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LOW CARBON ENERGY OBSERVATORY

HYDROPOWER
Technology development report

Joint Research Centre

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Contents

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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
- 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

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 gathers the most recent advances in hydropower technology. It is a deliverable of the Low Carbon Energy Observatory (LCEO), one of the European Commission (EC) projects, which assesses the technological progress of clean energy sources. A follow-up of the previous LCEO assessment (Kougias, 2019a), this report presents important research activities related to hydropower in the EU and abroad. Because operational hydroelectric facilities are complex systems that draw from different areas and scientific fields, great effort has been put into monitoring the broad range of research and development (R&D) activities of the sectors involved. Thus, besides focusing on technological projects, the report also touches upon studies that seek to improve the simulations of the 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 by Horizon 2020 (H2020), the present exercise screened other relevant projects supported by the national research councils of countries with a strong tradition in hydropower, including the U.S. Department of Energy (DoE) and the hydropower research organizations of Norway and Switzerland.

The activities identified fall into four main categories. The first category deals with efforts to increase the range of operation and flexibility of hydropower, which have been significant for some time, as identified in both this and the previous reports (Kougias, 2016, 2019a). It relates to projects on hydraulic design and hydropower mechanical equipment aiming at advancing the construction and operational characteristics of hydro stations, including advanced materials and computational models to minimise machinery wear. The second category deals with the generally untapped low-head hydropower with R&D efforts extending to the advanced technical characteristics of hydrokinetic turbines and reaching competitive levels of cost. A third group of activities looks at projects that assess the environmental and ecological impact of hydropower plants with strong focus on fish population, fish-friendly turbines, sediment transport, and the issue of securing the required environmental flows to allow ecological conservation. The final category includes projects that create forums and collaboration channels between hydropower stakeholders. Their aim is to generate a common hydropower strategy that identifies priorities and coordinates activities within the hydropower sector.

1 Introduction

Hydropower technology has provided clean energy for more than a century and is regarded a mature low carbon energy technology. Technological progress and R&D focus on improving the operation of existing and future hydro facilities rather than radically transforming hydropower technology. This is the main difference between hydropower and modern 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 tandem perovskite solar cells), hydropower technology mainly seeks marginal improvements, while major breakthroughs target sub-technologies and individual hydropower components. Presently, approximately 160 countries use hydropower for energy production and more than 1292 GW of hydro capacity is installed, globally. 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. Reservoir hydropower is 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 and this is also reflected by the research efforts covered in this report.

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. The necessity for tailored-made, ad hoc solutions is common in several hydropower components. Thus, hydropower R&D 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 scale (<10 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 were 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 compatibility with environmental restrictions with the timeline being 2018–2023. Specifically, dams and barriers generally obstruct free water flow, sediment transport, and fish migration with negative impacts on river ecosystems. This report shows that EU projects have also focused on these priority areas.

The present technology development report analyses recent technological advances of hydropower. Its main focus is EU-funded projects that have been either recently completed or that are ongoing. The analysis of projects also aims to identify the general R&D tendencies and needs of the hydropower technology.

It is important to note that the report distinguishes research in scientific hubs over corporate R&D activities because the latter are closely related to market developments 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 for new dam construction. Thus, opportunities for the construction of new large-scale hydropower stations on 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. Moreover, the development of low-head and hydrokinetic technologies that do not require dam construction aims to render the exploitation of a new type of sites economically viable. Naturally, this is also related to cost-reduction approaches and optimal operation to increase the output. More importantly, it is dependent on market conditions and the regulatory framework of electricity generation, flexibility, storage, as well as the degree of support for clean energy sources. Research 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 to complex and dynamic environmental conditions. Large-scale hydropower deployment has encountered social and scientific opposition due to its ecological impact on the environment, to water availability and to population relocation. The present report also analyses the latest research addressing the ecological and social impact of hydropower as well as the pathways to mitigate the negative consequences and increase its positive contribution. Besides, hydropower is increasingly linked to the environmental science field due to climate change, and hydro infrastructure needs to become more adaptive to climate variabilities. 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. Thirteen large-scale projects were identified and are listed below. Their budget ranges between EUR 1 million and EUR 18 million, while a number of additional projects with a relatively smaller budget were also identified and are presented in a separate section (§3.2).

AFC4Hydro[1]: Active Flow Control system FOR improving HYDRaulic turbine performances at off-design Operation (ongoing);

HydroFlex[1]: Increasing the value of Hydropower through increased Flexibility (ongoing);

XFLEX: Hydropower Extending Power System Flexibility (ongoing);

ECO-DRILLING[1]: Environmentally efficient full profile drilling solution;

DP Renewables[1]: 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;

HyPump[1]: Enabling Sustainable Irrigation through Hydro-Powered Pumps for Canals (ongoing);

HyKinetics: An innovative axial turbine for conversion of hydro-kinetics energy to electricity in rivers and canals (ongoing);

Turbulent: A revolutionary hydro power technology to sustainably exploit super-low-head water steps (ongoing);

FIThydro[1]: Fishfriendly Innovative Technologies for Hydropower (ongoing);

AMBER: Adaptive Management of Barriers in European Rivers (ongoing);

HYPOS: Hydro-power-suite (ongoing);

Hydropower Europe: Bringing together stakeholders of the hydropower sector in a forum (ongoing);

HYPOSO: Hydropower solutions for developing and emerging countries (ongoing).

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 2 provides information of earlier projects, for reference.

[1] These projects were reviewed in an earlier LCEO report (Kougias, 2019a) and here an update is provided.

Table 1. Basic information of the analysed projects

Project acronym	Main targets	# of partners	H2020 call	Budget (€)	EU share
AFC4HYDRO	- Active flow control; - Hydraulic turbines; - Off-design operation.	6	H2020-LC-SC3-2018-RES-TwoStages	4,711,589	100%
Hydroflex	- Increased flexibility; - Extend oper. range, ramping rates, start-stop cycles; - Reduce fatigue.	16	H2020-LCE-2017-RES-RIA-TwoStage	5,716,989	95%
XFLEX	- Provide flexibility to grid; -Integrate system solutions.	19	H2020-LC-SC3-2019-RES-IA-CSA	18,162,950	83%
ECO-DRILLING	- Full profile directional drilling - Cost-effective, environmental friendly technology.	1	H2020-SMEINST-2-2016-2017	2,811,875	70%
DP Renewables	- Hydrokinetic turbine; - Reach market maturity.	1	H2020-SMEINST-2-2016-2017	2,927,031	66%
HyPump	- Convert energy of irrigation canals for pumping water.	1	H2020-SMEINST-2-2016-2017	2,545,390	70%
HyKinetics	- Micro hydrokinetic axial turbine for rivers & canals.	1	H2020-SMEInst-2018-2020-2	2,192,125	70%
Turbulent	- Very low head (<3m) turbine for mini-scale hydropower	1	H2020-SMEInst-2018-2020-2	3,511,500	70%
FIThydro	- Fish damage: Mitigation measures and strategies; -Decision support System.	26	H2020-LCE-2016-RES-CCS-RIA	7,171,550	82%
AMBER	- River fragmentation in EU; - Restore stream connectivity; - Adaptive barrier manag.	21	H2020-SC5-2015-two-stage	6,238,104	97%
HYPOS	- Earth Observation technologies and modelling; - Hydropower data collection.	5	H2020-SPACE-2019	2,397,120	83%
Hydropower Europe	- Bring together hydropower stakeholders in a forum.	8	H2020-LC-SC3-2018-Joint-Actions-3	993,571	100%
HYPOSO	- Hydropower market in developing economies.	13	H2020-LC-SC3-2019-RES-IA-CSA	2,938,374	100%

Source: Author's compilation

Table 2. Basic information of completed projects covered in earlier reports (Kougias, 2019a)

Project acronym	Main targets	# of partners	H2020 call	Budget (€)	EU share
CaFE	- Computational models for cavitating flows, surface erosion and material loss	8	H2020-MSCA-ITN-2014	3,939,999	100%
Hydrolowhead	- Mini-scale hydro	2	H2020-SMEINST-2-2015	1,512,893	70%
EUROFLOW	- European network of environmental flow.	10	H2020-MSCA-ITN-2017	3,923,989	100%
BINGO	- Water resources management under climate change.	20	H2020-WATER-2014-two-stage	7,822,423	100%
DAFNE	- Water-Energy-Food Nexus in developing economies.	14	H2020-WATER-2015-two-stage	5,420,223	63%
IMPREX	-Improving prediction and modelling of hydrological extremes,	24	H2020-WATER-2014-two-stage	7,996,848	100%

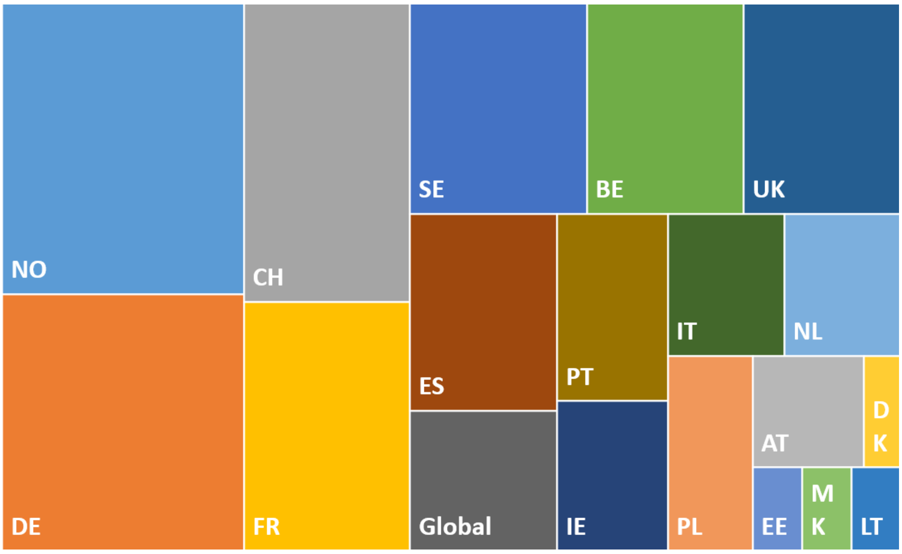
Source: Author's compilation

A deeper analysis of the participants shows that their total number is 105, which is smaller than the number identified in the 2018 exercise. Indeed, the previous technology development reports (Kougias, 2016, 2019a) identified 112 and 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 just one 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 Lulea University of Technology (Sweden - 2 participations), the Polytechnic University of Catalonia (Spain - 2), and the Polish Academy of Sciences (Poland - 2). As far as corporate R&D is concerned several companies participate in more than one project. This includes Statkraft the hydropower company owned by the Norwegian state (3), Sintef Energy (Norway - 2) an energy research company, equipment manufacturer Voith Hydro (Germany - 2), utilities Vattenfall (Sweden - 2) and EDF (France - 2) and relevant to hydro associations IHA (UK - 2) and EREF (Belgium - 2). The reduction in the number of participating institutions is calculated at ≃6%.

However, it is worth noting that the recent projects have a stronger focus on issues and challenges lying in the core of the hydropower sector. This development reflects a tendency to address specific technological bottlenecks and challenges that limit hydropower deployment rather than implementing projects that have a wider scope related to water resources. Hydropower technology development is directly related to such projects as it can definitely benefit from them. Indeed, a better simulation of river water discharge 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.

Leading countries in hydro technology development are traditionally Germany, Norway, Sweden, Austria and Switzerland. Figure 1 visualises a tree-mapping analysis of the project partners in terms of their host country.

Figure 1. Treemap chart of the origin of participating partners

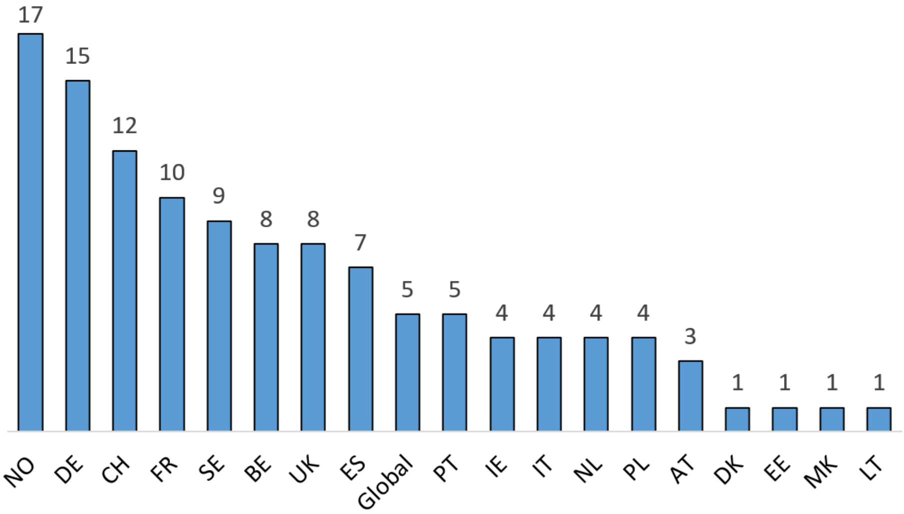


Source: Author's compilation

The specific numbers of country representatives are shown in

. Institutions based in Norway participate 17 times as partners in the analysed projects, where Germany-based partners appear 15 times and Swiss institutions 12 times. France, Sweden, UK, Belgium, and Spain are also very active. Partners based in Portugal, Ireland, Italy, and Netherlands also appear in several occasions, indicating the active hydropower R&D in these countries.

Figure 2. Number of research project participants per country



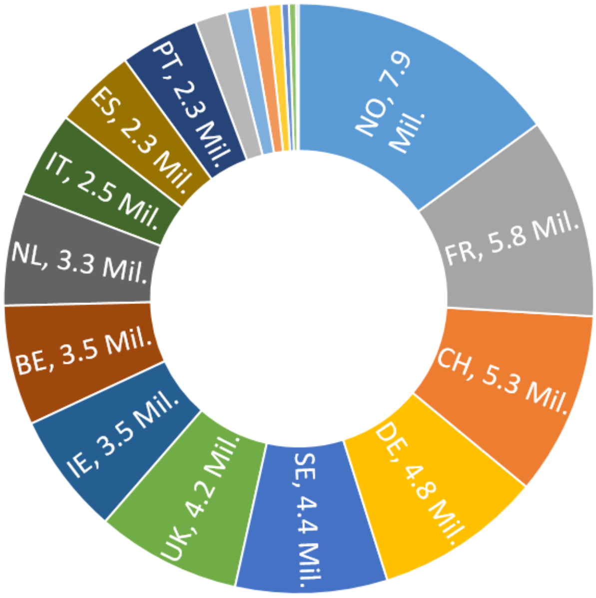
Source: Author's compilation

Compared to earlier analyses, the highest increase of participants is identified in France, where the number of institutions has risen from three to ten. The highest decrease in number of participants is found in Netherlands (from twelve to four).

Five partners represent (sub-Saharan) Africa and South America, showing the sustained interest in supporting sustainable hydropower development in these regions. Furthermore, one partner represents Western Balkans, a region with significant untapped hydropower potential.

As expected the number of participants relates to the share of the EU funding directed to each EU Member State and the UK. Detailed information is shown in . The analysis includes all (thirteen) analysed projects that receive a total EUR 52.8 million from EU finds (their total budget is EUR 62.3 million). Norway-based institutions and companies receive the lion's share (≈15% of the total) followed by institutions in France (11%) and Switzerland (10%). The five non-European participants receive just a small fraction of the budget (1.3%), an indication that their participation in the consortium aims to provide knowledge transfer and consultation rather than plain access to funding.

Figure 3. EU funding allocated to hydropower research projects in EU MS and the UK in Horizon 2020



Source: Author's compilation

1.1 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 operated. 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 hydropower from a wider perspective. One of the project categories focuses on hydropower's flexible operation, a topic that is important for the role of the technology in future energy systems also relating to pumped hydropower storage (PHS). A second group of projects focuses on low-head and hydrokinetic hydropower a topic that has attracted attention due to the low impact of such systems on the environment, as well as on the possibility for EU-based companies to play a leading role globally. A third group includes the environmental and ecological implications of hydropower and their interactions with energy production. Accordingly, the identified projects can be categorised into the following groups[2]:

1.1.1 Flexible operation of hydropower

The first group includes developing active flow control, increase turbine efficiency and reduce stress (AFC4Hydro). 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). This category of projects aims at providing a better understanding of hydropower fleet's future working conditions (HydroFlex) as well as extending its limits and flexibility (XFLEX). Important part of such activities is the digitalisation of hydropower stations with the use of sensors and advanced simulation and modelling methods to reach real-time system monitoring and control.

1.1.2 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 low (<10 m) or even very-low (<3 m) hydraulic head (Turbulent project). This group also embeds research activities on hydrokinetic turbines for river currents (DP Renewables project) and canals (HyKinetics) of the mini-scale (below 100 kW). It also includes advancing the technological maturity of hydro-powered pumps to support irrigation in remote areas (HyPump).

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

1.1.3 Environmental-friendly hydropower

The third cluster 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 ecological impact of dams and barriers in an original attempt to create a commonly accepted decision tool on dam construction as well as to assess the potential benefits of well-targeted dam removal (AMBER). The use of Earth Observation technologies is also employed to assess the ecological status of hydropower reservoirs (HYPOS).

The creation of an environmental-friendly hydropower is an additional priority. Developments in this area would minimize hydropower's negative impacts and could possibly unlock a part of the untapped hydropower technical potential in Europe that is currently unexploited due to reasons related to environmental, ecological factors and the resulting risks (licensing, financing etc.).

1.1.4 Forums and initiatives

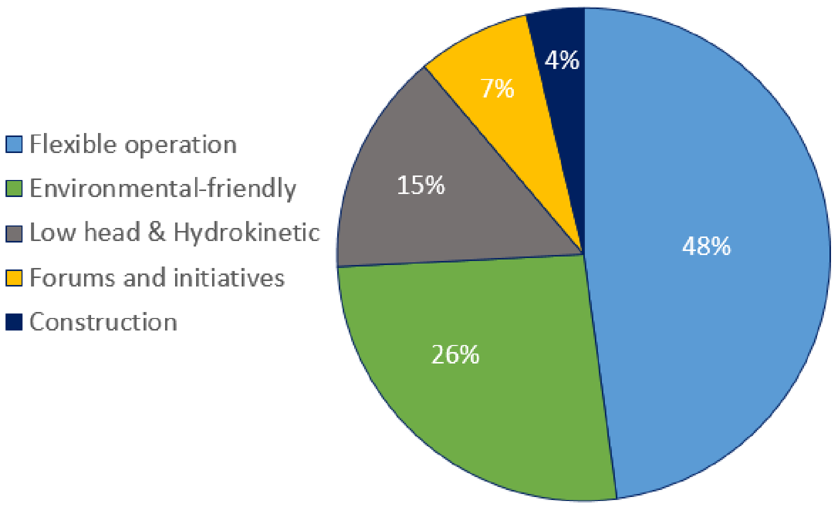
The fourth cluster includes projects that bring together the various hydropower stakeholders in order to foster collaborations as well as create forums to discuss priority areas for research and common strategies (Hydropower Europe). Such initiatives aim to address the absence of a European association or body exclusively for hydropower stakeholders similar to e.g. those for wind and solar energy. This category includes an initiative to create links between the European hydropower industry and stakeholders in Africa and South America (HYPOSO).

One of the analysed projects (ECO-DRILLING) does not belong to any of the above categories and could be considered belonging in fifth category related to construction methods and technologies. The budget allocation between these categories is shown in

Figure **4.** Share of each group of projects in the allocated EU budget

, in which the dominant position of flexible operation is evident.

Figure 4. Share of each group of projects in the allocated EU budget



Source: Author's compilation

1.2 Indicators

The present report adopts some indicators to evaluate technological developments related to hydropower. Conventional hydropower systems are generally technologically mature. However, hydropower components and new designs are still under development. This is particular the case of hydropower sector's digitalisation, since the vast majority of stations uses obsolete digital means that cannot fully exploit the resource and provide the required levels of (digital) security (Vasiliev, Zegzhda and Zegzhda, 2016). Such advances generally refer to the categories presented in sections 1.1.1-1.1.4 and their status of development is quantified by the technology readiness level (TRL) index. Hydropower's TRL definitions were 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 LCEO report on hydropower emerging technologies (Kougias, I. and Moro, A. (eds.), 2018).

The parameter of cost is taken into account using estimates of capital expenditure (CAPEX) and operation expenses (OPEX). 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 plant lifetime ranges between 30 and 80 years with several plants operating for more than 100 years (International Renewable Energy Agency - 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, 2016), underlining its possible under-estimation in the global climate targets. The Intergovernmental Panel on Climate Change (IPCC) estimates the lifecycle median emissions of hydropower at 4 gCO_2-eq/kWh (Moomaw *et al.*, 2012; Fearnside, 2015). Recently, the International Hydropower Association an UNESCO/IHA collaboration published an analysis of nearly 500 hydropower reservoirs that calculated that the median GHG emission intensity was 18.5 gCO_2-eq/kWh over a life-cycle (International Hydropower Association - IHA, 2018). Other sources claim that emissions can be even higher (up to 100 gCO_2-eq/kWh), but recognise that such estimations are highly uncertain (Pehl *et al.*, 2017).

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.

2 Technology state of the art and development trends

2.1 State of the art

Hydropower technology is classified according to the operation characteristics of the various types of stations. Accordingly, hydropower stations can be distinguished as run-of-river, reservoir, pure and mixed pumped storage plants. All four types can vary from the small to the very large scale and power capacity, depending on the specific installation.

2.1.1 Run-of-river hydropower

Run-of-river projects (RoR) utilize the flow of water within a river's natural range and are different in design from conventional hydroelectric projects, where dams are built to store water in artificial reservoirs that flood large areas. RoR hydros exploit either large rivers with gentle gradient (high values of water discharge and low values of hydraulic head) or small, steep rivulets in mountainous areas (low values of water discharge and high values of hydraulic head). In many RoR a diversion is used to channel a portion of the river flow to the turbine, through a canal or penstock. Such systems generally don't require a dam, but in certain cases a small weir offers short-term water storage and supports the continuity of flow. Accordingly, they only have small water storage capacity in forebays -if any- and their electricity generation depends on water discharge regimes following the seasonal river flow.

Due to their design characteristics, RoR schemes do not impose the environmental impact associated with dam construction and artificial reservoirs, which places them among the most environmentally friendly hydropower technologies. An additional advantage of RoR schemes is the reduced civil works cost, compared to stations that require building large dams. A subset of RoR systems are the hydrokinetic energy converters that extract the kinetic energy of river currents.

2.1.2 Reservoir hydropower

Conventional hydropower schemes store large water quantities behind dams. Reservoirs reduce the dependence on the variable river flow and offer flexibility to the operation of the station. Water availability, wholesale electricity prices and addressing non-energy needs (e.g. provision of irrigation water, flood risk mitigation) determine the water quantities that will be stored and released. Contrary to RoR systems, reservoir hydropower plants are typically used for peak-load generation and support the optimal operation of base-load systems. They can respond quickly to demand changes and adjust their generation to sudden fluctuations of demand.

The dams of such stations affect river ecology and biodiversity by obstructing natural water flow and inducing a change in the hydrologic characteristics of the river. Moreover, dams disrupt sediment transport and fish migration and may affect river's chemical and biological characteristics.

2.1.3 Pumped storage hydropower

Pumped hydropower storage (PHS) is the main source of bulk electricity storage and currently provides 99% of electricity storage for grid systems, globally. PHS stations operate in two modes i.e. storage and production, by transporting water between two reservoirs. In periods of surplus electricity in the grid, PHS stations pump water upstream from the lower water reservoir to the upper one. In production mode, they release water stored in the upper reservoir downstream and produce electricity in the turbines-generators located in the lower reservoir.

PHS plants that convey water between two reservoirs in a closed loop are pure PHS stations. However, in certain cases a river may serves as one of the two reservoirs. Then, the PHS stations are of the mixed type, because they combine the functionality of conventional reservoir hydros with that of pure PHS. In other words, mixed PHS stations are reservoir hydros with an additional pump-back (storage) feature.

Energy losses in pumping operation make PHS plants energy consumers in their overall operation (round-trip efficiency is in the range of 70-85%). However, the provided service of energy storage has such an operational and economic value that PHS stations are an important element of electricity systems.

2.2 Technology trends

Hydropower is generally considered a mature technology; however, there is significant room for research activities and improvements mainly due to the following factors:

Continuous breakthroughs and advances in the ICT sector provide opportunities for the design, operation and maintenance of future hydropower. This refers to the extensive use of sensors, the digital transformation of hydropower, the optimised operation of available water resources, the mitigation of risks, and the minimisation of environmental impacts. A second factor is the ongoing transformation of the energy systems that have altered the role and requirements of hydropower. Climate change also influences hydropower by increasing uncertainties and creating risks (Vliet *et al.*, 2016; Schae *et al.*, 2019) and/or opportunities (Ali *et al.*, 2020). The needs of retrofitting and upgrading existing stations is an additional driver for research as new approaches and technological solutions are needed to prolong the lifetime of existing stations, increase their productivity and reduce environmental impacts. In the EU context this is particularly important when considering that the average age of the stations is more than 40 years (Kougias, 2019b). Research in small-scale hydropower and hydrokinetic technologies (Laws and Epps, 2016) is a driver aiming to provide clean electricity, support growth in remote or off-grid areas, and provide an alternative low-impact energy option. Emerging technologies responding to market needs and technological trends are presented in (Kougias *et al.*, 2019).

An overarching target of research activities is the design of flexible systems that provide an even higher value to the grid. This affects both conventional and pumped storage hydropower stations (PHS). The latter, however, face additional financial and regulatory challenges that hamper PHS deployments.

Regarding the environmental constraints and the relevant costs, hydropower still needs to make steps forward to reach the construction of sustainable hydropower stations. This would mitigate several issues that affect hydropower investment, deployment, operation and maintenance such as licensing, social acceptance, concessions, and climate change. Hydropower industry and the relevant stakeholders are confident that it is possible to mitigate at large extent the environmental and ecological impacts of hydropower by employing advanced design characteristics and operation strategies. The recent *fitness check* of the EU Water Legislation[3] found that the legislation in place is sufficiently prescriptive and recognises the need for a better integration of water objectives in energy policy. Technological progresses that reduce pressures on water bodies would facilitate green-field hydropower development especially in regions with significant untapped hydro potential (Western Balkans, Africa).

[3] Information, findings and support studies are available online at: https://ec.europa.eu/environment/water/fitness_check_of_the_eu_water_legislation/

3 R&D overview and impact assessment

3.1 EU Co-funded projects

3.1.1 AFC4Hydro

The full title of the AFC4Hydro project is: *Active Flow Control system for improving hydraulic turbine performances at off-design operation*. It started on 01/06/2019 and with a total duration of 48 months, it is expected to end by 31/05/2023. Its overall budget is ≃ EUR 4.7 million, all covered by EU sources. AFC4Hydro develops technologies to improve the operation of turbines at off-design conditions.

To do so, AFC4Hydro designs, implements and validates an active flow control system in a full-scale hydro turbine. The two main objectives of the system is to increase the turbine efficiency and reduce the loads on the structure of the turbine particularly at off-design and transient operation conditions (also relevant to the objectives of the "HydroFlex" project). Special attention is given to the vortex rope formation in the draft tube. A combination of technologies is used to mitigate the occurrence of excess pressure and load fluctuations. These quasi-novel technologies are already known and extensively studied by groups in the Romanian Academy (Resiga *et al.*, 2006). Still the specific analysed technologies are at relatively low levels of technological maturity (TRL 3). The two technologies include the injection of pulsating momentum by means of actuators and the injection of continuous momentum with water jets. A comprehensive review of efforts and projects working on this very topic is presented in a recent scientific article developed in the framework of the LCEO project (Kougias, I. and Moro, A. (eds.), 2018).

An additional innovative feature of AFC4Hydro is the introduction of a digital avatar that monitors the system conditions. The so-called structural health monitoring (SHM) system incorporates fiber-optic sensing technology and will evaluate the effects of the two technologies in improving the overall system performance and minimizing the wear. The SHM measurements will enable modelling and optimizing the operation of the injection systems in real time conditions. Coupling the SHM with active control techniques is expected to extend the operating range of hydraulic machinery, increase its efficiency and reduce O&M costs.

The implementation of the AFC4Hydro project can be divided into four main objectives. Firstly, the injected pulsating momentum system will be developed to advance the current levels of technological maturity. Initially a reduced-scale turbine model will be built (reaching TRL 3-4) and eventually a full-scale prototype will further advance the technology (TRL 4-5). The second stage of the project involves the development of advanced ("2nd generation") flow control technologies in reduced- (TRL 3-4) and full-scale (TRL 4-5). The third pillar of AFC4Hydro is the development of the AFC monitoring system on the turbine runner and shaft (TRL 3-4) and in a full-scale prototype (TRL 4-5). The fourth objective of AFC4Hydro is to share findings and experience with scientific organizations and the industry. This report was compiled in early 2020, while AFC4Hydro was still at an early stage; therefore implementation progress of the project was still at an early stage. Expectations also refer to suitability and affordability of the developed system so that its addition to existing stations will be possible and economically advantageous.

3.1.2 HydroFlex project

The full title of the HydroFlex project is: *Increasing the value of Hydropower through increased Flexibilty*. It started on 1/5/2018 and with a total duration of 48 months it is expected to end by 30/4/2022. Its overall budget is ≃ EUR 5.7 million, with the vast majority (≃ 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 increase of variable RES coupled with decreasing capacities of gas turbine power plants[4].

HydroFlex 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,

[4] 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, Kirsten and Prchlik, 2017).

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 pumped hydro storage (PHS) stations, this problem affects both conventional and PHS 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 operation, 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.

Hydroflex also focuses on variable speed turbines. The aim is to develop a new hydraulic design for a variable speed Francis turbine that is numerically optimised, evaluated and tested in the lab. This also extends to the power stations' electrical layouts, generator components and control systems.

To date (late 2019), HydroFlex has progressed with the mechanical design of the Francis turbine as it has performed numerical optimization and validated the hill diagram with the use of CFD analysis. The project identified reference sites and parametrised the scenarios to be analysed for each site. This also includes tests to calculate the expected lifetime of the turbine. Further tests in a model turbine are about to start and further advance TRL. Advanced, intelligent control practices are an important part of HydroFlex and are advancing. 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. This includes flow scenario modelling in case studies and evaluation of the applied mitigation technology on fish populations.

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[5] (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.

3.1.3 XFLEX

The acronym XFLEX stands for the full title: *Hydropower Extending Power System Flexibility*. The project started on 01/09/2019 and with a total duration of 48 months it will be completed by 31/08/2023. It has an overall budget of approximately EUR 18.1 million, with EUR 15.1 million covered by EU sources. The importance of XFLEX is shown by the fact that it has –by far- the highest budget among the hydropower-related projects that were recorded in terms of the LCEO activity. XFLEX is financed under the H2020 priority "low-cost, low-carbon energy supply".

XFLEX aims to provide solutions that increase the energy system flexibility in view of the very high share of variable RES in the EU electricity mix. The main objective of the project is to improve the efficiency of hydroelectric machinery improving the performance and response of hydropower plants. The scope also includes variable speed generation in both new, existing, and upgraded facilities. Since the flexible operation of hydro will impose increasing level of stress and fatigue on the machinery. Accordingly, XFLEX focuses on the digitalization of operation that also optimizes maintenance requirements.

XFLEX aim is to create a smart hydropower unit control that provides additional operating points compared to conventional stations. This will be based on dynamic simulations and modelling that take advantage of the novel digital features of the hydropower unit. Findings will be demonstrated in pumped hydropower storage

[5] NTNU: Coordinator of HydroFlex project

stations in Portugal and France. The expected outcome will improve the value of produced hydroelectricity in the markets and allow the integration of larger amounts of RES capacities in the system.

XFLEX builds on technological progresses made in terms of the FP7 Hyperbole project that brought some of the sub-technologies to TRL 5. The aim of XFLEX is to advance the technological maturity to TRL 7, beyond the current state of the art.

3.1.4 Eco-Drilling project

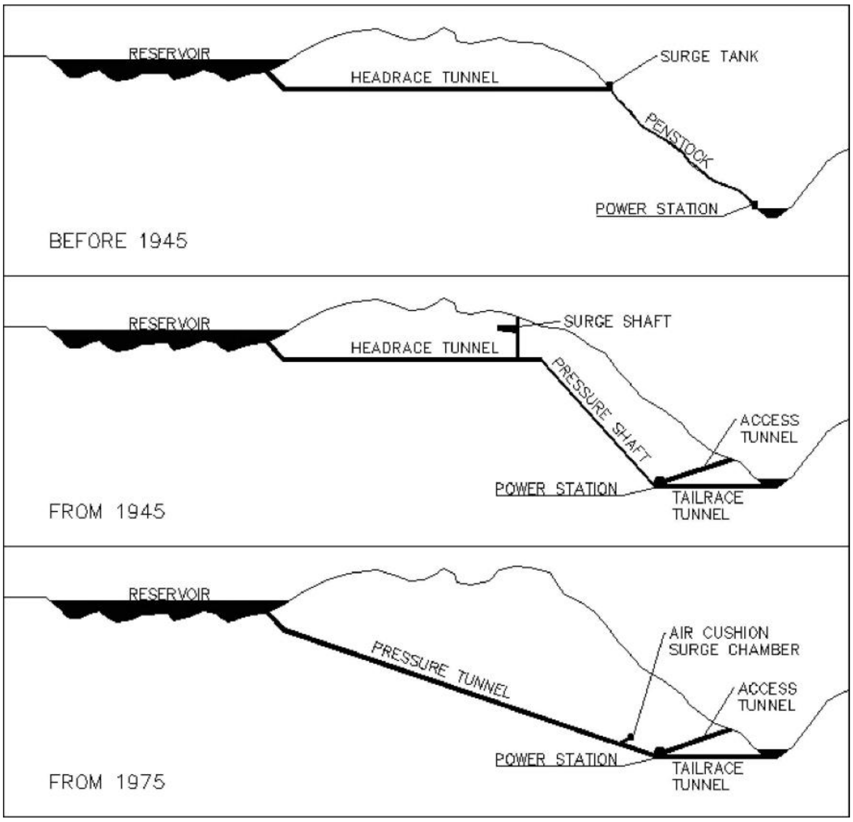
The full title of the Eco-Drilling project is: *Environmentally efficient full profile drilling solution*. It started on 1/9/2017 and with a total duration of 30 months it will end on 29/2/2020. Its overall budget is ≃ EUR 2.8 million, with the main part (≃ EUR 2 million) covered by EU funds. It is funded 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, Bruland and Brevik, 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 5).

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 (≃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. ECO-DRILLING targets the small-scale (1-10MW) hydropower market for the provision of drilling services to locations that otherwise could not been utilized due to e.g. the prohibitive costs of road construction, and/or technical-environmental challenges.

Figure 5. Historical development of hydropower tunnel system



Source: (Bråtveit, Bruland and Brevik, 2016)

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. This leads to advancing the technology from the current TRL 7 to TRL 8 and eventually to full commercialization TRL 9. Large-scale piloting was still ongoing and advancing in December 2019.

Eco-Drilling has also assessed the available market opportunities and the place of the developed technology within the competition. The interim results show a relevant advantage of the technology. The final market report included a screening of the available opportunities and identified that the developed technology is ready for immediate commercialization. Specific countries were also highlighted as priority markets, since the company is currently providing services only in Norway.

3.1.5 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 31 months will be completed by 31/03/2020. It has an overall budget of EUR 2.9 million out of which EUR 1.9 million is an EU Grant. 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. 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 infrastructure.

DP Renewables deployed a full scale 25kW unit in the Garonne river (advancing from TRL 6 to TRL 8), Bordeaux, France, while a larger 60kW device is currently completing build phase and under the revised schedule is set to be deployed in early/mid 2020. Accordingly, the project was prolonged by four months (the original duration was 27 months) in order to deploy and test the larger unit. The 60 kW turbine will be deployed in a tow test plan to minimize environmental risk and associated costs meaning a prototype system test in intended environment rather than a first of a kind system where all manufacturing issues are solved. According to the TRL definition for hydropower (Kougias, I. and Moro, A. (eds.), 2018), this corresponds to TRL 6-7.

Market readiness and competitiveness have also been studied, showing that the products can be developed at costs competitive with similar projects but, as expected, higher than renewable technologies such as wind and PV. DesignPro reported in late 2019 that is in the middle of discussions to establish partnerships and investments that will enable the products' commercialization.

3.1.6 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 2.5 million, EUR 1.8 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 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.

Initially the HyPump concept was at TRL 6 and the aim of the project was to commercialise the product by optimizing the system installation. In terms of the project, the industrial design of HyPump has been defined and two alternative versions were developed adopting a hydrostatic pressure wheel (see HyLow FP7 project, (Kougias, 2016) and an overshot water wheel, respectively. The first demonstration was tested in late 2019 in Spain while two additional tests are planned until the completion of the project. HyPump focused on experimental analysis of the spiral pump, a concept that had not been extensively studied previously. Analyses resulted in a configuration tool that allows seamless installation and improves performance. Parallel to technological advancements, HyPump works on a marketing and communication plan to support the successful system commercialization.

3.1.7 HyKinetics

The acronym HyKinetics stands for the full title: *An innovative axial turbine for conversion of hydro-kinetics energy to electricity in rivers and canals*. The project just started on 01/01/2020 and with a total duration of 24 months it will be completed by 31/12/2021. It has an overall budget of approximately EUR 2.2 million, EUR 1.5 million of which is covered by EU sources. HyKinetics has been developed by manufacturer of mechanical equipment named COS.B.I. (costruzione bobine Italia) and it is financed under the H2020-SME instrument. It is worth mentioning that HyKinetics is a follow up activity of a small-scale project (EUR 70,000) that was implemented in 2018, see (Kougias, 2019b).

HyKinetics project focuses on hydropower that utilizes solely the kinetic energy in streams and canals. It develops mini-scale hydrokinetic turbines that do not require any dam/weir construction and have a nominal capacity of 20 kW. The projects targets installation downstream of existing large-scale hydropower facilities

The device was successfully tested in the past in a pilot installation in Po River, Italy. The objective of HyKinetics is to manufacture ten 20 kW prototypes and install-validate them in real conditions. Installations are expected to be located in rivers (two in Po River) and canals (eight in artificial canals of the Aosta region). This will lead to improvements of the manufacturing process and cost reduction. COS.B.I. anticipates that moving to industrial production will reduce the manufacturing cost by at least a factor of 3. Eventually, it will allow the certification of the product bringing it one step closer to commercialization.

Currently, the turbine is at TRL 7 since the prototype has been demonstrated in operational environment. The project aims to bring the technological maturity to TRL 8 and reach a pre-production phase of a product that is ready to access the market.

3.1.8 Turbulent

The acronym Turbulent stands for the full title: *A revolutionary hydro power technology to sustainably exploit super-low-head water steps*. The project started on 01/08/2019 and with a total duration of 24 months it will be completed by 31/07/2021. It has an overall budget of approximately EUR 3.5 million, with EUR 2.5 million covered by EU sources. Turbulent is the name of a Belgian start-up company that designs and develops easy-to-install low-head hydropower plants. Turbulent is financed under the H2020 priority "societal challenges". It is worth mentioning that in 2017, Turbulent received the first prize at the Business Booster event that organised by the European Institute of Technology and Innovation (EIT) while in 2018, it took the third place at the EIT Venture Awards.

Turbulent aims to bring to commercialization a novel modular and easy-to-install low-head (below 3 m) hydropower device. This mini-scale hydropower system has a power capacity that ranges between 15 and 100 kW. The unique characteristics of its device is its small size and turnkey design that substantially reduces the cost of civil works. Turbulent turbines can, thus, effectively utilize the abundant untapped low-head hydropower potential with negligible environmental impact and landscape change. Due to reductions of the required civil works and construction time, it is expected that Turbulent will reach very competitive cost of electricity production when commercialized and allow the utilization of sites previously not economically viable. This includes rural electrification and off-grid systems in remote areas and/or developing countries.

The current technological status of the Turbulent device is TRL 7 as the real scale demonstration sites have been successfully tested. Next steps towards commercialization involve raising capital to increase the size of the company (staff and production means). The aim of the project is to support Turbulent's efforts to reach TRL 8 and eventually TRL 9 during the two-year course of the project. The main steps are demonstrating the technology at large scale and making the preparations for market entrance. Technical aspects to be further improves include the efficiency, materials and durability, electronics (simplify control) and design optimization (modularity, transportability).

3.1.9 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 7.2 million of which EUR 5.9 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).

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. It developed a mortality model that provides quantitative information of fish passage through hydropower turbines, with a particular focus on Kaplan turbines. The model employed CFD analysis of small-scale hydropower stations (35 kW – 10 MW) in the European context and quantified fish injury and mortality rates.

FIThydro brought together existing data and knowledge on fish population ecology in Europe. It, thus, developed a European Fish Population Hazard Index (FPHI) that acts as a decision and management tool for hydropower stations. The index classifies new installations according to the induced risk for species. To do so, an analytical approach was developed analysing the impact of various parameters (e.g. dam height, operation mode, turbine type, mitigation measures) and assigning relevant scoring to each parameter. FIThydro claims that the FPHI is the first step in an integrated decision support system.

The key elements of the project sub-technologies are advancing the TRL of specific technologies namely a 3D optical tracking (from TRL 1 to TRL 4), the solutions for bypass-migration (from TRL 1 to TRL 3), a dummy sensor fish (from TRL 2 to TRL 5), and a 3D sensor less tracking (from TRL 4 to TRL 5). According to the latest available reports (mid-2019), FIThydro has collected the first and promising results, but significant progress is needed to develop prototype applications in real rivers.

3.1.10 AMBER

The full title of the AMBER project is: *Adaptive Management of Barriers in European Rivers*. It started on 01/06/2016 and with a total duration of 52 months, it is expected to end by 30/09/2020. Its overall budget is

EUR 6.2 million, almost all covered by EU sources. AMBER identifies innovative solutions to mitigate river fragmentation caused by dams and barriers.

AMBER creates an inventory of stream barriers in Europe and implements a methodology – toolkit to assess the effects on the ecosystem including a socio-economic evaluation. The aim is to create a commonly accepted decision support tool of barrier mitigation schemes. AMBER also analyses barrier removal experience in the EU. Eventually, the project quantifies the benefits of an adaptive reservoir management in specific case studies and disseminates findings to the wide public. AMBER builds on knowledge developed in previous EU-funded projects such as the Hylow (FP7) and RESTOR HYDRO (IEE), while it is also linked to the ongoing H2020 project FIThydro (Kougias, 2019b) that focuses on fish-friendly hydropower.

AMBER is an interdisciplinary project spanning a wide spectrum of fields. Its aims is to create an integrated approach that gradually advances the TRL from laboratory to application. The initial high-resolution hydrodynamic analyses and organism response is fundamental research and experiments l at relatively low level of technological maturity (TRL 1-3). AMBER also adopts the use of advanced telemetry approaches and the use of drones to quantify species movement (TRL 3-5). The development of databases and models (TRL 6-8) will eventually lead to inventories and decision support tools that will be replicable in different environments (TRL 7-9).

AMBER also allows for participatory approaches through the development of a mobile app named "The Barrier Tracker" that allows specialists and citizens to report and identify existing barriers contributing to the development of the barrier atlas. A project deliverable is a freely available software named "Rapid Barrier Passability and Hydropower Assessment Tool" that allows calculating the passability for all species assigning a score to each analysed barrier.

3.1.11 HYPOS

The acronym HYPOS stands for the full title: *HYdro-POwer-Suite.* The project started on 01/12/2019 and with a total duration of 30 months will be completed by 31/05/2022. It has an overall budget of EUR 2.4 million with almost EUR 2 million covered by EU sources. HYPOS is financed under the H2020-SPACE instrument.

The objective of HYPOS is to assess the untapped hydropower potential based on Earth Observation technologies and modelling. Analyses will consider the environmental conditions, hydrological parameters and sediment transport.

To do so, HYPOS will combine and harmonise high-resolution data from different satellite services. Specific focus will be given on aspects and priority areas such as sediment load, algae bloom, reservoir temperature and evaporation. The collected and harmonized information will feed into a model that will enable access to important information to hydropower asset managers via user-friendly graphic user interfaces. The developed toolkit will be validated in various European areas and globally (Switzerland, Georgia, Albania), with the support of the industry. HYPOS also intends to create a business concept that will allow a global coverage and upscale of the developed tool. HYPOS main focus is on hydrological and environmental aspects of hydropower.

HYPOS is related to and complements the work implemented in terms of IMPREX project (see below) that identified the needs in hydropower sector to collect, process and analyse hydrological data especially as far as extreme events are concerned. HYPOS takes advantage of the Earth Observation data to regularly update the relevant info from satellite images.

3.1.12 Hydropower-Europe project

Hydropower-Europe project started on 01/11/2018 and with a total duration of 36 months it will end on 31/10/2021. Its overall budget is ≃ EUR 1 million, all covered by EU funds. It is funded under the H2020 LC-SC3-CC-4-2018 call support to sectorial fora and it brings together stakeholders of the hydropower sector to develop a Research and Innovation Agenda, and a corresponding Technology Roadmap mapping implementation. This initiative is coordinated by the International Commission on Large Dams (ICOLD).

The project identifies the needs of hydropower sector and records the current technological statues. It also identifies priority areas for research and innovation (R&I) activities highlighting known challenges of the sector. The aim is to define a future direction for the sector and produce a strategic R&I agenda. An additional point is the definition of specific domains, leading actors and assessment of the needed funding. Implementation will use traditional information channels i.e. the members of the consortium and partner organisations but will also aim for wider audiences via online media and other channels. The project also targets to address non-technical challenges related to financing, investors' concerns and social opposition.

3.1.13 HYPOSO

The acronym HYPOSO stands for the full title: *Hydropower solutions for developing and emerging countries*. The project started on 01/09/2019 and with a total duration of 36 months will be completed by 31/08/2022. It has an overall budget of EUR 2.9 million all covered by EU sources.

HYPOSO brings together the European hydropower industry with stakeholders from countries that host significant untapped hydropower resources. The initiative targets developing and emerging economies and particularly sub-Sahara African states (Cameroon, Uganda) and countries in South America (Bolivia, Colombia, Ecuador). The project aims to identify pilot projects and provide capacity building for local stakeholders promoting sustainable hydropower designs and the European industry. It also intends to participate in shaping new policies for clean energy in the selected regions. To effectively do so, the consortium composed of EU-based organisations as well as five universities or hydropower organisations in the concerned countries.

HYPOSO analyses exclusively small-scale hydropower (SHP) with a power capacity up to 30 MW. It will identify and map potential hydropower sites in the target countries with the use of spatial tools (expected number of potential sites exceeds 2000). HYPOSO does not prioritise technical or scientific advancements. On the contrary, it underlines the need for capacity building and close collaboration with the target countries to pave the way for increased share of SHP that represent advantageous investment options. This aim will be supported by a web-based hub that will link European industry with stakeholders in the target countries. Relevant EU-funded activities is the ongoing Hydropower-Europe project (the European Renewable energies federation is member and the connection point being member in both consortia) and the 2012-2015 RESTOR Hydro project (Kougias, 2016).

3.2 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.

3.2.1 HYDROGO

HYDROGO (Energy from water in motion: efficient, customisable off-grid hydro-electricity for rural areas with stream access) was a H2020-SMEs project with a budget of ≃EUR 71,500 (EUR 50,000 covered by EU). It was a short project with a duration of four months (01/11/2018-28/02/2019).

Its objective was off-grid energy solutions based on small hydropower energy with a very low hydraulic head (below 2 m). Its aim was to put on the market two models: one of the mini scale (two configurations with a nominal maximum power capacity 80kW and 160 kW) and one of the micro scale (15 kW). AHYDROGO focuses on the transport of the products as mini-scale plants will be installed in a container, while the micro-scale in small boxes that can be carried by two persons. HYDROGO focused on commercial feasibility and costs. In order to develop competitive products it identified off-the-self components. Estimations show the potential to develop a competitive product for this segment.

3.2.2 SMART Slowflow

SMART Slowflow (Kinetic Micro Hydro System for electrification of rural areas) was a H2020-SMEs project with a budget of ≃EUR 71,500 (EUR 50,000 covered by EU). It was a short project with a duration of six months (01/06/2018-30/11/2018).

SMART Slowflow scope is pico-scale (below 1 kW) hydrokinetic systems for the electrification of remote rural areas. The aim of the project was the industrialization and commercialization of a system. The project focused on preliminary designs and the definition of supply chains, as well as a business analysis.

3.2.3 SHYDRO-ALP

SHYDRO-ALP (Quantifying ecological effects of small hydropower in Alpine stream ecosystems) was an H2020-MSCA project that assesses the impacts of small-scale hydropower in the Alpine context. It had a 24-month duration (01/05/2017 – 30/04/2019).

The project modelled temporal and spatial alterations associated with the installation and operation of small hydro stations. Analysis included lab test (simulation in experimental devices) that were then validated using field-based measurements.

3.2.4 Lost-Biodiv

Lost-Biodiv (Predicting changes in species interactions following species loss in hydroelectric reservoir islands) is an H2020-MSCA project that assesses the ecological impacts of hydropower on biodiversity. It has a 24-month duration (01/12/2019 – 30/11/2021).

The project will assess the ecological impacts induced by hydroelectric dams on ecosystem functioning. To do so it analyses species interactions across one of the largest hydroelectric reservoirs in South America.

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

4.1 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. During the recent past (2014-2019) the allocated annual budget to the water programme (hydropower branch) doubled from USD 17 million to USD 35 million.

The main areas of support of the 2019 Water Power programme were: i) Technology R&D for low-impact hydropower (HydroNext initiative), ii) hydropower's support to the grid (HydroWIRES), iii) Environmental and hydrologic R&D, and iv) R&D to support retrofitting and upgrades for existing hydropower fleet.

The 2020 budget of the Water Power is USD 45 million for both hydropower and ocean[6] technologies. This is an overall reduction by 57% compared with 2019. Still, this is the smaller decrease in budget allocation, since solar and wind funding was decreased by 73% and 74%, respectively[7]. The 2020 Water Power programme supports early-stage R&D on novel hydropower concepts and specifically modular approaches to hydropower development that can lower overall project costs. A second priority area is hydropower's role as a provider of flexibility with a strong focus on PHS technologies. Support is also provided to technologies that mitigate environmental impact of hydropower that enable reduced licensing time, costs, and uncertainty.

4.2 Hydropower technology development in Norway

Norway hosts a number of institutions and universities that have played a leading role in hydropower R&D. The Norwegian Hydropower Centre (HydroCen) was established in 2016 at the NTNU University develops 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 fish protection, market integration of environmental design options, and adaptation of environmental designs to increased variable operation of hydropower. Hydrocen also hosts a dedicated work package that analyses hydropower's position in the power markets, the optimal design and operation of water resources, as well as assessments of risk and uncertainties. The annual budget of Hydrocen is EUR 4.8 million.

SINTEF, a leading and independent research organisation that hosts more than 2000 researchers, has a sustained interest in hydropower research. The main focus of SINTEF's energy systems laboratory (≈50 scientists) is hydropower and its interaction with modern renewables and electricity grids. Over the last decade, SINTEF has conducted more than 20 research projects that are directly or indirectly related to hydropower technology and operation[8]. Recent projects are the *HDVC inertia provision* and the *PRIBAS* (pricing balancing services in the future Nordic power market) that analyse among others the role and value of hydropower in electricity systems.

4.3 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. According to the Swiss Federal Office of Energy (SFOE), public funding on energy research in Switzerland ranges between EUR 190 and EUR 280 million, annually with approximately EUR 10 million targeting the research area of hydraulic power. The SFOE supports *pilot, demonstration, and flagship projects* with a focus on the following hydropower sub-technologies:

1. hydrokinetic project;
2. different turbine designs of the mini-scale (1-100 kW);

[6] The US DoE adopts the term marine and hydrokinetic (MHK) technologies.

[7] Detailed information is available online at: https://www.energy.gov/sites/prod/files/2019/03/f60/doe-fy2020-budget-in-brief_0.pdf

[8] Detailed information is available at the SINTEF website: https://www.sintef.no/en/projects/#topic=310005

3. prototype installation in artificial watercourses (e.g. drainage canals).

Notable ongoing research projects supported by federal funds is the *RENOVHydro* (2017-2020, EUR 550,000) that developed a decision making assistant for hydropower project potential evaluation and optimization and the ongoing Demonstrator for flexible Small Hydropower Plant (2017-2021, EUR 350,000) that aims to SHPs role on providing winter peak energy and ancillary services, whilst remaining eco-compatible.

The Swiss National Science Foundation (FNSNF) currently supports hydropower through two national research programmes (NRPs). NRP70 *Energy Turnaround* (EUR 36 million) focuses on the scientific and technological aspects of the change in energy strategy. NRP71 deals with the socioeconomic and regulatory side of hydropower (EUR 7.5 million). In its overview and recommendations, the NRP underlines two needs namely the need to invest on existing plants taking into account issues relevant to concessions and the necessity to assess hydropower in a holistic approach. The latter relates to conflicts with the ecology and biodiversity of ecosystems and the risk/opportunities of retreating glaciers. NRP70 supports three projects: i) *Hydropower and geo-energy* that assessed the potential for hydropower additions in Switzerland; ii) *The future of Swiss hydropower* that analysed the regulatory and market challenges that hydropower faces; and iii) *Sustainable floodplain management and hydropower* that models, simulates and monitors the consequences of adaptive flow management downstream of hydropower schemes. NRP71 includes a project titled *Acceptance of renewable energy* that assessed the social acceptance of renewables, including hydropower.

The Swiss Competence Center for Energy Research – Supply of Electricity (SCCER-SoE) has carried innovative research in the areas of geo-energy and hydropower and acted as the connection point for 30 Swiss scientific institutions. Its activities have included interconnected research projects with pilot-demonstration applications. The second phase of SCCER-SoE lasted from 2017 until 2020.

4.4 Hydropower technology development in China

China is the world leader of hydropower with 352 GW of installed hydropower capacity (30 GW of which is PHS) that continues to increase steadily (International Hydropower Association - IHA, 2018). China hosts a number of manufacturing companies of hydropower equipment, as well as leading international constructors. Access to publicly-funded research programs and project results is difficult to access as it is only available in Chinese language. However, there are clear indications that R&D activities in China are intense such as the patent activity presented in the next section. Chinese entities participate in the International Energy Agency's technology cooperation programme on hydropower (IEA TCP Hydro), a platform that facilitates collaboration and knowledge exchange.

In October 2017 the National Energy Administration of China published the 13th 5-Year Plan for Hydropower Development plan[9] that 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). Secondly, it foresees specific R&D activities that focus on seawater PHS, digital hydropower, and smart hydropower stations operations. More specifically, activities focus on strengthening the autonomy of major components and reaching market readiness levels (Gosens, Kåberger and Wang, 2017).

4.5 Impact assessment of hydropower R&D: patent analysis

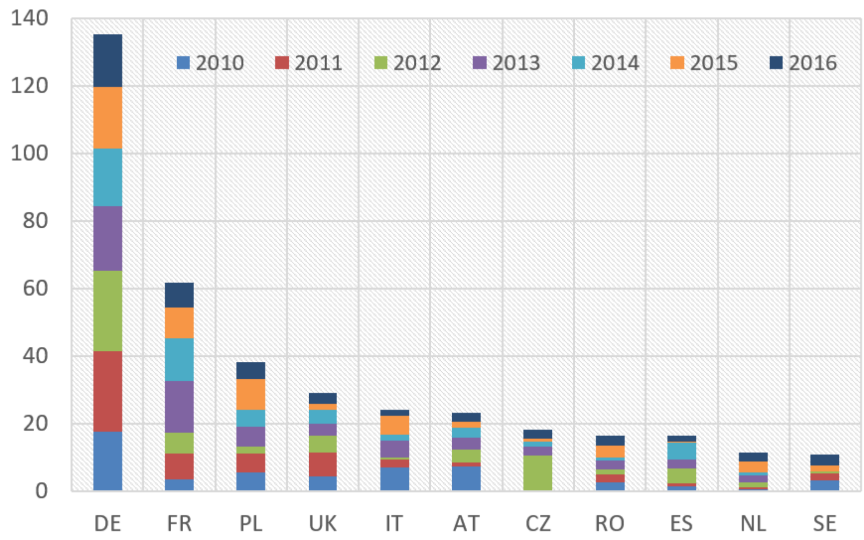
Patents on hydropower are identified by using the relevant Y code families of the Coordinated Patent Classification (CPC) for climate change[10]. Relevant to hydropower are the following classes of patents:

- Y02E Hydro energy: Energy generation through RES10/20 Hydro energy
  - 10/22 Conventional
  - 10/223 Turbines or waterwheels
  - 10/226 Other parts or details
  - 10/28 Tidal stream or damless hydropower
- Y02B Integration of RES in buildings
  - 10/50 Hydropower

[9] Available online at http://zfxxgk.nea.gov.cn/auto87/201611/t20161130_2324.htm (in Chinese language)
[10] Information on the CPC codes at: http://www.cooperativepatentclassification.org

The present patent analysis was based on data available from the European Patent Office (EPO). Possible differences with data reported previously are due to improvement in the JRC data processing of the raw patent dataset provided by EPO. This process increases data coverage, particularly for Asian countries that are often associated with incorrect or missing country codes, because of the incomplete provision of information from the national patent authorities. Furthermore, periodic revisions of the PATSTAT database run by the EPO (i.e. technological reclassification of patent applications or addition of new attributes to patent applicants) could potentially have an effect on the consistency and reproducibility of time series based on subsequent database versions. Details of the analysis are described in detail in dedicated JRC publications (Fiorini, Georgakaki, Pasimeni, *et al.*, 2017; Pasimeni, 2019). The number of patents per MS are provided in Figure 6 and covers the period 2010-2016. The graph includes only countries with notable patent activity, with the minimum threshold set for countries hosting at least 10 inventions. Compared to earlier analyses (Kougias, 2019a), we identify an increasing trend in the number of inventions, especially after 2010. Indeed, the average annual number of inventions in the EU increased from ≈20 in the 2000-2009 period to ≈60 for 2010-2016.

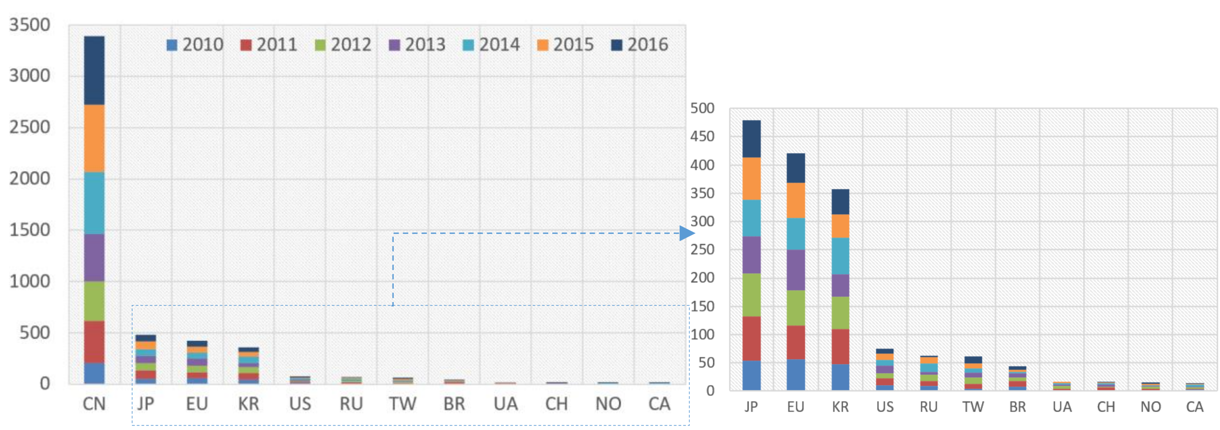
Figure 6. Patent activity in selected EU Member States and the UK by number of inventions



Source: (Pasimeni, Fiorini and Georgakaki, 2019)

A similar analysis was performed at global scale covering the main R&D hubs for hydropower. Findings are presented in Figure 7 covering the main hubs. The graph in the right side of Figure 7 excludes China that hosts a disproportionately large number of inventions (>3000) and provides a closer look into the remaining hubs. Patent activity in China has been increasing at impressive rates since 2010 reaching 668 inventions in 2016. However, this is also due to the different patenting process in China.

Figure 7. Patent activity in selected countries by number of inventions

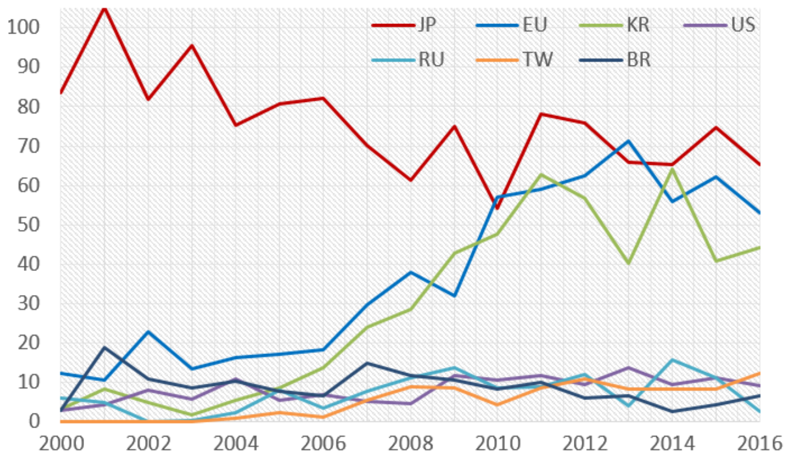


Source: (Pasimeni, Fiorini and Georgakaki, 2019)

Figure 7 (right side) includes the overall patent activity in EU (including UK) and shows that together with Japan and South Korea, EU is an important hub of hydropower inventions. EU patent activity is higher than the US, Russia, Taiwan, Brazil, Switzerland, Norway, and Canada. Notable, of this group, EU and South Korea are the main locations, where patent activity has an overall increasing tendency, while patent activity in Japan has been clearly decreasing.

This is also shown in Figure 8 that shows patent activity in the leading countries (except China). The share of China in the global patent activity has increased from 7.2% in 2000, to more than 75% in 2016 (668 recorded patents). Patent activities in other leading countries is relatively stable over the analysed period with small variations.

Figure 8. Patent activity in selected countries 2000-2016

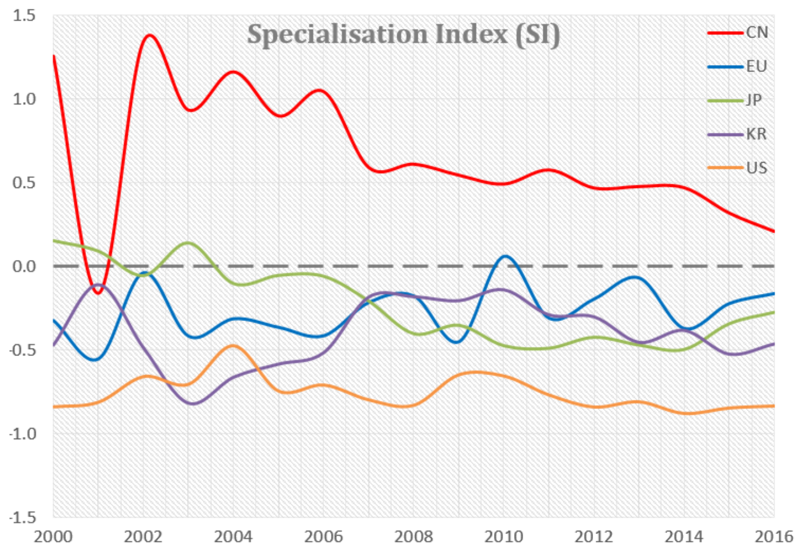


Source: (Pasimeni, Fiorini and Georgakaki, 2019)

The Specialisation Index (SI) represents the patenting intensity in hydropower technology for a given country relative to geographical area taken as reference. Its calculation is described in the dedicated JRC work and the previous hydropower market report (Kougias, 2019b).

According to the SI definition, if in a given country the SI = 0, the patenting intensity is equal to the global average. In case SI < 0, the country's intensity is lower than the world's average while if SI > 0 the intensity is higher (Fiorini, Georgakaki, Navarro, *et al.*, 2017). Figure 9 shows the SI for China, EU Japan, South Korea and the United States of America. EU's patent intensity on hydro is near but clearly below the global average. This is mainly due to the dominance of China's R&D, which is the only country/region with a positive SI.

Figure 9. Values of Specialisation Index (SI) for selected countries and the EU (2000-2016)



Source: (Pasimeni, Fiorini and Georgakaki, 2019)

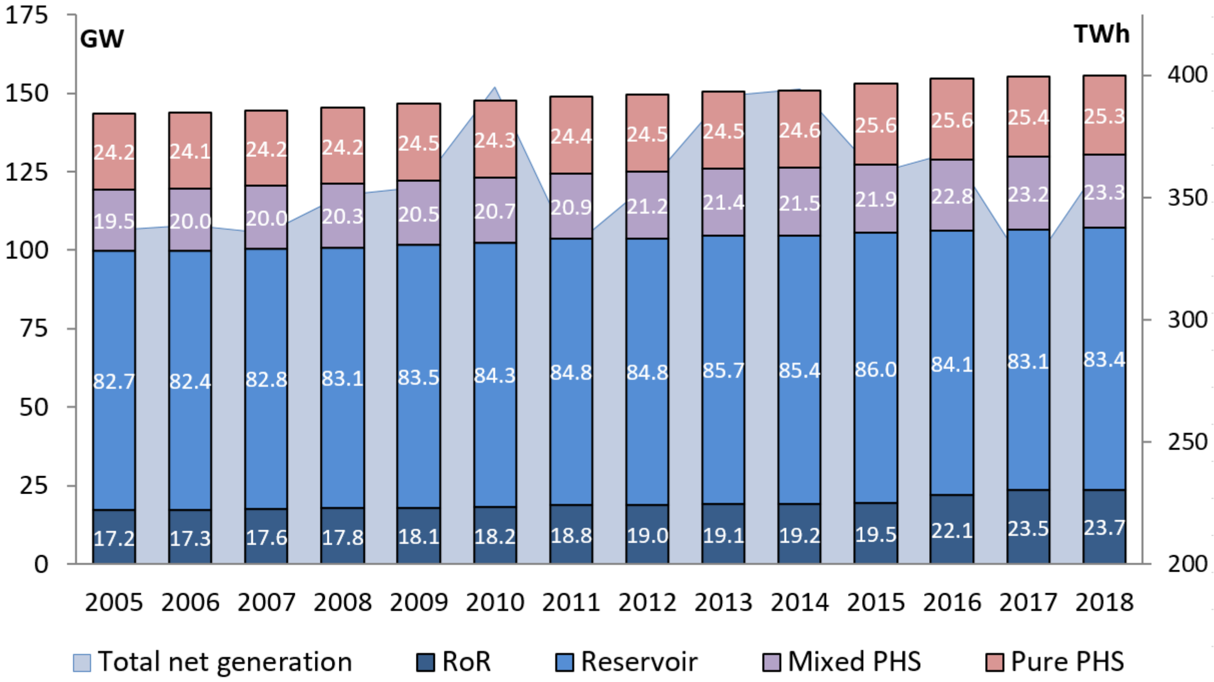
5 Technology development outlook

5.1 Existing fleet and generation in the EU Deployment targets and current progress in EU

Figure 10 shows the installed hydropower capacity in the EU for the period 2005-2018. The bars show the cumulative power capacity of each type of station namely run-of-river (RoR), reservoir (conventional) hydropower, mixed and pure pumped hydro storage. It appears that additions between 2017 and 2018 were marginal, at the decimal place (from 155.26 GW to 155.60 GW). The upper columns of Figure 10 provide information for the pure PHS stations and the mixed PHS 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.

The background graph in Figure 10 shows the annual net electricity generation of hydro in the EU for the same period (light blue colour). Annual variability is mainly dependent on the hydrologic year rather than on the rather small capacity additions.

Figure 10. Installed capacity and annual generation of hydropower in the EU



Source: Author's compilation on Eurostat data (Eurostat, 2019)

The low number of additions reflects a series of reasons that hamper hydropower growth in the EU. Firstly, a significant part of the existing potential in the EU has already been utilised, and this includes most of the locations that advantageous characteristics. A second important reason is hydropower financing. Hydropower is capital-intensive and requires large upfront payments. The current dynamic electricity markets and the increased uncertainties do not favour hydropower investments. In the case of pumped hydro storage and important driver are the decreasing wholesale electricity prices that have diminished arbitrage opportunities. Environmental constraints, hydropower's impact on biodiversity, and social opposition are additional limiting factors.

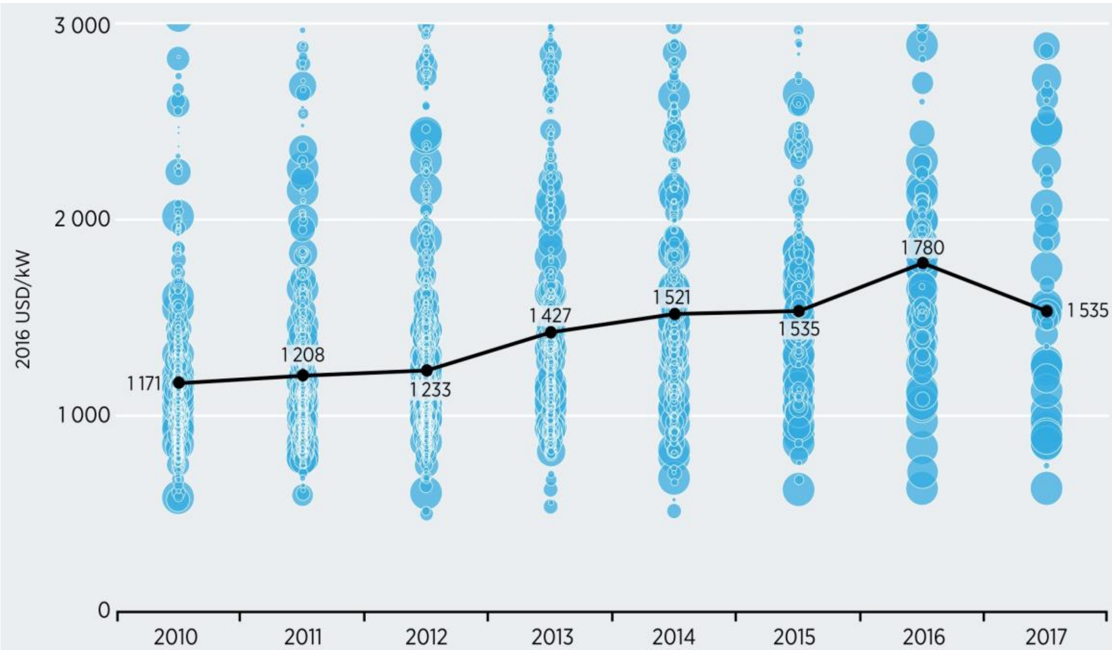
5.2 Economics of hydropower

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 (International Renewable Energy Agency - 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, 2016).

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 (International Renewable Energy Agency - IRENA, 2018). Figure 11 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. 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 11. Total installation costs by project and global weighted averages.

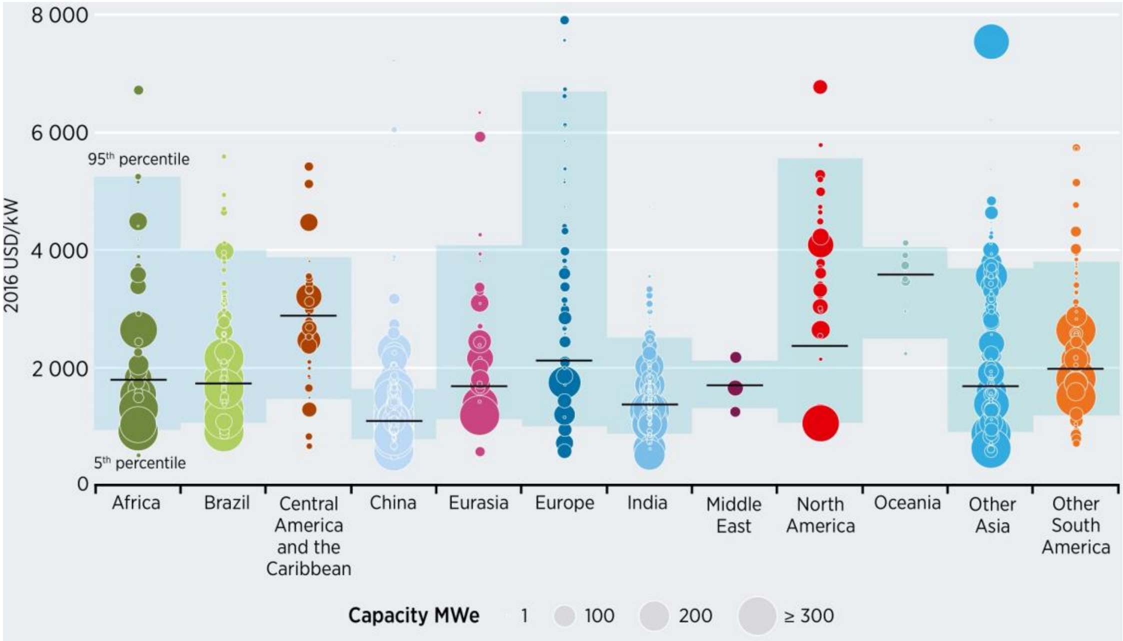


Source: (International Renewable Energy Agency - IRENA, 2018)

As expected, hydropower development costs are higher in Europe compared to the other regions (Figure 12). 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 (International Renewable Energy Agency - 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 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. 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 (International Energy Agency - IEA, 2010).

Figure 12. Hydropower's total cost range and weighted average by region.



Source: (International Renewable Energy Agency - IRENA, 2018)

5.3 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.

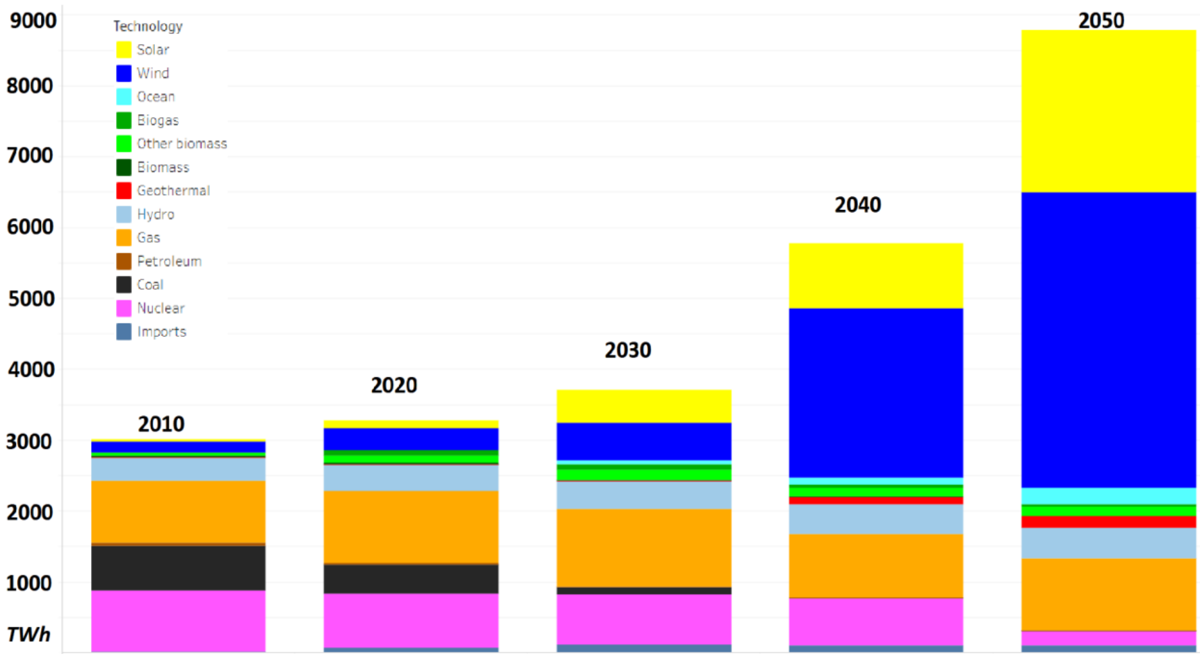
— **ProRES:** 80% CO_2 reduction by 2050; no new nuclear; no CCS.

In addition, a further 13 sensitivity cases were run and the detailed results are available in (Nijs *et al.*, 2018). The present report presents the results of the ProRES scenario and the associated sensitivity case Res4_SET which assumes targets of similar ambition with those of the current EU strategy. Under this model assumptions EU technology innovation is made consistent with the targets of the SET Plan i.e. very high GHG emission reductions by 2050, no significant additions of nuclear and significant improvements both in terms of technology efficiency and cost for solar PV, wind, geothermal and ocean energies.

Specific inputs include: a) CAPEX and fixed OPEX cost trends, together with learning rate values for three hydropower deployment options: RoR, reservoir LHP with advantageous characteristics (low-cost LHP) and LHP in less advantageous locations (high-cost LHP); 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 13 shows the JRC-EU-TIMES results for electricity generation under the selected scenario. Projections are provided for years 2020, 2030, 2040, and 2050. Hydroelectric generation increase in absolute terms over the analysed period from approximately 327 TWh annually in 2010 (374 TWh in 2020) to 426 TWh by 2050 (average values, excluding PHS). However, the overall share of hydropower decreases significantly, due to the rapid increase of wind and solar PV generation.

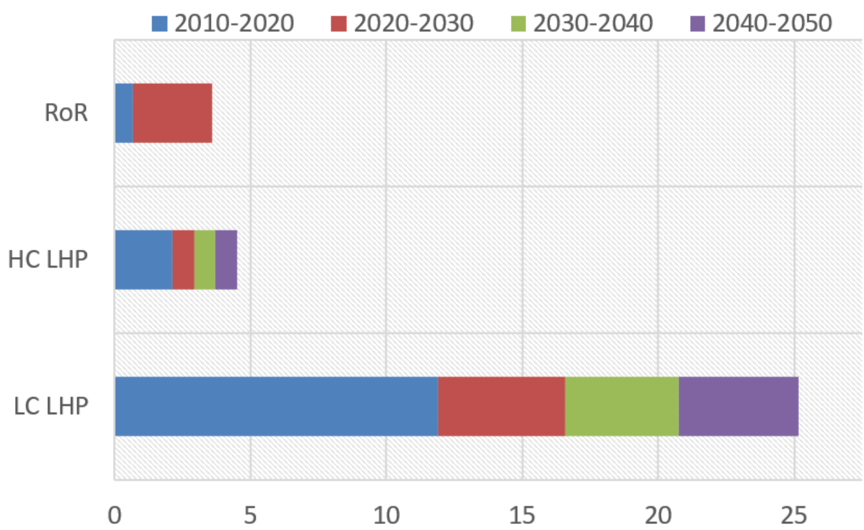
Figure 13. JRC-EU-TIMES model: distribution of generation (TWh) by technology for the pro-RES scenario (RES4_SET)



Source: JRC-EU-TIMES model results. Hydropower generation is shown with light blue

The overall capacity additions for all the energy technologies (low- and high-cost LHP and RoR) are provided in Figure 14. Overall, the model projections anticipate ≈33.2 GW of hydropower additions between 2010 and 2050 (18.5 GW in 2020-2050). Notably, JRC-EU-TIMES anticipates most of the installations to take place between 2010 and 2020 (14.5 GW). However, the developments to date and the short-term expectations show that this is not likely (see Figure 10).

Figure 14. Projections of the total added hydropower capacities (GW) in EU MS and the UK

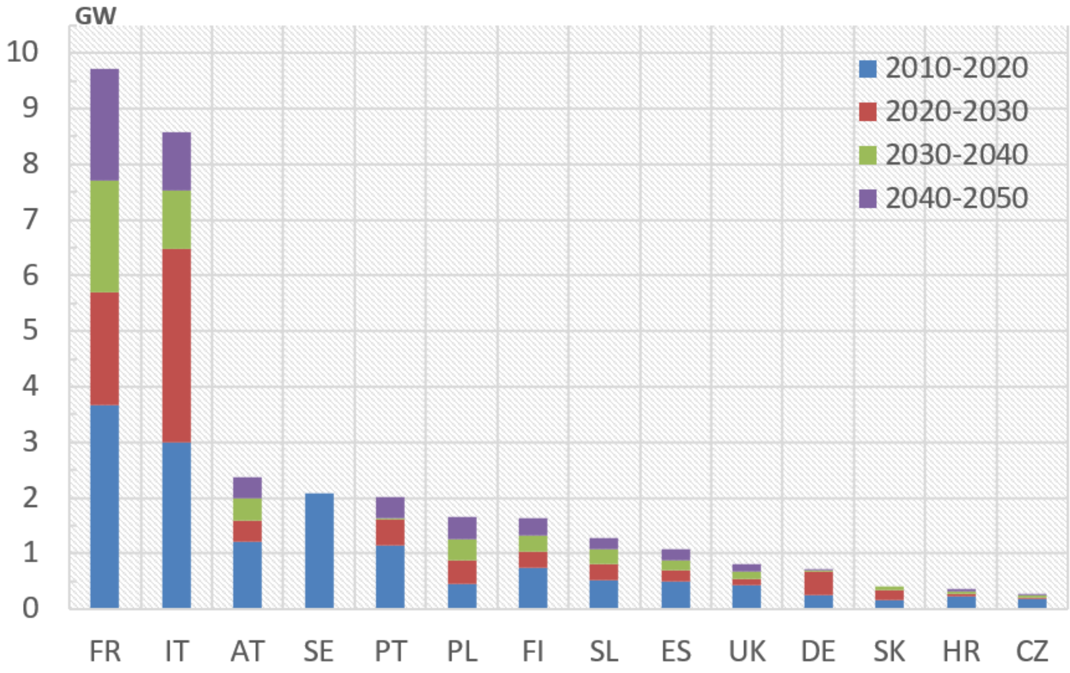


Source: JRC-EU-TIMES model results for the RES4_SET scenario

Three-quarters of the projected capacities for 2050 refer to stations larger than 10 MW (LHPs) with advantageous characteristics (LC LHPs). LHPs in less advantageous locations (involving higher-costs) constitute an additional 4.5 GW, while RoR stations 3.5 GW.

The scope of continental energy system models typically exceeds the provision of specific country-level results. Future projections are anyhow depending on a series of parameters and assumptions; accordingly, country-level results would require a different approach. Model output still shows plausible futures and reflect potential developments in MS. Figure 15 provides such country-level capacity additions over the analysed periods. Overall, JRC-EU-TIMES anticipates notable activity in fifteen MSs. The lion's share of projected installations are in France and Italy (≈55% of the total).

Figure 15. Hydropower capacity additions in the EU Member States in 2010-2050



Source: JRC-EU-TIMES model results for the RES4_SET scenario

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 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. 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 additional PHS deployment under all three analysed scenarios.

6 Conclusions and recommendations

The topic of wide-range and flexible operation is very high on the hydro R&D agenda. It has also been the subject matter of recent projects (AFC4HYDRO, Hydroflex, XFLEX) and is expected to be the focus of future projects, as highlighted in the emerging technologies analysis (Kougias *et al.*, 2019). Topics include 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 existing fleet of PHS and conventional hydropower stations will need to bear the growing demand for storage and dispatchable electricity generation. Increased levels of uncertainty under a variable climate may also exert additional stress on hydropower stations (De Felice *et al.*, 2020).

To reach higher levels of innovation, the electro-mechanical equipment of the hydropower sector calls for more digitalisation. The majority of existing hydroelectric facilities were built decades ago and use obsolete automation and control systems. Hydropower's operation and management should embrace progress in the IT sector to bring advancements in data availability-accuracy, analytical methods, simulation and operation strategies, which in turn will provide advanced levels of flexibility, secure operation at dynamic loads and frequent start/stop, and increase lifetime. Exploiting locations with a low- and very low-hydraulic head is a common aim of numerous research and deployment activities, due to the large percentage of untapped low-head potential in Europe. In most cases, low-head technologies are considered technically feasible, although they are not always economically viable or profitable. Therefore, priority is given to economic analysis aiming at cost-reduction strategies that will enhance the role of low-head hydropower. An additional reason for fostering this technology relates to the minimal impact it has on the environment, as it does not involve the construction of dams. So far, hydro equipment manufacturers have mainly been concerned with size and cost reductions. It is, however, essential to prioritise the costs of civil works and the development of new, cost-effective methods that can be replicated.

Efforts to minimise the environmental impacts of hydropower attract significant R&D attention. Designing fish-friendly technologies will improve hydropower's environmental footprint and lower its effects on biodiversity. More importantly, technical solutions could be applicable both in existing and new stations. Research activities have also focused on supporting decision-making on dam construction and operation. Earth Observation technology is an important tool for hydropower in terms of design, operation, and maintenance. It is also a basis to mitigate risk and reduce climate-induced uncertainties.

Hydropower R&D spans over a wide range of scientific disciplines and sectors. Recent efforts have thus focused on setting up forums and initiatives that enable the creation of a common strategy. Notably, such efforts target the EU as well as have a global perspective.

Recommendation: For some time the EU hydropower sector has highlighted the need to upgrade the aging EU fleet. To date progress is, however, limited. Future research activities need to focus on this priority area and provide a set of designs and components that facilitate the extended operation of hydropower at a competitive cost. Hydropower stations and PHS will continue to play a major role for the EU power systems for several decades. The modernization of existing stations is a unique opportunity to improve their environmental footprint and minimise impacts related to ecological flows, sediment transport, and biodiversity. This requirement has already triggered policy discussions and actions at EU level and internationally (International Energy Agency - IEA, 2016). R&D activities could be enabling factors and accelerate implementation.

Overall, Europe is driving the technology development of the global hydropower sector. EU-based institutions in collaboration with those of Switzerland and Norway are world leaders in hydropower R&D. This central role has been maintained despite the limited large-scale hydropower development in the EU over the last decades. In terms of hydropower component manufacturing, global leader companies are based in the EU and, together with numerous smaller ones, can supply electro-mechanical components and services globally, either directly or through subsidiaries. Technological advancements and a supporting policy framework are necessary to maintain the EU leading role in hydropower R&D. Moreover, a supporting framework will enable hydropower to contribute to the realisation of a low-carbon energy system compatible with the ecological conservation requirements. Flexible power systems coupled with PHS unique capability to provide bulk electricity storage services and significant amounts of low-carbon hydroelectricity are essential elements in reaching the energy and climate goals both at EU and global levels.

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List of figures

List of tables

KJ-N-BK-21-001-EN-N

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