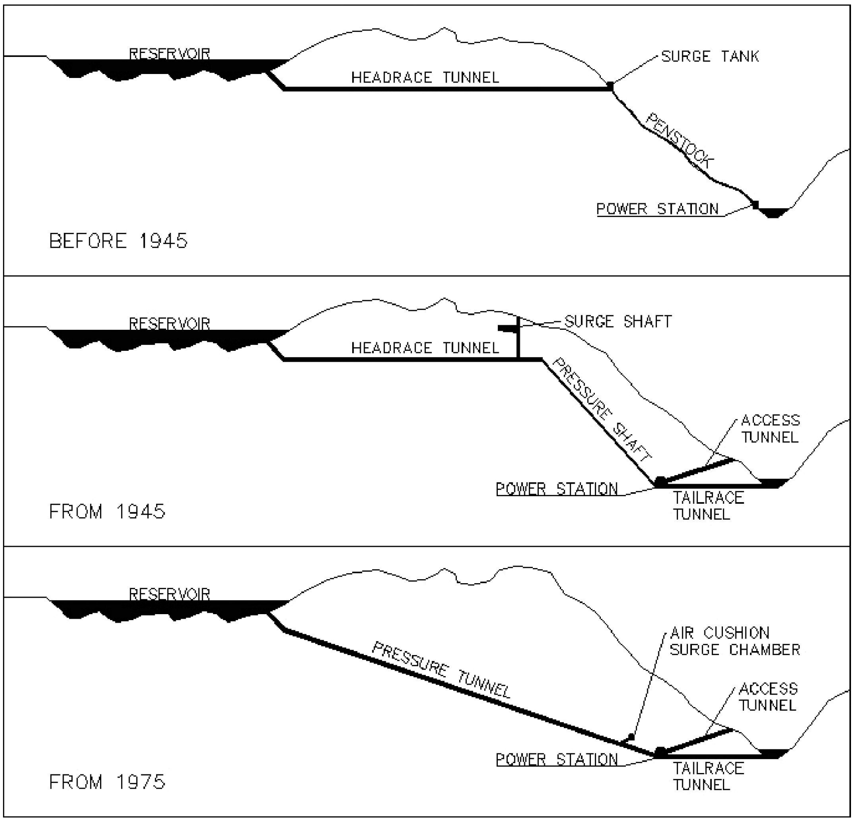

Figure 3: Historical development of hydropower tunnel system. Source: (Bråtveit et al., 2016)

The Eco-Drilling project aims at using a non-rotatory drill string for tunnel construction that significantly reduces the CO_2 emissions and the overall cost ($\simeq$50%). Due to the fact that the construction of temporary access roads is not required with this technique, additional environmental impacts can be avoided in hydropower development. Tasks include further strengthening the existing designs to withstand larger forces and consequently to increase the capacity to drill over larger distances and heights, both horizontally and vertically. Advanced navigation and control techniques will also allow a higher degree of automation. Large-scale piloting is planned for October 2018 with the aim to allow full commercialization (i.e. supply chain, up-scaling) of the technology.

The Eco-Drilling project can be characterised as a cross-sectoral research activity, as it is classified into the geotechnical engineering scientific field. However, its objective is targeted for hydropower development and aims to address a common challenge in large-scale, high-head hydropower development. Untapped locations with such characteristics are limited in the European context. Therefore R&D achievements and breakthroughs of the Eco-Drilling project are expected to allow exporting scientific excellence abroad, e.g. in South-East Asia or Latin America, where large-scale hydropower development is still blooming. Indeed, the work package 4 includes a market and regulatory monitoring of the aforementioned regions in order to establish detailed market strategies. Equally, important it is expected to allow the development of hydropower plants at locations where it was not previously possible, due to technical or environmental constraints.

3.4 Hydrolowhead project

The full title of the Hydrolowhead project is *Profitable low head hydropower*. It started on 1/11/2015 and with a total duration of 24 months and it was completed on 31/10/2017. Its overall budget was $\simeq$ EUR 1.5 million, with the majority ($\simeq$ EUR 1 million) covered by EU funds. It was funded under the Small and Medium-sized Enterprises instrument and its main difference with previously analysed projects is that the consortium consists of only two companies.

The Hydrolowhead project dealt with the deployment of SHP capacities that, contrary to large-scale stations, can have a lower environmental impact as they do not involve irreversible intervention to the environment that often has a social and ecological impact. Presently, deployment of SHP capacities in EU is rather slow, with most of the EU member state (MS) failing to reach the plans foreseen in their National Renewable Energy Action Plans (NREAPs) (see Tables 2, 3).

Hydrolowhead identifies this challenge and highlights the fact that installing conventional turbines at smaller scales is not always economically competitive, due to the relatively low efficiency and the high investment cost that also needs to be made upfront. Considering that the project aims at utilizing low-head sites, increases its scope as the majority of low-head potential sites in Europe are still untapped. Accordingly, Hydrolowhead aims at building a final product that has a high efficiency ($\simeq$ 75%) that can be installed in a very short time (1-2 days).

This tendency was also identified in a recent JRC analysis that assessed the emerging technologies of the hydro sector (Kougias et al., 2019). R&D breakthroughs in marine energy converters could be transferred to onshore applications enabling cost reductions that would render untapped low-head sites economically reasonable investments. The aim is to reach a sufficient market maturity of clean energy systems that are part of a collective suite of marine and hydrokinetic (MHK) technologies and convert the kinetic energy of river currents into electricity.

Accordingly, in terms of the Hydrolowhead project, new axial turbines have been developed with a nominal power capacity of $\simeq$ 60 kW (mini-scale), operating at a hydraulic head of just 3.5–4.5 m. According to the project reporting, the design of the axial turbine has been completed and it is ready for fabrication in real scale (TRL-5). In terms of market maturity, the project aimed at reaching EUR 1.2/W installed for the integral product in order to have an attractive investment (payback time less than 4 years). The methodology to eventually reach this target has been established. Due to some unforeseen problems, the large-scale pilot plant that would operate in near-real conditions was not completed on time and was foreseen to be ready with some delay. The update of mid-2018 mentions that although the installation of the turbine to the selected pilot site was not completed yet, the turbine was ready to be installed (in situ inspection). Moreover, a second prototype that was not initially foreseen in the proposal (1:5 scale) was also manufactured and tested giving very good results. The completion of these activities signal the technology reaching TRL-6.

3.5 DP Renewables project

The acronym DP Renewables stands for the full title *A range of economically viable, innovative and proven HydroKinetic turbines that will enable users to exploit the huge potential of clean, predictable energy in the world's rivers, canals and estuaries*. The project started on 1/7/2017 and with a total duration of 27 months will be completed by 30/9/2019. It has an overall budget of EUR 2.877 million out of which EUR 1.935 million is an EU Grant. Similarly to Hydrolowhead, DP Renewables is financed under an instrument for SMEs, with the beneficiary being an Irish company (DP Designpro ltd).

The aim of the project is to bring to commercial state a range of innovative hydrokinetic turbines, by mid-2019. This is related to SHP stations of the mini scale, with a power capacity ranging between 25 kW and 60 kW. Hydrokinetic turbines employ a non-conventional hydropower technology as they only convert the kinetic energy of river streams (Yuce and Muratoglu, 2015). Accordingly, they are suitable for the development of environmental-friendly hydropower technologies in suitable stream locations with a low hydraulic head (<10 m). So far, such turbines have not reached the technological or market maturity to be widely installed. DP Renewables aims at creating a final product that will enter the RES market in an ambitious manner. To do so, DP Renewables has also conducted a market research including a sales' lifecycle plan, resources and infrustructure.

The developed 25 kW system was standardised and validated, in order to be ready for commercialization. The activities comprise design, building and extensive testing to meet pre-defined quality and safety criteria, including optimised power-curve validation and environmental impact assessment. The TRL-8 device will also be used for training, dissemination and promotion as well as to improve design feautures of the 60 kW device. As a follow-up activity, DP Renewables plan to deploy a 60 kW device at a specific site in Bordeaux, France.

3.6 FIThydro project

The acronym FIThydro stands for the full title *Fishfriendly Innovative Technologies for Hydropower*. The project started on 1/11/2016 and with a total duration of 48 months will be completed by 31/10/2020. It has an overall budget of EUR 7.172 million of which EUR 5.888 million is an EU grant. FIThydro is financed under the H2020-LCE instrument that promotes the development of market-competitive low carbon energy sources.

Dam construction directly affects the river ecology, by altering the hydrology of the basin and reducing fish diversity. The fish population is affected due to the fact that dams do not generally allow migratory species to complete their life cycles. Accordingly, dam site selection is crucial for conserving biodiversity. While hydropower projects' development manages to a great extent to address important energy challenges, it often underestimates the effects on biodiversity and important fisheries (Winemiller et al., 2016). For this reason, an increasing opposition in large dam construction has called for a fundamental reform of the way decisions are made. Such voices claim that the ecological impact raises the question of whether or not to build dams rather than simply improving the methodologies to design–manage dams (Fearnside, 2016). Besides, a possible impact on the fish population directly relates to the local human population, because large rivers are productive inland fisheries and basic food source (Grumbine and Xu, 2011). Other scientists recommend milder approaches, where addressing hydropower's social impact (i.e. human resettlement) is prioritised over the ecological impact. Accordingly, they suggest transfer payments and compensation to the local communities coupled with advanced management strategies (Tang, 2016).

FIThydro aims at creating solutions and suggestions for this much-debated issue. It combines both existing and innovative technologies as a measure to mitigate impact to the fish population. Accordingly, it evaluates different bypass systems in the European context in both analytical and experimental manner. While there exists some evidence that fish passages have not been successful or even harmful in the neotropics (Pelicice and Agostinho, 2008), FIThydro aims to provide solutions to this controversial issue, mainly in Europe. Moreover, good practices and innovations can be of vital importance for Africa, the Americas and South East Asia, where one-third of the freshwater fish is at risk due to new dam construction (Winemiller et al., 2016).

FIThydro will bring together existing data and knowledge on fish population ecology in Europe. The aim is to develop a European Fish Population Hazard Index that will act as a decision and management tool for hydropower stations. This includes identifying knowledge gaps and developing customised and innovative solutions. The parameter of the cost will also be analysed, in order to develop cost-effective strategies that are applicable to existing hydropower stations, in an economically viable manner. Eventually, FIThydro aims at providing a holistic approach that may even enable new hydropower development in Europe, with the minimum possible ecological impact.

3.7 Turbulent project

Related to the Hydrolowhead, DP Renewables and FIThydro projects is a project supported by the KIC-Innoenergy, supporting scheme. Turbulent project is included in the renewable energies category and, as a relatively mature concept in terms of technology, it is considered as a venture and not as an innovation project[7]. Turbulent suggests the installation of standard low-head axial turbines in existing canals or regulated streams. The main innovative characteristic of Turbulent is its aim to build a turnkey solution that can be replicated to other sites. Additional characteristics such as fish-friendliness, low cost of O&M and minimal environmental impact are generally identical to the characteristics of similar mini-hydro stations. Apart from the KIC-Innoenergy support, "Turbulent startup" has received additional funding in terms of rewards in international startup summits of at least additional USD 160,000.

3.8 EUROFLOW project

The acronym EUROFLOW stands for the full title *A EUROpean training and research network for environmental FLOW management in river basins*. The project started on 1/9/2017 and with a total duration of 48 months will be completed by 31/8/2021. It has an overall budget of EUR 3.924 million all of which is provided by EU sources. EUROFLOW is financed under the H2020-MSCA-ITN instrument that promotes the development of innovative training networks.

EUROFLOW project deals with a very important topic in hydropower operation, the regulation of river flows. As dams alter the natural flow of water and force its storage in water reservoirs, securing sufficient residual flow in the rivers is very important. Besides, insufficient environmental flow is one of the biggest challenges that affect river ecosystems globally. Accordingly, the supply of fresh water to support human well-being (energy production, drinking and irrigation water) needs to simultaneously sustain healthy, functioning ecosystems. Defining this equilibrium is one of the great environmental challenges of our times and it is expected to be exacerbated in light of increasing uncertainty due to the climate change and the population growth and economic development stressors (Poff et al., 2016). Recent findings reveal that conventional actions to increase water security typically result in environmental degradation such as reduced fish diversity and water quality (Vörösmarty et al., 2010).

EUROFLOW project aims at creating a network that will define and promote sustainable water management systems that enable meeting societal needs of energy and water while maintaining key ecological functions. This initiative is in-line with the viewpoint that suggests balancing ecological and human needs (Palmer, 2010), also promoted by major legislative efforts in EU and other countries (e.g. EU WFD, U.S. Clean Water Act, Australian Water Resources Act, South Africa National Water Act).

As the main objective of EUROFLOW is to create a network, it has a strong direction towards collecting and sharing the current knowledge on environmental flow regimes. The project consortium comprises of ten participating institutions

---

[7] This is the reason Turbulent was not listed in Table 1 with the main analysed projects.

from seven MS. Accordingly, the project includes training plans, online courses and PhD research. However, it also includes a solid analytical and experimental component to advance the current knowledge. Leeds University will perform environmental flow experiments, while field experiments in real conditions will take place in Switzerland (Swiss Federal Institute of Aquatic Science and Technology). The aim is to identify the various river types and the ways they are influenced by different pressures. This extends to flood risk assessment exercises, by monitoring the hydro-morphological responses to flood flows. Eventually, EUROFLOW aims at developing analysis methodologies that enable quantifying the interplay between land and water management strategies with the effects of climate change. The objective of these methodologies is to up-scale the biodiversity responses to hydrological alteration imposed by hydropower stations' operation.

3.9 BINGO project

The acronym BINGO stands for the full title *Bringing INnovation to onGOing water management - A better future under climate change*. The project started on 1/7/2015 and with a total duration of 51 months will be completed by 30/9/2019. It has an overall budget of EUR 7.822 million all of which is provided by EU sources. BINGO is financed under the H2020-WATER instrument that aims at boosting the value of water for EU through innovation.

Similarly to FIThydro and EUROFLOW, BINGO is not a strict hydropower technology project. It focuses on climate modelling aiming to anticipate different weather scenarios and downscale them to drainage basin level. Following that, the different stakeholders of water resources analyse the various uses and needs with less uncertainty. One component of the analysis is energy and hydropower, however, it is a minor one for the project. Naturally, the environmental and ecological dimension of the project is strong, as it is in FIThydro and EUROFLOW.

Work package four assesses the impact of extreme events due to climate change on the water cycle. The different scenarios, defined in previous work packages, support the analysis of near future impacts on hydropower production. This is a challenge that lies very high in the concerns of the international hydropower industry and it is commented in the conclusions section of the present report. Naturally, the hydropower industry has also underlined the role of hydro to mitigate the effects of climate change (IHA, 2015), as hydro is, generally, a low-emission technology that allows clean energy production with no direct GHG emissions.

3.10 DAFNE project

The acronym DAFNE stands for the full title *Use of a Decision-Analytic Framework to explore the water-energy-food NExus in complex and trans-boundary water resources systems of fast-growing developing countries*. The project started on 1/9/2016 and with a total duration of 48 months will be completed by 31/8/2020. It has an overall budget of EUR 5.420 million out of which EUR 3.409 million is provided by EU sources. DAFNE is financed under the H2020-WATER instrument that aims at boosting the value of water for EU through innovation.

According to the project's website, DAFNE is related to HydroENV project, a relatively small Swiss project also coordinated by ETH Zurich. The objective of HydroEnv is to analyse the interplay of hydropower production in Switzerland with a possible rise in environmental degradation in river systems. DAFNE is also related to the H2020-WATER project MAGIC nexus that deals with WEF without, however, including hydropower in its scope.

The unique characteristic of DAFNE is that it has a global scope that extends EU. In particular, it focuses on sub-Saharan Africa and trans-boundary river basin management. It aims to develop WEF nexus approaches to promote expanded energy and food production in developing countries in a sustainable manner. Findings of the project will be applied to two case studies, the Zambezi and the Omo river basins in Africa. In order two achieve that, three African Universities and one African research institution participate in the research group[8]

Initially, DAFNE collected data related –among others– to existing hydropower infrastructure characteristics and operating rules. This includes a time series of inflows, water levels, production and demand for energy etcetera. Subsequently, strengths and weaknesses will be assessed, mainly focusing on hydropower's efficacy to cover the demand. Planned hydropower schemes will be then simulated and along with alternative operational policies of the existing ones, they will present the WEF interactions under different scenarios. The very important aspect of environmental flow (see section 3.8) will also be taken into account.

A novelty of DAFNE is the integrated analysis of biomass and hydro energy sources, which is very important particularly in sub-Saharan Africa where biomass represents 60% of the energy consumption. In order to analyse the WEF dynamics, DAFNE will develop a distributed model that builds on agent-based numerical analysis. The aim is to identify the operational strategies of hydro stations that satisfy future demand in an optimal manner. Overall, DAFNE does not aim at advancing a specific hydropower component or sub-technology. It creates a rather integrated framework, where energy production and its interaction with other water uses are analysed in a holistic manner.

3.11 HyPump project

The acronym HyPump stands for the full title *Enabling Sustainable Irrigation through Hydro-Powered Pumps for Canals*. The project started on 1/10/2017 and with a total duration of 33 months it will be completed by 30/06/2020.It has an overall budget of EUR 2.545 million, EUR 1.782 million of which is covered by EU sources. HyPump has been developed by a startup company named aQysta and it is financed under the H2020-SME instrument.

HyPump lies in the core of the WEF nexus, but in a more specific objective than DAFNE project (§3.10). It deals with the energy needs of irrigation activities and particularly for the required energy to convey water from rivers and canals to the fields with a significant amount of pressure. HyPump is an innovative hydropower pump which converts the kinetic energy of irrigation canals to pressurized water. The latter can irrigate the fields without the need of fuel-based or electrical pumps. It is, thus, a hydro-powered pump explaining the project's title selection.

---

[8] The consortium includes the University of Zambia, the Arba Minch University in Ethiopia, the Eduardo Mondlane University and the African Collaborative Centre for Earth System Science.

HyPump was previously tested and operated in a relevant environment in two test fields in Indonesia and Spain. The scale of the prototype was smaller than the intended end-product to facilitate the testing. Accordingly, HyPump is at TRL-6[9]. Compared to solar-powered pumps (Kougias et al., 2018), HyPump claims to involves reduced cost by up to 37%. When switching from an electric pump to HyPump the payback is estimated to range between 2.6-3.8 years and have a lifetime of 25 years.

The aim of the project is to industrialise the product, reaching the final product design, size and configuration. The project will also create a software that will process collected data in order to optimize the installation of HyPump. The demonstration, marketing and logistics management are also objectives of the project.

3.12 IMPREX project

The acronym IMPREX stands for the full title "IMproving PRedictions and management of hydrological EXtremes" The project started on 1/10/2015 and with a total duration of 48 months will be completed by 30/9/2019. It has an overall budget of EUR 7.997 million all covered by EU sources. IMPREX is financed under the H2020-WATER instrument.

The objective of IMPREX is similar to the one analysed in BINGO i.e. the optimal strategies of hydropower under the uncertainty of hydro-meteorological events and climate change. It aims to provide decision support through the development of heuristic optimisation models coupling energy and agricultural production. Flood and drought risks will be also analysed. The ultimate target of IMPREX project as far as hydropower production is concerned is to increase the economic gains of energy production. Estimations predict raising the income by up to 5% following advanced hydro-meteorological ensemble forecasts, similar to the strategies (agent-based modelling) of DAFNE project.

IMPREX will analyse a great number of river basins that cover the different characteristic regimes of Europe. The river basins include Ume river in Sweden, Thames in the UK, Júcar, Llobregat and Segura in Spain, Bisagno river and Lake Como in Italy and Messara in Creta-Grece.

IMPREX identified the needs in hydropower sector to collect, process and analyse hydrological data especially as far as extreme events are concerned. It then presents potential benefits of better hydrometeorological predictions for the hydropower sector. This is also linked to a specific deliverable that showcases the improved risk assessment for hydropower by applying the developed approaches on case studies.

---

[9] The TRL definition of hydropower is available at (Kougias, I. and Moro, A. (eds.), 2018).

4 R&D overview and impact assessment of smaller projects

The previous section presented recent and ongoing research projects of the large scale with a budget exceeding EUR 1 million. This section will also present EU-funded research projects that have a significantly lower budget and limited scope. This overview allows identifying the tendencies and needs of the hydropower sector. Moreover, it provides a better understanding and a full picture of the current R&D activities related to hydropower.

4.1 EcoCurrent

EcoCurrent (Innovative water current picoturbines for the economic and sustainable exploitation of the renewable energy from rivers and estuaries) is a H2020-SMEs project with a budget of $\simeq$EUR 71,500 (EUR 50,000 covered by EU). It is a short project with a duration of four months (1/12/2017–31/3/2018).

Its objective is off-grid energy solutions based on hydropower energy of the pico scale ($<$5 kW). The beneficiary is the French micro-enterprise EDIE ECoCinetic that invented the hydrokinetic pico-turbine EcoCurrent, that harnesses the kinetic energy of canals, rivers and tidal currents. The company's aim is to introduce a 2 kW unit in early 2020 with a competitive cost of EUR 4,000. Such a solution is expected to attract the interest of developing and emerging economies in Sub-Saharan Africa, South America and South East Asia, where off-grid rural electrification is an economically prime solution. Since all the components of the turbine have already been developed and tested, the EcoCurrent project aims at finalizing the project, optimizing its industrial design and eventually getting a step closer to commercialization. The latter also includes a market analysis to identify opportunities.

4.2 KEEPFISH

KEEPFISH (Knowledge Exchange for Efficient Passage of Fishes in the Southern Hemisphere) is an H2020-MSCA project that promotes innovation and staff exchange. It has an overall budget of $\simeq$EUR 135,000 (EUR 126,000 covered by EU). It is a project with a duration of 48 months (1/1/2016–31/12/2019) that involves universities of the UK, Germany and Denmark.

KEEPFISH focuses on the same topic with FIThydro project (analysed in §3.6) i.e. the protection of the diversity of the fish population, a critical issue in new dam construction. KEEPFISH involves two universities in Brazil, as South America is a hub of new hydropower dam construction. Its aim is not to create new knowledge, but to rather collect the existing one in a systematic manner. Equally important, it aims to engage stakeholders and support the work of researchers in South America ensuring sustainable strategies in hydropower development.

4.3 HydroKinetic-25

HydroKinetic-25 (Commercialization of a viable and proven HydroKinetic Turbine that will harness the power of the world's rivers, canals and estuaries in a sustainable, innovative and cost-effective way) is an H2020-SMEs project with a budget of $\simeq$EUR 71,500 (EUR 50,000 covered by EU). It is a short project that ran for six months (1/3/2016–31/8/2016).

The aim of HydroKinetic-25 is similar to the one of EcoCurrent i.e. to develop a hydrokinetic turbine that will be in 2020 ready for the market. At the time of the submission, the hydrokinetic turbine had reached a TRL–6 going from TRL–1 to TRL–6 in 24 months. The aim of the project was to reach TRL–7 and at the same time secure further financing and establish cost-effective manufacturing processes. The prototype has a power of 25 kW and the company intends to also develop larger devices of 50, 100 and 250 kW power capacity in order to provide additional market solutions. The estimated production cost is EUR 90,000 while its retail price is estimated at EUR 140,000 (EUR 5600/kW).

4.4 HyKinetics

HyKinetics (An innovative axial turbine for conversion of hydro-kinetic energy to electricity for river applications) is an H2020-SMEs project with a budget of $\simeq$EUR 71,500 (EUR 50,000 covered by EU). It is a short project that ran for six months (1/2/2018–31/7/2018).

HyKinetics deals with a 1-20 kW axial hydropower turbine that exploits the kinetic energy of rivers. The solution has a low visual and environmental impact as it consists of a floating control station, anchored to the river bank. Similarly to the previous projects, the main barrier to overpass is the manufacturing cost. The production cost is still relatively high, 2-5 times higher than conventional hydropower stations of larger scale and not fully competitive with market-mature RES. Accordingly, the aim of HyKinetics is to manufacture and test an optimized prototype in real conditions as well as fine-tune the supply chain and the turbine manufacturing process. This will eventually allow achieving lower production costs (EUR 1300/kW) and a retail price of EUR 2000/kW. Such a cost will correspond to a highly competitive LCOE equal to EUR cent 7/kWh. Product certification will be coupled with a simplification of the otherwise costly authorization procedures, by standardizing them for the entry markets (Italy, Germany, France, Spain, Austria).

4.5 RIVER-POWER

RIVER-POWER (Water flow kinetics energy exploitation for mini/micro hydropower plants) is an H2020-SMEs project with a budget of $\simeq$EUR 71,500 (EUR 50,000 covered by EU). It is a short project that ran for five months (1/6/2017–31/10/2017).

As in the previous projects, RIVER-POWER is a hydrokinetic technology of the mini-scale (in this case 50 kW). The project aims at reaching market maturity and competitive prices identical to those of the HyKinetics project (EUR 2000/kW, LCOE$<$EUR cent 7/kWh). The beneficiary is EOL power, an Italian company that aims to advance the current TRL–6 of the technology and introduce it to the market. The main technological advancement foreseen in the project is an innovative design of the vertical axis turbine that will focus on the reduction of the mechanical resistance. This includes placing the support arms out of the water, reducing the passive torque and improving efficiency. The 4 kW prototype was fabricated and tested in 2016.

4.6 HyPump (initial project)

HyPump (Enabling Sustainable Irrigation through Hydro-Powered Pumps for Canals) was an H2020-SMEs-1 project with a budget of ≃EUR 71,500 (EUR 50,000 covered by EU). It was a short project that ran for six months (1/8/2016–31/1/2016). It was the project that proceeded the large-scale HyPump project presented in section §3.11. The objective of this smaller HyPump project was to validate through simulation and modelling the performance of the proposed system and ensure the modular character of the design. This is crucial for producing turnkey solutions and a single universal design for various sites. Moreover, this project validated the business opportunity.

5 R&D overview and impact assessment in non-EU countries

5.1 Hydropower technology development in the U.S.

The DoE promotes hydropower technology development through its Water Power Program and the relevant Water Power Technologies Office. In late 2015, the DoE published its "Quadrennial Technology Review: An Assessment of Energy Technologies and Research Opportunities" (U.S. Department of Energy, 2015). In this report, the DoE outlines both the market and technological challenges as well as explain the factors that are driving changes in the hydropower technology. Accordingly, it underlines the need for SHP to reduce its costs and reach even lower levels of environmental footprint. The required trade-off between energy production and environmental performance requires evolving designs. The cost and economic viability of the latter needs also to be better understood.

As an important factor for the continued operation of existing facilities and new deployment is the development and successful operation of environmental mitigation technologies. Conventional designs are characterized by footprints "that may be too expensive with too many environmental impacts to be acceptable". The National Hydropower Asset Assessment Program uses an innovative spatial analysis to assess the potential for new hydropower development in U.S. streams that do not currently have hydroelectric facilities. This is part of the New Stream-reach Development Resource Assessment, coordinated by the Oak Ridge national laboratory. Low-head hydropower ($<$25 ft or less than $\simeq$7.5 m) is important for new hydro deployment with cost reduction highlighted as priority areas for technology development.

More specifically the DoE underlines the need to integrate environmental mitigation and resilience over climate change into turbine designs. This includes advances computational models for fluid dynamics (including fish kinematics) coupled with laboratory and field testing. Innovations to decrease production cost and increase efficiencies include advanced materials and designs as well as innovative concepts such as monitoring sensors that support flexibility of operation over a range of hydraulic head and flow rates. Finally, the DoE underlines the need to assess the impact of future operational strategies to hydropower equipment and the development-planning of new strategies for O&M.

5.2 Hydropower technology development in Norway

With 32 GW of installed hydropower capacity, Norway is the biggest European hydro producer, after Russia. Hydropower technology development has a long tradition in the country and takes place in the leading research centres.

The Norwegian Hydropower Centre (HydroCen) is the national hub to develop research and education in hydropower technology. It is a cooperation between universities, research institutions, industry and Norwegian authorities. The four pillars of research are hydropower structures, turbines and generators, market and environmental design of hydropower. The main ongoing tasks as far as structures are concerned are the adaptation of new technologies for hydropower tunnels, penstocks and surge chambers as well as developing new approaches for dam construction, safety and handling sediment transport. Research on turbines focuses on fatigues loads and lifetime, variable speed turbines and retrofitting methods for existing PHS stations. Environmental design of hydropower includes WEF nexus approaches, fish protection and social acceptance of hydropower. The Norwegian University of Science and Technology (NTNU) is also involved in research on the dynamic stress of Francis turbines (HiFrancis project), as already mentioned in §3.2.

SINTEF, a leading and independent research organisation that hosts more than 2000 researchers, has a sustained interest in hydropower research. Over the last decade, SINTEF has conducted more than 20 research projects that are directly or indirectly related to hydropower operation[10]. This includes projects for advanced information technology (IT) systems, automation and control of hydropower stations to better utilize the equipment, mitigate risks and prolong their operation lifetime (MonitorX project). In term of hydrological analysis, SINTEF participated in projects for better snow conditions' monitoring and forecasting (SNOWHOW project). Research on environment-friendly hydropower includes balancing energy and water resources (EcoManage project), protecting fisheries and salmon (EnviDORR) and assessing the effects of rapid and frequent flow changes (EnviPEAK project). It is important to note that the main number of projects is dedicated to analysing electricity market mechanisms (PRIBAS, MultiSharm, SOVN projects) and the role of hydro for the integration of RES (HydroBalance, FutureHydro, HydroPEAK projects).

Norway's role in the EU hydropower R&D is also enhanced through national and European Economic Area (EEA) grants. Fifteen MS are eligible for EEA grants and although such grants generally support the implementation of technologically mature projects, they also promote R&D and knowledge transfer. The RONDINE program supports RES projects' R&D also including financing for the refurbishment and construction of SHP plants. In Spain, the design of a prototype 45 MW turbine-generator has been co-financed with €317,752 from EEA (total €2,148,256) and the results of the research were followed by the manufacturing of two innovative systems[11]. In Romania, the Sistemenergetic project (total €742,800) included eight research studies on the implementation of hydropower pilot projects[12]. The Anchor project (total €209,549, €164,956 from EEA) assessed the effects of hydropower on the ecological status of Bulgarian rivers [13]. EEA-Norway grants co-financed an industrial research project in Spain[14] that designed-developed an environmentally-safe system for cleaning hydroelectric grills (total €553,759, €81,908 from EEA).

An additional highlight of Norway's hydropower R&D is the activity of a large number of hydroelectric machinery developers. Norway hosts a large number of leading hydropower companies. Their activities range from designing-development of components to consulting. This high number of actors is also illustrated in the number of Norwegian partners in the analysed EU-funded projects (see Figure 1). This is also due to the steady interest for SHP development in Norway as resulted from a series of major R&D projects funded by the Norwegian government from 1990 and on. Norwegian excellence in SHP deployment is shown by the very high number of small- and mini-scale stations as well as from ongoing collaboration for knowledge transfer with China (Nie, 2010).

---

[10] More information is available at SINTEF website.

[11] More information: https://www.genewsroom.com/press-releases

[12] More information: http://sistemenergetic.ro

[13] More information: https://www.niva.no/en/projectweb/anchor

[14] More information: https://eeagrants.org/project-portal/project/ES02-0063

5.3 Hydropower technology development in Switzerland

Switzerland, hosting 17 GW of hydropower, has a significant tradition in hydropower development and, accordingly, is a leading R&D hub for hydropower. Apart from the independent institutions and universities, the Swiss Competence Center for Energy Research – Supply of Electricity (SCCER-SoE) carries innovative research in the areas of geo-energy and hydropower. It is the connection point for 30 Swiss scientific institutions. Its activities include interconnected research projects with pilot-demonstration applications. Accordingly, ongoing plans include a demo SHP station, controlling the fine sediment release from a reservoir by developing a hydrodynamic mixing device (SEDMIX project) and operating a complex large-scale hydropower scheme (FLEXSTOR project). Specific projects include the "Development of a Decision Making Assistant for Hydropower Project Potential Evaluation and Optimization" (RenovHydro project) and the development of a new mini-scale hydro turbine (DUO TURBO project). DUO TURBO is a counter-rotating micro-turbine that is at a proof-of-concept level of development. The aim is to develop a plug-and-play concept of a power lower than 25 kW, representing a low-cost mini-hydro option. In section §3.10 HydroEnv project, funded by the Swiss government, has already been mentioned as a research project on the Environmental Flow of future hydropower operation.

5.4 Hydropower technology development in China

China is the world leader of hydropower with 341 GW of hydro capacity that continues to increase steadily. Indeed, in 2017 9.12 GW of new hydropower capacities were added (IHA, 2018). The China Institute of Water Resources and Hydropower Research (IWHR) is the main Chinese hydropower research organization. It is a national research institution under the supervision of the Chinese Ministry of Water Resources. Its total 11 research departments cover the whole spectrum of hydropower-related sciences from hydrology and water resources to hydraulic machinery and automation. In October 2017 the National Energy Administration of China published the 13^{th} 5-Year Plan for Hydropower Development[15] that foresees a total 380 GW of hydropower by 2020, of which 40 GW of PHS (Gosens et al., 2017). The 5-year plan for Hydropower Development prioritizes large- and very large-scale projects over smaller-sized ones in order to avoid the environmental impact due to a large number of stations (Gosens et al., 2017). This plan includes two main technology targets: Firstly, to strengthen the cooperation, training and exchanges with Asia, Africa, South America and other countries (in terms of the "one belt, one route" strategy). Moreover, it also includes conducting specific R&D activities such as R&D on seawater PHS (see §5.5) and the establishment of digital water resources management, and a digital hydropower, that promotes smart hydropower stations and smart grid operations. More specifically this includes strengthening the autonomy of major components, improving the level of monitoring and reaching the market maturity of construction and components manufacturing. This target is in-line with an emerging technology that was highlighted in a recent JRC report (Kougias, I. and Moro, A. (eds.), 2018) titled "Modelling and controlling hydraulic turbines and pump-turbines operation by a digital avatar".

---

[15] Available online at: http://zfxxgk.nea.gov.cn/auto87/201611/t20161130_2324.htm (in Chinese)

5.5 Hydropower technology development in Japan

Japan is the fifth largest hydropower market, in terms of capacity ($\simeq$50 GW). It has previously hosted significant hydropower R&D, including the development of the 30 MW Okinawa Yanbaru PHS, a pioneer demonstration plant that was using seawater for energy storage (Cavazzini et al., 2017). This station was operational between 1999 and 2016; it adopted some unique structural features of the mechanical equipment in order to prevent seawater corrosion. The plant was dismantled in mid-2016 as its operation was not economically viable.

Ongoing R&D is currently limited, as the present exercise did not identify specific projects that focus on hydropower. Japan's New Energy and Industrial Technology Development Organization (NEDO) was established in 1980 as a governmental organization promoting new energy technologies[16]. Its 2011-2017 activity does not include hydro-related research, apart from a joint declaration with RusHydro. Similarly, the National Institute of Advanced Industrial Science and Technology (AIST) has not conducted recently hydropower R&D and the hydropower technology is not included among the topics of the renewable energy research centre.

The limited number of R&D activities in Japan are also indicated by the increasing need for technology transfer from EU-based companies. While interest in investing in SHP in Japan has steadily increased, the local know-how is limited. Thus, apart from Tanaka hydropower, Japanese companies working in SHP have shown an interest in foreign hydro-energy technology or create partnerships with foreign companies (EU-Japan Centre for Industrial Cooperation, 2016). This is the case of Japan Small Hydropower Co. that partnered with Mavel, a company based on the Czech Republic, and WWS-Japan a subsidiary of the Austrian manufacturer WWS Wasserkraft.

---

[16] More information is available online at http://www.nedo.go.jp

6 Technology development outlook

6.1 Deployment targets and current progress in EU

Table 2 provides the hydropower capacity targets per MS, as defined in the NREAPs. The first column provides cumulative values of conventional hydropower stations i.e., plants with no pumped storage funcionality. Information is broken down in large-scale hydropower (LHP), small-scale hydropower (SHP) ranging between 1 and 10 MW and mini-scale stations (less than 1 MW).

Table 2: EU national targets for hydropower. Planned power capacities for 2020 in MW.

Country	Conventional hydro total	Mini-scale <1 MW	SHP 1-10 MW	LHP >10 MW
BE	140	9	65	66
BG	2424	50	272	2102
CZ	1097	153	191	753
DK	10	0	10	0
DE	4309	564	1043	2702
EE	8	7	1	0
IE	234	18	20	196
EL	4531	39	216	4276
ES	13,861	268	1917	11,676
FR	23,496	483	1807	21,206
HR	2456	0	100	2356
IT	17,800	650	3250	13,900
CY	0	0	0	0
LV	1550	27	1	1522
LT	141	0	40	101
LU	44	3	41	0
HU	67	6	22	39
MT	0	0	0	0
NL	68	2	21	45
AT	8998	497	794	7707
PL	1152	142	238	772
PT	9548	0	750	8798
RO	7729	109	620	7000
SI	1353	120	57	1176
SK	1812	60	122	1630
FI	3100	30	280	2790
SE	16,317	140	765	15412
UK	4920	0	1060	3860
EU 28	127,165	3377	13,703	110,085

Source: National Renewable Energy Action Plans (NREAPs) (Banja et al., 2013)

Table 3 illustrates the installed hydropower capacity in late 2016, for the different MS. It appears that EU in total requires additional 21.1 GW of conventional hydropower until 2020 in order to reach the NREAPs projections. A large proportion of this is due to the 18.3 GW of LHP that need to be deployed in EU by 2020. EU's environmental regulation and the Water Framework Directive 2000/60/EC (WFD) put constraints on new dam construction. This is particularly important for LHP deployment and makes the licensing a new large-scale project a challenging process. Thus, it is very unlikely that 18.3 GW of LHP can be developed between 2016 and 2020 covering the main gap between the 2016 and NREAPs values.

The targets on the SHP have also not progressed sufficiently, with 3042 MW missing in 2016 installed capacity to reach the 2020 target. Despite the fact that the NREAPs foresee additional installations of 4256 MW for SHP for the 2005-2020 period, until 2016 only 1214 MW of new SHP was added in EU. Given the fact that the target for mini-scale stations was low (just additional 647 MW for the period 2005-2020), it had already been exceeded by 256 MW in 2016.

Table 3: EU national installed capacities of hydropower (2016)

Country	Conventional hydro total	Mini-scale <1 MW	SHP 1-10 MW	LHP >10 MW	Pure PHS	Mixed PHS
BE	115	11	58	46	1310	0
BG	2210	63	258	1889	864	149
CZ	1090	156	181	753	697	475
DK	10	4	6	0	0	0
DE	4573	608	718	3247	5540	1187
EE	6	6	0	0	0	0
IE	237	20	21	196	292	0
EL	2693	35	188	2470	0	699
ES	14,040	279	1668	12,093	3329	2687
FR	18,382	443	1653	16,286	1728	5407
HR	1912	2	35	1875	0	293
IT	14,991	742	2557	11,692	3982	3325
CY	0	0	0	0	0	0
LV	1565	28	1	1536	0	0
LT	117	19	8	90	760	0
LU	34	2	32	0	1296	0
HU	57	4	12	41	0	0
MT	0	0	0	0	0	0
NL	37	0	0	37	0	0
AT	8458	396	936	7126	0	5231
PL	596	93	186	317	1413	376
PT	4389	31	373	3985	0	2571
RO	6377	88	447	5842	92	265
SI	1113	118	37	958	180	0
SK	1608	28	49	1531	916	0
FI	3250	34	273	2943	0	0
SE	16,367	177	784	15,406	0	99
UK	1835	246	180	1409	2444	300
EU28	106,062	3633	10,661	91,768	24,843	23,064

Source: Eurostat Infrastructure, electricity, annual data (nrg_113a)

The columns on the right side of Table 3 provide information for the pure PHS stations and the mixed storage stations, the main source of bulk electricity storage of power systems. Pure PHS, also known as closed-loop pumped hydro, stores water in an upper reservoir and uses it to produce electricity by releasing it to the lower reservoir, with no additional natural (river) inflows. It is opposed to mixed PHS stations (also known as pump-back PHS) that utilize natural river discharge in addition to the released stored water, when in production mode.

At the time the present report was compiled the official Eurostat data for the 2017 installed hydropower capacity was not available. Studies provided by industrial associations (IHA, 2018) show that in 2017, 21.9 GW of hydropower was added globally with the majority installed in East Asia (9.8 GW), South America (4.1 GW) and South and Central Asia (3.3 GW). In EU, 1258 MW of new hydro were reported in 2017, including 1050 MW in Portugal, 112 MW in France. 38 MW in Finland, 32 MW in the United Kingdom, 14 MW in Austria and 12 MW in Romania. 2017 figures, although not verified yet by the official Eurostat data, show that hydropower growth in EU is only moderate. Considering that most (83.4%) of the annual additions were made in Portugal where the 780 MW Frades-2 and the 270 MW Foz Tua PHS projects were put into commission, it becomes clear that hydro development in the other MS is stagnant.

This is also indicated by the fact that the largest hydro stations commissioned in 2017 in EU are pumped storage stations that provide the required flexibility to power systems. Besides, the remaining hydro potential in EU is rather limited. Most of the untapped European hydropower potential lies in the Western Balkan region, where local governments are working to expand the existing capacities and provide balancing services to neighbour countries through interconnections.

6.2 Economics of hydropower

Hydropower generally provides low-cost electricity. Due to its technological maturity, further major cost reductions are not foreseen. As already mentioned, hydropower is a capital-intensive technology with the major part of the investment being required in the early stages of development. Hydropower deployment may require feasibility and environmental impact assessments, planning, design and civil engineering work that increase the construction types up to 7-9 years for conventional LHP (IRENA, 2018). The main cost components for hydropower stations are the civil works and the electro-mechanical equipment. These two cost components represent 75-90% of the total capital costs. In LHP the civil works represent the main part of the CAPEX, while the electro-mechanical equipment represents roughly the 30% of the total cost. However, for SHP the electro-mechanical equipment can represent up to half of the total cost.

The total installation costs for new hydropower projects' development vary significantly according to the scale, the local conditions (e.g. topography, geology, available hydraulic head), the already existing infrastructure (e.g. road, transmission network), design characteristics (e.g. type and height of dam) and other. Moreover, costs vary from country to country and are lower where favourable locations remain unexploited (e.g. China). Moreover, local market conditions (e.g. labour cost) can also play a role. Typically installation costs for a hydro range between less than EUR 1000/kW and can even reach or exceed EUR 6000/kW (Kougias, 2016a).

According to the International Renewable Energy Agency (IRENA) Renewable Cost Database, hydropower installation cost ranged between EUR 450/kW and EUR

3900/kW for the years 2010-2017 (IRENA, 2018). Figure 4 shows this database's values of global weighted average total installed costs, capacity factors and LCOE for hydropower for the period 2010-2017. Higher costs refer to projects at remote sites, far from existing transmission networks, of smaller scale and with no existing infrastructure. It is clear that the weighted average cost does not decrease with time, as the possibilities for technological and market maturities are very limited. As shown in Figure 4, the global weighted average cost increased from EUR 1000/kW in 2010 (USD 1171/kW) to EUR 1350/KW in 2017 (USD 1558/kW).

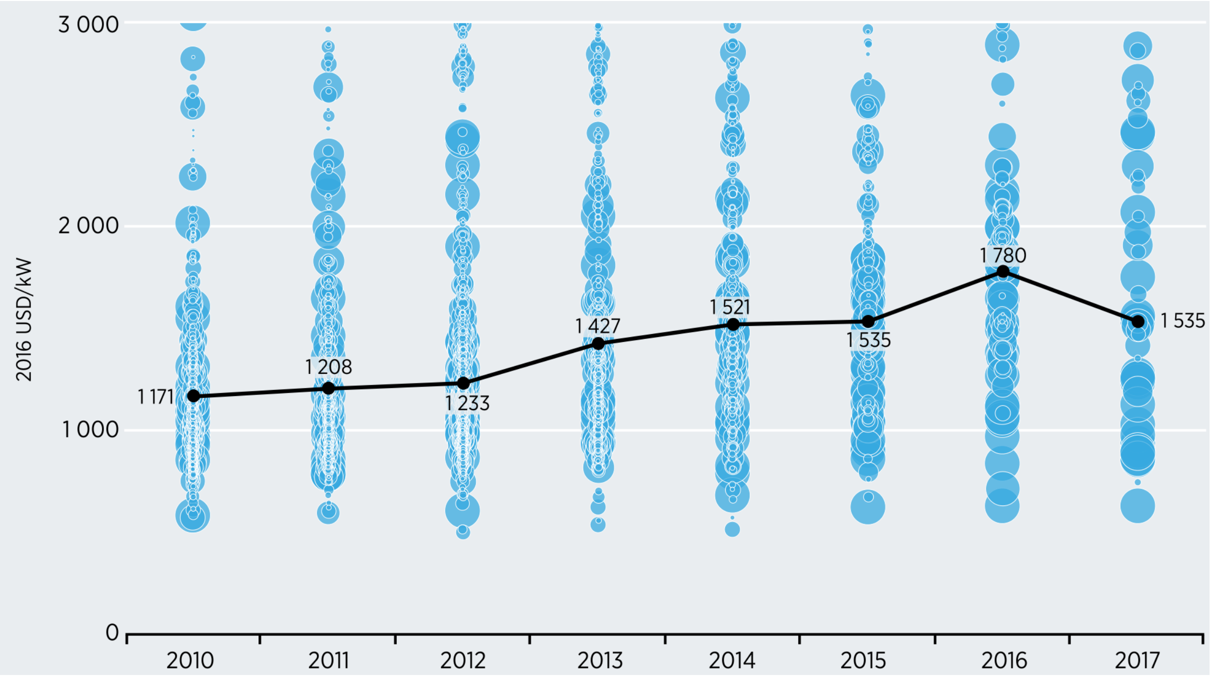

Figure 4: Total installation costs by project and global weighted averages. Source: (IRENA, 2018).

As expected, hydropower development costs are higher in Europe compared to the other regions (see Figure 5). Installation costs in Europe are on average just below EUR 2000/kW and only comparable to the costs of North America. This is due to the lower scale of the developed projects during the studied period (2010-2017) since the vast majority of European projects relates to projects of the small- and mini-scale. Besides, in Europe, almost all the prime locations have been developed a few decades ago. Accordingly, current development utilizes less favourable locations with less attractive techno-economic characteristics. If we only consider projects of the mini-scale (<1 MW), average costs for Europe are EUR 3000/kW (IRENA, 2018). The LCOE for European hydropower stations is EUR 95/MWh, while for stations of the mini-scale is EUR 120/MWh.

Hydropower, generally, has very low OPEX. The particularly long lifetime of hydropower is due to its long-lasting components. The civil works have a lifetime of more than 80 years, the electro-mechanical equipment can operate for 30-40 years, penstocks and tail-races typically last for 50 years or more. Accordingly, the modelling scenario analysis in section 6.3 assumed lifetime for hydropower equal to 60 years. Annual OPEX costs are estimated as a share of the investment cost (EUR/kW/year). Typical values provided by the International Energy Agency (IEA) assume assumes 2.2% for LHP and 2.5% for SHP (IEA, 2010).

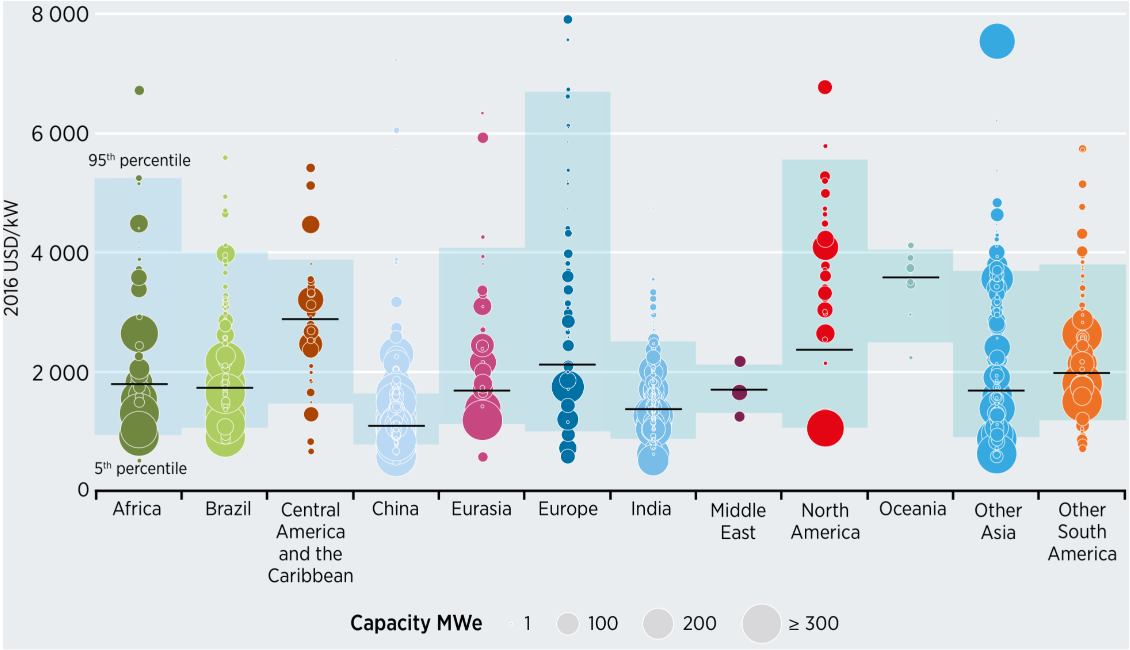

Figure 5: Hydropower's total cost range and weighted average by region. Source: (IRENA, 2018)

6.3 Deployment rates based on different scenarios

The JRC-EU-TIMES model (Simoes et al., 2013) offers a tool for assessing the possible impact of technology and cost developments. It represents the energy system of the EU plus Switzerland, Iceland and Norway, with each country constituting one region of the model. It simulates a series of 9 consecutive time periods from 2005 to 2060, with results reported for 2020, 2030, 2040 and 2050. The model was run with three scenarios:

Baseline: Continuation of current trends; it represents a "business as usual" world in which no additional efforts are taken on stabilising the atmospheric concentration of GHG emissions; only 48% CO_2 reduction by 2050.

Diversified: Usage of all known supply, efficiency and mitigation options (including carbon capture and storage (CCS) and new nuclear plants); 2050 CO_2 reduction target of 80% is achieved.

ProRES: 80% CO_2 reduction by 2050; no new nuclear; no CCS.

In addition, a further 13 sensitivity cases were run and the detailed results are available in (Nijs et al., 2018). The present report focuses on the 3 baseline scenarios and the associated sensitivity cases with high and low learning rates, looking at hydropower deployment in the EU as a whole. Further analysis including country breakdowns will be included in the technology market report.

Specific inputs include: a) CAPEX and fixed OPEX cost trends, together with learning rate values for three hydropower deployment options: RoR, conventional reservoir LHP with advantageous characteristics ("LHP economical") and LHP in less advantageous locations ("LHP expensive"); b) Load factor: country-specific values are included for the available resource in terms of full load hours per year, as well as an upper bound on installed capacity. Simulations do not include PHS, which is considered energy storage technology rather than an energy production one.

Figure 6 shows an overview of the results of the simulations for the three main scenarios. The projected power capacities are provided for years 2020, 2030, 2040 and 2050. Notably, all three scenarios project similar results with very small deviations. Accordingly, the ProRES scenario, in spite of being favourable to RES, does not foresee increased hydropower capacity additions. The overall capacity additions for all the energy technologies are provided in Figure 7. In all three scenarios, the role of hydropower in terms of power capacity remains unchanged.

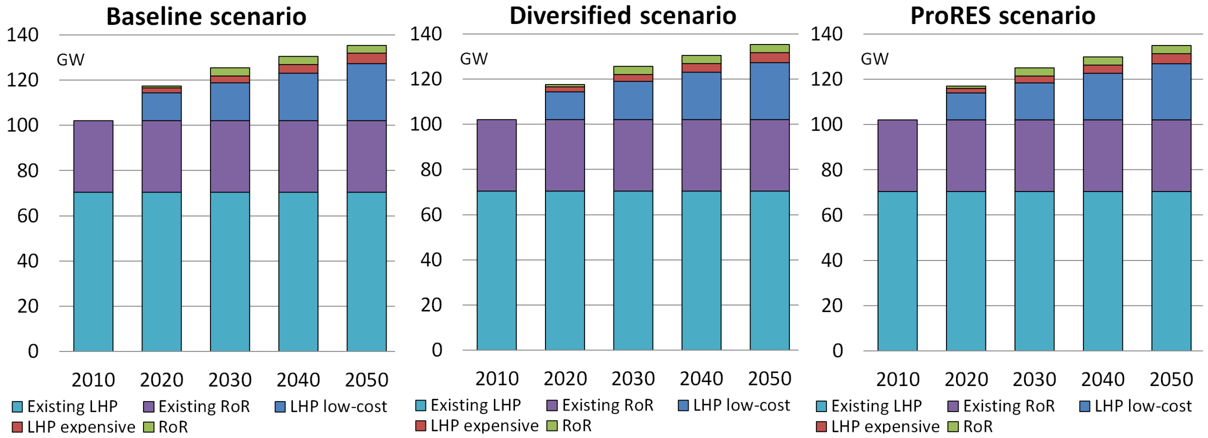

Figure 6: Projections of the total installed hydropower capacity in EU, for three scenarios

This uniform projections for hydropower growth is common in all 15 scenarios analysed by the JRC-EU-TIMES model. Even the ProRES scenario with high technology learning rates projects similar levels of deployment. This is due to the high technological maturity of hydropower that only allows minor improvements.

(a) (b) (c)

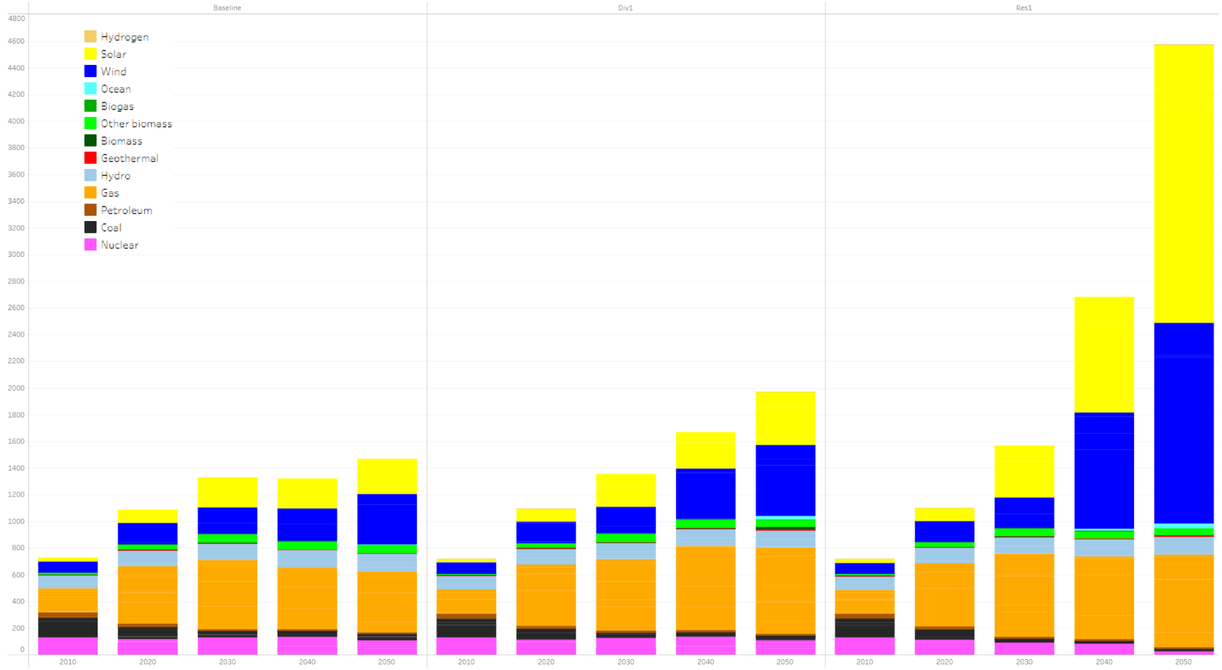

Figure 7: JRC-EU-TIMES model: distribution of power capacity (GW) by technology for the: a) baseline , b) diversified and c) pro-RES scenarios. Hydropower is represented by the light blue segments

JRC-EU-TIMES model provides power capacity projections only for conventional hydropower since PHS is a net consumer of electricity. The model, however, assesses the requirements for PHS indirectly, by analysing the storage needs under the various scenarios. The results show that under the Baseline and Diversified scenarios (Figures 7a, b) the need for additional PHS capacities is negligible. For the Pro-RES scenario, however, storage requirements increase, due to the very high share of variable RES (solar PV, wind) that cover a large share of the consumption (Figure 7c). However, increased storage needs are not followed by proportional increases of PHS capacities. The Pro-RES scenario assumes that technological breakthroughs will make cost-competitive the alternative storage technologies (batteries, hydrogen) in the mid-term. Accordingly, JRC-EU-TIMES anticipates only negligible PHS deployment under all three analysed scenarios.

6.4 Barriers to large-scale deployment

An important barrier to large-scale deployment is the existing measures to protect the environment and river ecology that hamper new dam construction in EU rivers. This is due to the effort to simultaneously pursue RES and environmental goals, as described in the EU Renewable Energy Directive (RED) and the WFD. This explains why hydropower lies at a crossroad between being considered a RES and a local environmental challenge that may result in degradation of river ecosystems and local biodiversity (Abazaj et al., 2016). Hydropower deployment is affected by the WFD, despite the fact that is not directly by this legal framework. The WFD aims at securing a good ecological status of EU water bodies and the irreversible changes that a dam imposes on rivers create a conflicting situation. The increased targets (32%) for clean energy's share in the final mix by 2030 (European Commission, 2018) further increase hydropower's role to achieve the set goals.

The impact of hydropower development on local ecosystems creates the necessity to involve the local authorities in decision making. Accordingly, local authorities are generally granted the responsibility to manage watercourse use rights for hydropower. European legislation on granting/renewing hydropower licensing is fragmented and varies among the various MS. Rights' duration varies from few years (e.g. United Kingdom) to indefinite contracts (e.g. Sweden). The processes to provide and renew licenses also vary among the MS; in some countries, competitive tenders are organised, while in others such a process is not required (Glachant et al., 2015). The current status creates two main barriers to hydropower deployment: complexity and uncertainty. Both barriers are particularly important for hydropower due to the high upfront investments that are required. Accordingly, long and complicated licensing processes significantly increase the investment risk of a hydropower project.

This is particularly important for the SHP stations that do not benefit from economies of scale of conventional LHP with a dam. A general rule is that the smaller the nominal power capacity and the more natural the watercourse, the less favourable is the investment (DG Environment, Management of Natura 2000 sites, 2018). Their installation cost is generally higher than that of LHP and delays in commissioning are a significant threat. Besides, the implementation of SHP projects is often managed by small companies that do not always have the means (resources, capital, manpower, expertise) to cope with long and complex procedures. Over the last years, the EU policy directions have focused on prioritizing the deployment of

SHP and run-of-river hydropower plants. This is due to their low environmental impact and the abundance of untapped locations. To date, the set targets for SHP (see Table 2) can be characterised as rather modest.

One reason for their limited ambition may be the very different available untapped SHP potential in the various MS (Patsialis et al., 2016). This is clearly shown in Figure 8, where some MS have fully utilized their SHP potential (e.g. Denmark, Sweden, Spain), while many others (e.g Italy, Greece, UK) have large non-utilised capacities[17]. This very different situation among MS leads to very different priorities among the various stakeholders and perhaps makes it difficult to reach a common direction on implementation policies. Taking into account that the available SHP potential in ten MS is insignificant, explains the comparably lower interest for SHP deployment.

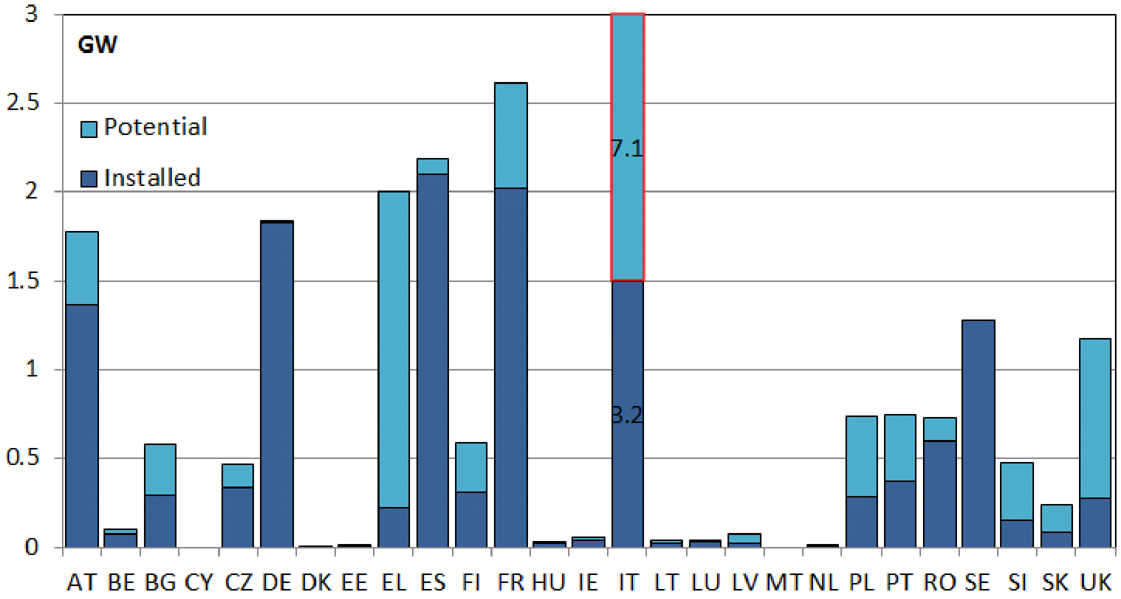

Figure 8: Utilization of the existing small-scale hydropower potential in the MS. Source: (International Center on Small Hydro Power, 2016).

The definition of SHP is not consistent among the national legislation of the MS. The nominal power capacity threshold varies significantly among the various countries and ranges between 1.5 MW and 15 MW (Glachant et al., 2015). The threshold that is generally used in EU-level is that of 10 MW. Some analysts raise the cumulative effect that even SHP can have. This particularly stated in MS policies related to virtually undisturbed waters, or those where re-naturalisation is planned, where the use of hydropower should be renounced (DG Environment, Management of Natura 2000 sites, 2018), even if it refers to small-scale installations. The cumulative ecological effect of mini-scale hydros mainly lies in the need to deploy a large number of them in order to have a meaningful effect from the energy and GHG emissions point of view. Indeed, out of the 23,000 installed station in EU 91% is SHP, but it only produces the 13% of the total hydroelectric production (DG Environment, Management of Natura 2000 sites, 2018). The remaining 9% of stations are LHP producing the vast majority (87%) of hydroelectricity.

---

[17] Installations and available potential of Italy have been scaled down to facilitate visualization.

6.5 Pumped hydropower storage

PHS is undoubtedly the most mature bulk electricity storage technology and the majority of its components and equipment has already reached a TRL–9. The present report did not identify an EU-funded project that focuses exclusively on PHS. This is contrary to the previous report (Kougias, 2016a), where ESTORAGE project (EUR 23 million) studied the possible conversion of fixed-speed PHS to variable-speed.

The need for operational flexibility of existing or new PHS stations plants creates a market that is expected to mobilise the further development of PHS technology. Besides, there still exists a significant potential to further develop the variable speed technology that allows changing the turbine's speed while in pumping mode. This makes it possible to alter the consumption rate and –more importantly– provide grid stability and frequency regulation. The presently limited range of this variation (± 10%) allows for further improvements (up to ± 100%). Developing, thus, a new generation of pump-turbines will increase the regulation capacity in pumping mode (EASE-EERA, 2017).

An additional obstacle for PHS development is the existing limitations on suitable sites. It is still a challenge to install very high-head (>700m) or relatively low-head (<100m) PHS. Utilizing such locations at a competitive cost will substantially increase the investment opportunities for PHS.

Developing new technologies for the deployment of non-typical PHS may also create new opportunities. This includes known concepts that need to be further developed such as small-scale PHS, new PHS in connection to existing reservoirs and PHS deployment in abandoned mines/caverns.

7 Conclusions and recommendations

The wide range of operation and flexibility is a topic that has been placed very high on the hydro R&D agenda and it was the topic of recent projects (Hyperbole, Hydroflex). It is also expected to be the focus of future projects as highlighted in the emerging technologies analysis (Kougias et al., 2019). This topic includes the future balancing role of hydropower inside the power systems as well as the role of PHS. A recent analysis of the EU PHS sector revealed that existing stations are often under-utilized (Kougias and Szabó, 2017), mainly due to unfavourable market conditions. This clearly shows that future PHS development might be limited and the conventional hydropower stations will be required to provide advanced levels of flexibility. The latter may need to be done under increased uncertainties, also due to climate change.

Indeed, a field that has attracted a lot of attention is hydropower's climate resilience. This is also highlighted in the recent reports (IHA, 2016, IHA, 2017) of the International Hydropower Association (IHA), where the findings of a survey implemented in collaboration with the World Bank (WB) are presented. Almost all respondents (98%), that represent 50 organisations involved in the hydropower sector, agreed that climate change impacts are already being felt or will be felt within the next 30 years by their organisation. The objective of the IHA–WB initiative is to develop a tool that promotes climate resilience in the design and operation of hydro projects, a target very much connected to the objectives of projects analysed in this report (e.g. BINGO project).

Industry-led organisations recognise the risks that climate change imposes on both the financial viability of future hydropower projects and the operation of existing ones. Accordingly, the industry has planned specific activities to increase hydropower's climate resilience, with the latest ones published in mid-2018, during the compilation of the present report. In its report (IHA, 2018), IHA outlines the project to design specific guidelines jointly with the WB and the European Bank for Reconstruction and Development (EBRD). The aim of these *Hydropower Sector Climate Resilience Guidelines* will be to provide practical information for all phases of a hydro station's life, from appraisal and design to construction and operation. Following a testing period, the guidelines will be published in mid-2019. Members of the IHA have also tested a fairly new technology solution that increases the discharge capacity of spillways to address extreme flood events, namely the piano key weir (Schleiss, 2011).

Thus, while hydropower operation provides GHG-free electricity and mitigates the effects of climate change, it is affected by the climate's increasing variability. The importance of this lies in the increased stress on reservoir operation strategies, advanced levels of risks for flood risk and failure of machinery or even the construction. Moreover, it increases the uncertainty of future electricity production, which is crucial for estimating future projects' economic viability and take financing-investment decisions. Resilience against such hazards is, thus, essential and needs to be supported by science-based evidence also led by independent organisations. Such unbiased research would quantify the probability and magnitude of the hazard and would allow understanding if, where and how the required interventions need to be implemented.

Exploiting locations with a low- and very low-hydraulic head is a common aim of numerous research and deployment activities. This is due to the fact that the percentage of untapped low-head potential in Europe is large. Low-head technologies are generally considered at sufficient maturity and technically feasible for most of the cases. However, the available technologies are not always economically viable or profitable. Accordingly, a priority is given to economic analysis, aiming at cost-reduction strategies that will enhance the role of low-head hydropower. An additional reason for that is the minimal environmental impact of such hydro stations that do not involve the construction of a dam. So far, hydro equipment manufacturers have mainly given priority to size and cost reductions. It is, however, essential to prioritize the costs of civil works and the development of new, cost-effective methods that can be replicated.

The innovation of hydropower's electro-mechanical equipment definitely needs to involve a higher degree of digitalisation. The majority of existing hydroelectric facilities built decades ago, use obsolete automation and control systems. Hydros' operation and management need to follow the progress of the IT sector and –on one hand– bring advancements in data availability-accuracy, analytical methods, simulation and operation strategies. On the other hand, such advancements will provide advanced levels of flexibility, secure operation at dynamic loads and frequent start/stop and increase lifetime. Equally important is providing high levels of cybersecurity and threat that causes increasing concern (Lee and Lim, 2016) among those involved in the hydropower field.

Overall, Europe is clearly driving the technology development of the global hydropower sector. EU-based institutions in collaboration with those of Switzerland and Norway are among the world leaders in hydropower R&D. This central role has been maintained despite the very limited large-scale hydropower development in EU over the last decades. In terms of hydropower component manufacturing, global leader companies are based in EU (e.g. Voith in Germany, Andritz in Austria). These companies, together with numerous smaller ones, are global suppliers of electro-mechanical components and services for hydropower both directly and through subsidiaries. Technological advancements and a supporting policy framework are needed to maintain EU's leading role in hydropower R&D. Moreover, a supporting framework can ensure that hydropower will contribute in realizing the future low-carbon energy system in a way compatible with the ecological conservation requirements. The provided flexibility for the power systems, PHS uniqueness for providing bulk electricity storage services, along with the significant amounts of low-carbon hydroelectricity are essential elements in reaching the energy and climate goals (European Commission, 2018) both at EU-level and globally.

References

Abazaj, J., 'Coherence issues between climate, energy and water in the case of european hydropower: Can we have it all?' In 'Legal Aspects of Sustainable Development', Springer, 2016. pp. 347–370.

Abazaj, J., Moen, Ø. and Ruud, A., 'Striking the balance between renewable energy generation and water status protection: hydropower in the context of the european renewable energy directive and water framework directive', *Environmental Policy and Governance*, Vol. 26, No 5, 2016, pp. 409–421.

Al-Smairan, M., 'Application of photovoltaic array for pumping water as an alternative to diesel engines in Jordan Badia, Tall Hassan station: Case study', *Renewable and Sustainable Energy Reviews*, Vol. 16, No 7, 2012, pp. 4500–4507.

Ali, M., 'Practices of Irrigation & On-farm Water Management', edited by M. Ali, Springer-Verlag, New York, US, 2011.

Banja, M., Scarlat, N., Monforti-Ferrario, F. and Dallemand, J.-F., 'Renewable energy progress in eu 27 (2005–2020)', *Ispra, Italy: Joint Research Centre*, 2013.

Barlow, R., McNelis, B. and Derrick, A., 'Status and experience of solar PV pumping in developing countries', In 'Tenth EC Photovoltaic Solar Energy Conference', Springer, pp. 1143–1146.

Bråtveit, K., Bruland, A. and Brevik, O., 'Rock falls in selected Norwegian hydropower tunnels subjected to hydropeaking', *Tunnelling and Underground Space Technology*, Vol. 52, 2016, pp. 202–207.

CanmetENERGY, 'An Emerging Hydropower Technology (EHT) R&D in Canada: A strategy for 2007-2011', Tech. rep., Natural Resources Canada, December 2007.

Cavazzini, G., Pérez-D*ι*az, J. I., Blázquez, F., Platero, C., Fraile-Ardanuy, J., Sánchez, J. A. and Chazarra, M., 'Pumped-storage hydropower plants: The new generation', *Energy Storage*, Vol. 4, 2017, p. 27.

DG Environment, Management of Natura 2000 sites, 'Guidance on the requirements for hydropower in relation to EU Nature legislation', Tech. rep., European Commission, June 2018.

EASE-EERA, 'European energy storage technology development roadmap', *European Association for Storage of Energy & European Energy Research Alliance*, 2017.

Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Kadner, S., Zwickel, T., Eickemeier, P., Hansen, G., Schlömer, S. and von Stechow, e., Christoph, 'IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation: Hydropower', Tech. rep., Intergovernmental Panel on Climate Change (IPCC), 2012.

EU-Japan Centre for Industrial Cooperation, 'Japan industry and policy news'. 2016. Accessed online at 27/5/2018: https://www.eu-japan.eu/news/japan-industry-and-policy-news-renewable-energy-2016.

European Commission, 'Europe leads the global clean energy transition: Commission welcomes ambitious agreement on further renewable energy development in the EU'. June 2018.

Fearnside, P. M., 'Emissions from tropical hydropower and the ipcc', *Environmental science & policy*, Vol. 50, 2015, pp. 225–239.

Fearnside, P. M., 'Tropical dams: To build or not to build?', *Science*, Vol. 351, No 6272, 2016, pp. 456–457.

Glachant, J., Saguan, M., Rious, V. and Douguet, S., 'Regimes for granting the right to use hydropower in Europe', Research Reports, European University Institute, Florence School of Regulation, 2015.

Gonzalez-Salazar, M. A., Kirsten, T. and Prchlik, L., 'Review of the operational flexibility and emissions of gas-and coal-fired power plants in a future with growing renewables', *Renewable and Sustainable Energy Reviews*, 2017.

Gosens, J., Kåberger, T. and Wang, Y., 'China's next renewable energy revolution: goals and mechanisms in the 13th five year plan for energy', *Energy Science & Engineering*, Vol. 5, No 3, 2017, pp. 141–155.

Grumbine, R. E. and Xu, J., 'Mekong hydropower development', *Science*, Vol. 332, No 6026, 2011, pp. 178–179.

IEA, 'Energy technology perspectives 2010: Scenarios and strategies to 2050', Tech. rep., International Energy Agency, Paris, 2010.

IHA, 'Hydropower Status Report', Tech. rep., International Hydropower Association, Central Office team, London, United Kingdom, 2015.

IHA, 'Hydropower Status Report', Tech. rep., International Hydropower Association, Central Office team, London, United Kingdom, 2016.

IHA, 'Hydropower Status Report', Tech. rep., International Hydropower Association, Central Office team, London, United Kingdom, 2017.

IHA, 'Hydropower Status Report', Tech. rep., International Hydropower Association, Central Office team, London, United Kingdom, 2018.

International Center on Small Hydro Power, 'World small hydropower development report', Executive Summary, United Nations Industrial Development Organization, 2016.

IRENA, 'Renewable energy technologies: Cost analysis series', 3/5 Hydropower Vol.1 Power Sector, International Renewable Energy Agency, June 2012.

IRENA, 'Renewable power generation costs in 2017', Tech. rep., International Renewable Energy Agency, Abu Dhabi, June 2018.

Kougias, I., 'Technology Development Report, Hydropower Energy', *JRC Science for Policy Report*, 2016a, pp. 1–51. JRC102278. Low Carbon Energy Observatory Deliverable 2.1.

Kougias, I., 'Technology Market Report, Hydropower Energy', *JRC Science for Policy Report*, 2016b, pp. 1–43. JRC102277. Low Carbon Energy Observatory Deliv. 4.1.

Kougias, I., Aggidis, G., Avellan, F., Deniz, S., Lundin, U., Moro, A., Muntean, S., Novara, D., Pérez-Díaz, J. I., Quaranta, E., Schild, P. and Theodossiou, N., 'Analysis of emerging technologies in the hydropower sector', *Renewable and Sustainable Energy Reviews*, Vol. 113, 2019, p. 109257.

Kougias, I., Karakatsanis, D., Malatras, A., Monforti-Ferrario, F. and Theodossiou, N., 'Renewable energy production management with a new harmony search optimization toolkit', *Clean Technologies and Environmental Policy*, Vol. 18, No 8, 2016a, pp. 2603–2612.

Kougias, I., Katsifarakis, L. and Theodossiou, N., 'Medley multiobjective harmony search algorithm: Application on a water resources management problem', *European Water*, Vol. 39, 2012, pp. 71–52.

Kougias, I., Patsialis, T., Zafirakou, A. and Theodossiou, N., 'Exploring the potential of energy recovery using micro hydropower systems in water supply systems', *Water Utility Journal*, Vol. 7, 2014, pp. 25–33.

Kougias, I. and Szabó, S., 'Pumped hydroelectric storage utilization assessment: Forerunner of renewable energy integration or Trojan horse?', *Energy*, Vol. 140, 2017, pp. 318–329.

Kougias, I., Szabó, S., Monforti-Ferrario, F., Huld, T. and Bódis, K., 'A methodology for optimization of the complementarity between small-hydropower plants and solar pv systems', *Renewable Energy*, Vol. 87, 2016b, pp. 1023–1030.

Kougias, I., Szabó, S., Scarlat, N., Monforti-Ferrario, F., Banja, M., Bódis, K. and Moner-Girona, M., 'Water-Energy-Food nexus interactions assessment: Renewable energy sources to support water access and quality in West Africa', JRC Technical Reports, EC Joint Research Centre, 2018. doi: 10.2760/1796.

Kougias, I. and Moro, A. (eds.), 'Emerging technologies in the hydropower sector', *JRC Conference and Workshop Reports*, 2018, pp. 1–47. JRC111048. Low Carbon Energy Observatory Deliverable 360.

Kumar, P. and Saini, R., 'Study of cavitation in hydro turbines—a review', *Renewable and Sustainable Energy Reviews*, Vol. 14, No 1, 2010, pp. 374–383.

Lee, K.-b. and Lim, J.-i., 'The Reality and Response of Cyber Threats to Critical Infrastructure: A Case Study of the Cyber-terror Attack on the Korea Hydro & Nuclear Power Co., Ltd.', *KSII Transactions on Internet & Information Systems*, Vol. 10, No 2, 2016.

Mekonnen, M. and Hoekstra, A. Y., 'The blue water footprint of electricity from hydropower', *Hydrology and Earth System Sciences*, Vol. 16, No 1, 2012, pp. 179–187.

Naudé, W. and Matthee, M., 'Short-Term Energy Outlook (STEO)', Independent Statistics and Analysis, U.S. Energy Information Administration, April 2018.

Nie, L., 'Hydropower development in Norway, and opportunities to cooperate with China', Tech. rep., Centre for Environment-Friendly Energy Research, May 2010.

Nijs, W., P, R. C., Tarvydas, D., Tsiropoulos, I. and Zucker, A., 'Deployment Scenarios for Low Carbon Energy Technologies', *JRC Science for Policy Report*, 2018, pp. 1–52. EUR 29496 EN. Low Carbon Energy Observatory Deliverable 4.7.

Palmer, M. A., 'Water resources: beyond infrastructure', *Nature*, Vol. 467, No 7315, 2010, p. 534.

Patsialis, T., Kougias, I., Kazakis, N., Theodossiou, N. and Droege, P., 'Supporting renewables' penetration in remote areas through the transformation of nonpowered dams', *Energies*, Vol. 9, No 12, 2016, p. 1054.

Pelicice, F. and Agostinho, A. A., 'Fish-passage facilities as ecological traps in large neotropical rivers', *Conservation biology*, Vol. 22, No 1, 2008, pp. 180–188.

Poff, N. L., Brown, C. M., Grantham, T. E., Matthews, J. H., Palmer, M. A., Spence, C. M., Wilby, R. L., Haasnoot, M., Mendoza, G. F., Dominique, K. C. et al., 'Sustainable water management under future uncertainty with eco-engineering decision scaling', *Nature Climate Change*, Vol. 6, No 1, 2016, p. 25.

Schleiss, A., 'From labyrinth to piano key weirs: A historical review', In 'Proc. Int. Conf. Labyrinth and Piano Key Weirs Liège B', pp. 3–15.

SET-Plan, 'The Integrated Roadmap: Part II – Competitive, Efficient, Secure, Sustainable and Flexible Energy System', Tech. rep., European Commission, 2014. Annex I: Research and innovation actions.

SET-Plan, 'Implementation Plan', Tech. rep., European Commission, January 2018. Increase the resilience and security of the energy system.

Simoes, S., Nijs, W., Ruiz, P., Sgobbi, A., Radu, D., Bolat, P., Thiel, C. and Peteves, S., 'The jrc-eu-times model', *Assessing the long-term role of the SET Plan Energy technologies, JRC Scientific and Policy Reports*, 2013.

Stevens, Lucy, 'Poverty and the water-energy nexus'. `https://practicalaction.org/blog/where-we-work/kenya/poverty-and-the-water-energy-nexus/`, March 2014. Accessed: 2017-09-07.

Szabó, S., Moner-Girona, M., Kougias, I., Bailis, R. and Bódis, K., 'Identification of advantageous electricity generation options in sub-Saharan Africa integrating existing resources', *Nature Energy*, Vol. 1, No 10, 2016, p. 16140.

Tang, W., 'Energy: Holistic hydropower scheme for China', *Nature*, Vol. 532, No 7597, 2016, p. 37.

U.S. Department of Energy, 'An Assessment of Energy Technologies and Research Opportunities', Quadrennial Technology Review, Office of the Under Secretary for Science and Energy, September 2015.

Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S. E., Sullivan, C. A., Liermann, C. R. et al., 'Global threats to human water security and river biodiversity', *Nature*, Vol. 467, No 7315, 2010, p. 555.

Whiteman, A., Sohn, H., Esparrago, J., Arkhipova, I. and Elsayed, S., 'Renewable Capacity Statistics', Tech. rep., International Renewable Energy Agency (IRENA), 2018.

Winemiller, K. et al., 'Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong', *Science*, Vol. 351, No 6269, 2016, pp. 128–129.

Yuce, M. I. and Muratoglu, A., 'Hydrokinetic energy conversion systems: A technology status review', *Renewable and Sustainable Energy Reviews*, Vol. 43, 2015, pp. 72–82.

List of Acronyms

AIST	National Institute of Advanced Industrial Science and Technology
CCS	carbon capture and storage
CAPEX	capital expenditure
CFD	computational fluid dynamics
DG RTD	Directorate-General for Research and Innovation
DoE	U.S. Department of Energy
EBRD	European Bank for Reconstruction and Development
EC	European Commission
EEA	European Economic Area
EFSI	European Fund for Strategic Investments
ESHA	European Small Hydropower Association
EU	European Union
FP7	EC Seventh Framework Programme
GHG	greenhouse gas
GW	gigawatt
HydroCen	Norwegian Hydropower Centre
H2020	Horizon 2020
IEA	International Energy Agency
IHA	International Hydropower Association
IRENA	International Renewable Energy Agency
IT	information technology
IWHR	China Institute of Water Resources and Hydropower Research
JRC	EC Joint Research Centre
KIC	Knowledge and Innovation Community
kW	kilowatt
LCEO	Low Carbon Energy Observatory

LCOE	levelised cost of energy
LHP	large-scale hydropower
MHK	marine and hydrokinetic
MS	EU member state
MW	megawatt
NEDO	New Energy and Industrial Technology Development Organization
NREAPs	National Renewable Energy Action Plans
NREL	National Renewable Energy Laboratory
NTNU	Norwegian University of Science and Technology
OCGT	open cycle gas turbine
O&M	operation and maintenance
OPEX	operation expenses
PHS	pumped hydropower storage
R&D	research and development
RED	Renewable Energy Directive
RES	renewable energy sources
RoR	run-of-the-river
SCCER-SoE	Swiss Competence Center for Energy Research – Supply of Electricity
SET-Plan	Strategic Energy Technology Plan
SHP	small-scale hydropower
SMEs	small-medium enterprises
SSA	sub-Saharan Africa
TRL	technology readiness level
U.S.	United States
WB	World Bank
WEF	water-energy-food
WEFE	Water-Energy-Food-Ecosystems NEXUS
WFD	Water Framework Directive 2000/60/EC

Annex List of participant organisations

CaFE	City University Of London	United Kingdom
	Chalmers Tekniska Hoegskola Ab	Sweden
	Technische Universiteit Delft	Netherlands
	Technische Universitaet Muenchen	Germany
	Institut Polytechnique De Grenoble	France
	Waertsila Netherlands B.V.	Netherlands
	Delphi Diesel Systems Ltd	United Kingdom
ECO-DRILLING	Avl List Gmbh	Austria
HydroFlex	Norhard As	Norway
	NTNU	Norway
	Lulea Tekniska Universitet	Sweden
	Uppsala Universitet	Sweden
	Chalmers Tekniska Hoegskola Ab	Sweden
	Sintef Energi As	Norway
	Lyse Produnited Kingdomsjon As	Norway
	Rainpower Norge As	Norway
	Vattenfall Ab	Sweden
	Statkraft Energi As	Norway
	Stiftelsen Norsk Institutt For Naturforskning Nina	Norway
	University Of Strathclyde	United Kingdom
	Ss. Cyril And Methodius University	North Macedonia
	Abb As	Norway
	Rheinisch-Westfaelische Tech. Hochs.	Germany
	Multiconsult Norge As	Norway
Hydrolowhead	Edr & Medeso As	Norway
	Tecnoturbines S.L.	Spain
DP Renewables	Sendekia Arquitectura-e Ingenieria Sostenible Sl	Spain
FIThydro	Dp Designpro Limited	Ireland
	Technische Universitaet Muenchen	Germany
	Assoc. Do Inst. Superior Tecn. Para A Investigacao E Desenvolvimento	Portugal
	Centre National De La Recherche Scientifique Cnrs	France
	Centro Tecnologico Agrario Y Agroalimentario Asociacion	Spain
	ETH Zuerich	Switzerland
	Forschungsverbund Berlin Ev	Germany
	NTNU	Norway
	Sintef Energi As	Norway
	Tallinna Tehnikaulikool	Estonia
	University Of Hull	United Kingdom
	Ecologic Inst.itut Gemeinnützige	Germany
	Sje Ecohydraulic Engineering	Germany
	Eigen Vermogen Van Het Instituut Voor Natuur- En Bosonderzoek	Belgium
	Af Consult Switzerland Ag	Switzerland
	Bayerische Elektrizitatswerke	Germany
	Bkw Energie Ag	Switzerland
	Hidroerg-Projectos Energeticos	Portugal
	Flussbau Ic Gesmbh	Austria
	Limmatkraftwerke Ag	Switzerland
	Peter Armin	Switzerland
	C H Salto De Vadocondes Sa	Spain
	Statkraft As	Norway
	Uniper Kraftwerke Gmbh	Germany
	Verbund Hydro Power Gmbh	Austria
	Voith Hydro Holding Gmbh & Co Kg	Germany
HyPump	Stichting Water Footprint Network	Netherlands
	Aqysta Holding Bv	Netherlands

EUROFLOW	Sweco Norge As	Norway
	University Of Leeds	United Kingdom
	Universidad De Cantabria	Spain
	eawag	Switzerland
	Norsk Institutt For Vannforskning	Norway
	The University Of Birmingham	United Kingdom
	Forschungsverbund Berlin Ev	Germany
	Stichting IHE Delft	Netherlands
	Helmholtz-Zentrum Fuer Umweltforschung Gmbh-Ufz	Germany
	Universita Degli Studi Di Trento	Italy
BINGO	Natural Environment Research Council	United Kingdom
	Laboratorio Nacional De Engenharia Civil	Portugal
	Kwr Water B.V.	Netherlands
	IWW Zentrum Wasser	Germany
	Aquatec Proyectos Para El Sector Del Agua Sa	Spain
	NTNU	Norway
	Interwies Eduard	Germany
	Freie Universitaet Berlin	Germany
	Sociedade Portuguesa De Inovacao	Portugal
	The Cyprus Institute	Cyprus
	I.A.Co Environmental And Water Consultants	Cyprus
	Epal-Empresa Portuguesa Das Águas Livres, Sa	Portugal
	Comunidade Intermunicipal Da Leziria Do Tejo	Portugal
	Ajuntament De Badalona	Spain
	Aigues De Barcelona	Spain
	Vitens Nv	Netherlands
	Wupperverband	Germany
	DG De Agricultura E Desenvolvimento Rural	Portugal
	Area Metropolitana De Barcelona	Spain
	Gelderland	Netherlands
DAFNE	Bergen Kommune	Norway
	ETH Zürich	Switzerland
	Politecnico Di Milano	Italy
	Int. Center For Res. on the Envir. & Economy	Greece
	Katholieke Universiteit Leuven	Belgium
	University Of Aberdeen	United Kingdom
	Universitaet Osnabrueck	Germany
	International Water Management Institute	Sri Lanka
	African Col. Centre For Earth System Science	Kenya
	University Of Zambia	Zambia
	Universidade Eduardo Mondlane	Mozambique
	Vista Geowissenschaftliche Fernerkundung	Germany
	Atec-3d Ltd	United Kingdom
	European Institute For Participatory Media	Germany
IMPREX	Water And Land Resource Center	Ethiopia
	Koninklijk Nederlands Meteorologisch Instituut	Netherlands
	Europ. Centre For Medium-Range Weather Forecasts	United Kingdom
	Sveriges Meteorologiska Och Hydrologiska Inst.	Sweden
	Irstea MOBILE	France
	Potsdam Institut Fuer Klimafolgenforschung	Germany
	Arctik Sprl	Belgium
	Barcelona Supercomputing Center	Spain
	Met Office	United Kingdom
	Polytechneio Kritis	Greece
	The University Of Reading	United Kingdom
	Helmholtz-Zentrum Geesthacht	Germany
	Stichting Deltares	Netherlands
	Stichting Vu	Netherlands
	Adelphi Research Gemeinnutzige Gmbh	Germany
	Hkv Lijn In Water Bv	Netherlands
	Futurewater Sl	Spain
	Cetaqua, Centro Tecnologico Del Agua	Spain
	Universitat Politecnica De Valencia	Spain
	Politecnico Di Milano	Italy
	Centro Int. In Monitoraggio Ambientale	Italy
	Helmholtz Zentrum Potsdam	Germany
	Bundesanstalt Fuer Gewaesserkunde	Germany

KJ-BK-19-006-EN-N

JRC Mission

As the science and knowledge service of the European Commission, the Joint Research Centre's mission is to support EU policies with independent evidence throughout the whole policy cycle.

EU Science Hub
ec.europa.eu/jrc

@EU_ScienceHub
EU Science Hub - Joint Research Centre
Joint Research Centre
EU Science Hub

Publications Office

doi:10.2760/49932

ISBN 978-92-76-12437-5