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Analysis of emerging technologies in the hydropower sector☆

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ABSTRACT

The paper reviews recent research and development activities in the field of hydropower technology. It covers emerging and advanced technologies to mitigate flow instabilities (active and passive approach) as well as emerging magneto-rheological control techniques. Recent research findings on flow instabilities are also presented, especially concerning fluid-structure interaction and transient operating conditions. As a great number of the existing large-scale hydroelectric facilities were constructed decades ago using technologies that are now considered obsolete, technologies to achieve the digitalisation of hydropower are also analysed. Advances in the electro-mechanical components and generator design are presented; their potential role to adapt hydropower to the current operating conditions is also highlighted. The text explores current efforts to advance hydropower operation, mainly in terms of European projects. It provides a detailed overview of the recent efforts to increase the operational range of hydraulic turbines in order to reach exceptional levels of flexibility, a topic of several recent research projects. Variable speed hydropower generation and its application in pumped storage power plants are presented in detail. Moreover, revolutionary concepts for hydroelectric energy storage are also presented with the analysis focusing on underwater hydro storage and hydropower's hybridisation with fast energy storage systems. Efforts to minimise hydropower's environmental footprint are also presented via the utilisation of small-scale and fish-friendly installations.

1. Introduction

The present article analyses recent innovations related to hydropower technology development. Hydropower has provided electricity and storage services to central power systems for more than a century and mechanical energy for civilization development since ancient times (water wheels). Compared to other clean energy sources (e.g. wind and solar) it has achieved high levels of technological maturity. Accordingly, there exist fewer possibilities to identify and implement radical design concepts that revolutionise the way hydro operates. However, a significant potential for novel approaches in the planning, design and operation of a hydropower station still exists.

This potential partially derives from the evolving role of hydropower in the transforming electricity systems. Being an important source of grid flexibility and the main bulk storage technology, hydropower needs to adapt to opportunities and challenges dictated by the changing conditions. Any innovation aims at increasing hydropower's efficiency, the flexibility of operation, lifetime and to reduce the costs of installation, operation and maintenance (O&M). Technological progress and breakthroughs will enable hydropower to

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respond to variabilities of electrical power systems (EPSs), markets and climate. In particular, the increasing share of variable renewable energy production creates additional challenges for hydro facilities. At the same time, new hydropower development, as well as the upgrades and renovations of existing facilities need to comply with strict environmental standards.

In the European Union (EU), a large share of the available hydro potential has been already utilised and many stations have been developed before the 1970s [1]. Upgrading and renovating such stations is, thus, of particular interest in the EU context. The ageing hydropower fleet will require refurbishment to extend its lifespan, address ownership and operation issues and increase the level of security. Such interventions mainly need to focus on the electro-mechanical equipment (i.e. guide vanes, turbine, generator) and the associated control systems.

Hydropower technology development involves *trans*-technology knowledge transfer as it has benefited from new concepts and the latest advances in other sectors. Hydropower facilities are complex systems that incorporate a wide spectrum of different technologies into their components. Hydro stations, thus, function as a system of components. Accordingly, the operational characteristics and capabilities of each system depend on the technological features of its elements. It is important to highlight that every hydropower station is a unique system specifically designed to fit the particular site. And this is an important difference between hydro and conventional thermal power-plants or modular renewable energy source (RES) (e.g. wind, solar photovoltaic (PV)).

The article describes recent research and development (R&D) activities and trends that have brought innovation in hydropower and/or improved its operational characteristics. It also analyses components and their current technology readiness level (TRL); relatively low TRL values indicate an available potential for R&D activities. In 2017, the European Commission (EC) published the "Guidance Principles" [2] to define hydropower TRL. In general, hydropower system-wide TRL is very high with the exception of novel concepts that this article aims to highlight.

This research does not follow the typical procedure to prepare a review type article i.e. extensive bibliographic research. On December 2017, the authors met in a workshop organised by the EC Joint Research Centre. There, they discussed emerging technologies related to hydropower, analysed their TRL maturity and considered existing technical challenges and knowledge gaps relevant to their further development. In many cases, the technologies assessed were related to the authors' institutional R&D activities. The article is by no means an exhaustive collection of research activities related to hydropower. It is, to the best of authors' knowledge, an outline of important fields that can shape the future role of hydropower.

The analysed technologies and concepts can be distinguished into six groups, each one analysed in a separate section.

1. Techniques supporting the wide-range operation of hydraulic turbines;
2. Instabilities in Francis turbines of pumped hydro energy storage stations;
3. The digitalisation of hydropower operation;
4. Hydro generators with current-controlled rotors;
5. Variable speed hydropower generation
6. Innovative concepts in hydroelectric energy storage;
7. Novel technologies in small-scale hydropower;
8. Fish-friendly hydropower technologies;

2. Emerging control technologies to mitigate flow instabilities

The variable electrical energy production from renewable sources (wind and solar) requires that hydraulic turbines operate at a wide range and variable conditions [3]. Therefore, the modern hydraulic turbines meet new challenges associated with the variable demand on the energy market as well as limited energy storage capabilities, resulting in great flexibility required in operation over an extended range of regimes far from the turbines' best efficiency point (BEP) [4,5]. When hydraulic turbines operate at off-design conditions, a moderate- or high-level residual swirl occurs in the draft tube due to a mismatch between the swirl generated by the wicket gates (guide vanes) and the angular momentum extracted by the turbine runner [6]. At such off-design operating regimes, hydraulic turbines with a fixed pitch runner (e.g. Francis and propeller turbines), experience an abrupt decrease in efficiency [7,8] and severe pressure fluctuations [9–14]. As a result, unsteady phenomena occur in hydraulic turbines operated far from the BEP. These phenomena interrupt the turbines' regular operation through severe pressure fluctuations [15] that lead to vibrations [16,17], damage of the mechanical components [18–20], failure of the runner blade [21,22] and power swing [23–25]. Therefore, the research topic summarised in this section is associated to the flow control techniques to mitigate self-induced instabilities and their potential use in new projects as well as in refurbishment/rehabilitation projects of aged hydropower units.

The standard approach to simulate the performance of a prototype hydraulic machine includes experiments on model turbines to evaluate the turbine efficiency for the whole range of admissible discharge and head. The efficiency "hill chart" usually displays peak efficiency at the so-called BEP. The draft tube, the machine component where the flow exiting the runner is decelerated, converts the excess kinetic energy to static pressure. It displays an abrupt increase in hydraulic losses as the operating regime departs from BEP. Practically, the shape of the hill-chart is dictated by the losses in the draft tube for modern medium/low head hydraulic turbines [6].

The unsteady phenomena associated to the rotor-stator interaction (RSI) are significant for high head reaction hydraulic turbines [26,27] and pump-turbines [28] due to narrow gap between the leading edge of the runner blades and the trailing edge of the guide vanes.

The hydraulic turbine operation on a wide range is hindered by self-induced instabilities during the different off-design operating regimes and transient conditions (e.g. start-up, emergency shut-down, load rejections, and runaway) [29–35]. Therefore, both the structural integrity and the lifetime of the hydraulic turbine are diminished due to fatigue damages [36–39]. As a result, several techniques have been tested and developed to mitigate the effects. They are distinguished as either active or passive depending on the energy injected in the main flow [40].

A successful control technique that supports the flexible operation of hydropower plants within a wide range has the following features: (i) the control technique addressed the main cause of the self-induced instability rather than its effects; (ii) the method has a minimal (no) effect on the efficiency; (iii) the control technique can be switched-off at operating points where it is not needed.

2.1. Passive control techniques

The earlier attempts to analyse passive control techniques that address hydraulic instabilities in turbines' draft tubes were provided by Thicke [41] and later on in Ref. [13]. Passive control techniques do not require auxiliary power and control loop while the active ones require energy. A number of passive control techniques have been developed and/or tested in recent years. These passive methods are listed in Table 1 together with their advantages/drawbacks and technological readiness level (TRL) defined by De Rose et al. [2] stabiliser fins [42], J-grooves [43,44], runner cone extensions including freely rotation (FRUCE) concept [45–50], stator installed immediately downstream to the runner [51], adjustable diaphragm installed in the draft tube cone adjustable diaphragm [52,53]. Although passive control techniques lead to significant improvements in turbine operation at far off-design regimes, their components cannot be removed when their presence is no longer required. This leads to unnecessary hydraulic losses and

Table 1
Passive control methods.

Passive control method	Advantages	Drawbacks	TRL
stabiliser fins [42]	diminishing the draft tube surge	local hydraulic losses, effective to limited regimes	#9
J-grooves [43,44]	diminishing the draft tube surge	additional local hydraulic losses, effective to limited regimes	#4
runner cone extensions including freely rotation (FRUCE) concept [45–50]	diminishing the draft tube surge	lateral forces, decrease in kinetic energy recovery within the cone, effective to limited regimes	#6
stator installed immediately downstream to the runner [51]	diminishing the draft tube surges	additional hydraulic losses, effective to limited regimes	#2
adjustable diaphragm [52,53]	diminishing the draft tube surges on wide range regimes	additional hydraulic losses	#3
water injection with flow feedback method (FFM) [52–55]	diminishing the draft tube surge on wide range regimes, no additional volumetric losses, self-regulating,	not identified yet	#3

unexpected pressure fluctuations at different operating regimes. An alternative approach is the axial control jet supplied by collecting a fraction of the discharge from downstream the runner at the discharge cone outlet by installing a small spiral collecting case connected through return pipes to the turbine tubular shaft and the jet nozzle [54]. The pressure excess at the discharge cone wall, mainly due to the swirl, with respect to the pressure deficit at the runner crown tip, drives the control jet [55]. This method is self-regulated, since the pressure difference that drives the control jet decreases near the best efficiency regime, thus reducing or cancelling the jet discharge when it is no longer needed. This passive method is called flow feedback (FFM) [53,54] no additional volumetric losses occur, and no additional energy is required to drive the control jet.

2.2. Active control techniques

The active flow control methods generally use either air or water injection, using an external energy source. The main active control techniques are listed in Table 2: air injection/admission [56–59], tangential water injection at the cone wall [60,61], axial water injection with high/low velocity and low/high discharge [62–67], water injection with flow feedback method and additional energy (FFM+) [54,68], axial water injection with co-flow and counter-flow tangential component [69], inverse modulate water jet [70–72] and two-phase air-water injection along the axis [73,74]. The water injection at the trailing edge of the wicket gates is developed to mitigate unsteady phenomena induced by the rotor-stator interaction [75–77]. An active FFM with additional energy called FFM+ was developed in Ref. [68], installing two ejector pumps on the return pipes. The ejector pumps partially compensate for the hydraulic losses in the return pipes to reach the required threshold value of the jet discharge. Extensive experimental investigations showed that the wall pressure fluctuations are successfully mitigated when the jet reaches 12% of the main flow discharge for a typical part load turbine operating regime [54]. About 10% of the jet discharge is supplied by the plain flow feedback, and only 2% boost is provided by the ejector pumps, diminishing the volumetric losses (Fig. 1).

2.3. Magneto-rheological control techniques

The magneto-rheological control technique was recently introduced in Ref. [31]. They considered magneto-rheological brake (MRB) to slow down the speed of the runner in order to control the swirling flow configuration downstream of it and associated self-induced instabilities. The MRB device was designed, manufactured and installed on a swirling flow test ring to assess its performance. The swirling flow configurations and its associated unsteady effects are controlled by changing the speed of the MRB [79,80]. This active magneto-rheological technique diminishes, thus, the axial flux of the circumferential momentum by controlling the speed of the runner. An approach to keep the swirling flow ingested by the draft tube closed to the optimal configuration (i.e. flow with minimum draft tube losses and maximum pressure recovery) while the turbine operating point spans a wide range of discharge values was introduced in Ref. [81], named “Francis turbine with tandem runners”. With this approach, a downstream variable speed runner named “low-pressure runner” operates in tandem with the Francis runner with constant speed.

This concept is functionally different from various counter-rotating tandem-runner axial machines such as the bulb turbine [82], the counter-rotating micro-turbine [83], or the counter-rotating pump-turbine [84]. Using an additional axial runner in tandem with the main radial-axial runner has also been proposed in Ref. [85] for a radial-axial pump-turbine (the RAPT concept), but in this case, both runners are installed on the same shaft and rotate with the same speed.

Table 2
Active control methods.

Active control method	Advantages	Drawbacks	TRL
air injection/admission [56,59]	diminishing the draft tube surges on wide range regimes	additional losses, amplification of the self-excitation at a few operating points	#9
tangential water injection at the cone wall [60,61]	diminishing the draft tube surge	additional volumetric losses	#6
axial water injection with high/low velocity [62–67]	diminishing the draft tube surge	additional volumetric losses	#4
water injection with flow feedback method and additional energy (FFM+) [54,68]	diminishing the draft tube surge	not identified yet	#3
water jet with tangential component [69]	diminishing the draft tube surge	additional volumetric losses	#3
inverse modulate water jet [70–72]	diminishing the draft tube surge, modulated frequency targets a specific value	additional volumetric losses	#4
two-phase air-water injection [73,74]	diminishing the draft tube surge on wide range regimes	additional losses	#4
water injection at the trailing edge of the wicket gates [75–77]	diminishing RSI effects	additional volumetric losses	#2

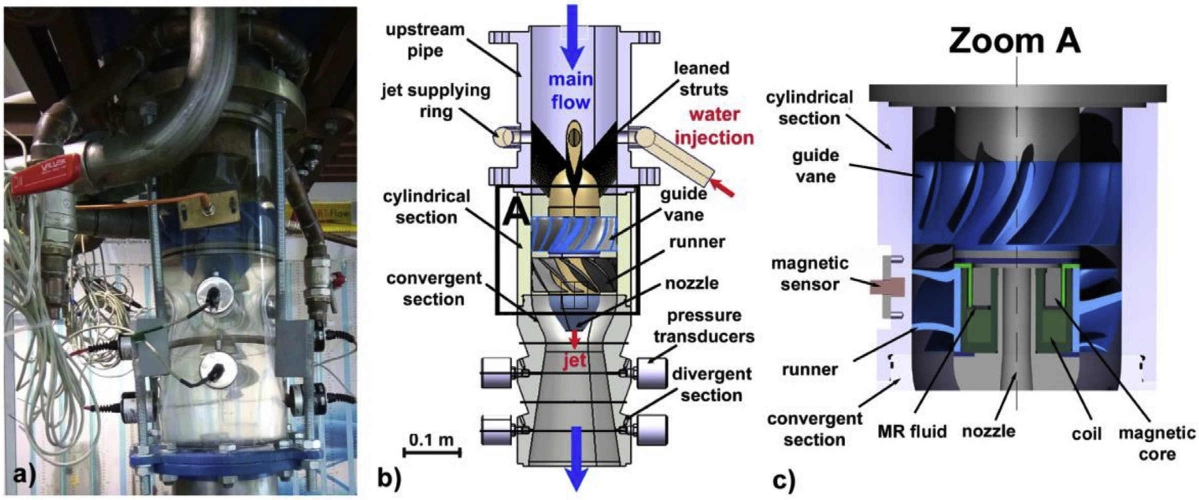

Fig. 1. Swirl generator test rig designed to investigate different control techniques: a) photo of the test section installed on test rig b) axial water injection [62–65] c) magneto-rheological control technique [78–80].

3. Instabilities in Francis turbines of pumped hydro energy storage stations

3.1. Fluid-structure interaction

Wider range and frequent changes in operating conditions including a large number of starts and stops, thin blade- and vane profiles due to high-performance requirements, and weight optimization, add complexity on hydro turbines' analyses of vibration behaviour and fatigue. Simulations during the design phase require the accurate determination of the dynamic response including dynamic stresses, hydrodynamic mass, and damping properties by means of reliable numerical simulations of Fluid-Structure Interaction (FSI) [86].

An important factor affecting the turbine lifetime and reliable operation are fatigue cracks in the runner, mainly from the rotor-stator interaction (RSI) and related pressure pulsations in the turbine. When the runner natural frequency is close to the RSI frequency, hydrodynamic damping is an important parameter in controlling turbine blade-forced response. A reliable technique that can predict the change in the runner natural frequency and damping is required. The frequency is mainly dependent on the added mass, but also on flow rate and flow conditions of the upstream and downstream of the runner and especially the draft tube. For a structure like the hydro turbine runners, the modal response is complex exhibiting many natural frequencies with entangled mode-shapes. Since for high head Francis turbine runners dynamic excitation due to RSI can be the main fatigue contributor, there is currently a big cooperative effort for investigating this problem, in terms of the HiFrancis project [87].

FSI-analysis of hydro turbines can be carried out in steps between the Fluid- and Stress analysis or fully coupled. Added-mass effect of surrounding water can be modelled with sufficient accuracy by an acoustic fluid approach, but the consideration of hydrodynamic damping effects and the identification of hydroelastic instabilities require more realistic descriptions of the fluid flow using Navier-Stokes (CFD) solvers. In contrast to aeroelasticity, where loose coupling schemes of different solvers are common, hydroelastic systems require strongly (iteratively) coupled solution procedures [88] or even monolithic formulations [89] in which the coupled system is assembled and solved in a single set of equations. The coupling between the Fluid and Stress analyses can be one-way or two-ways [90]. Structure's displacement affects the results of one-way and two-way coupling. Considering the large number of the parameters, two-way coupled analysis requires very large computing power and time. In addition, when the structure undergoes large deformations, the fluid mesh may be highly distorted and the mesh should, therefore, be repaired or iteratively adapted.

The fully coupled and the stepwise methods require validation and verification on simplified (disc or blade cascade) and real runner geometries' and high-quality model and prototype test data of natural frequency, pressure (including pressure propagation speed and dampening of pressure amplitudes), stress, speed, etc. at steady state and transient operating conditions.

The HiFrancis project performs experimental and numerical analyses of fluid-structure interaction focusing on the role of hydrodynamic damping, added mass effects on frequency, amplitudes of RSI, resonance and corresponding mode-shapes of high-head Francis runners. Understanding the fundamental physical mechanisms will help to develop accurate modelling and robust design procedures with increased dynamic loading of hydro turbines.

An important challenge is ensuring sufficient quality of laboratory and on-site tests to verify numerical tools. In the last 10–20 years, measurement techniques for strain gauge tests in rotating systems have been systematically improved. Nowadays, the stresses and other relevant parameters in a Francis runner are measured and transferred by a telemetry system [91–93]. Evaluations of strain gauge measurements in Francis runners show that RSI-induced stresses are especially relevant for medium to high head runners. The onboard measurements provided evidence of high mechanical stresses on the runner blades during the synchronization of the machine at speed no-load (SNL) operating condition. There is also evidence of the large fluctuations of the strain rate at the trailing edge of the runner blades close to the junction with the hub during the part load operation. Furthermore, damping assumptions are derived from strain gauge measurements. However, the extrapolation of these measurement results to new runner designs may lead to inaccuracies, because the influences of vibration mode shapes and flow conditions at different operating points are not fully understood yet.

3.2. Transient operating conditions

In the operation of hydro turbines, the transient processes such as start-up, no-load, load rejection and very low load are among the most damaging. Even though there is no power generation, there is still a significant amount of energy which needs to be entirely dissipated, mainly in the runner, where the flow is quite complex, with flow blockage and unsteady vortices resulting from partial pumping.

Computational Fluid Dynamics (CFD) has proved to be a tool for assessing the transient operating conditions with sufficient accuracy compared to measurements [94–96]. These simulations help the investigation of unsteady pressure pulsations during challenging operating conditions allow a better understanding of transient operations. 3D-CFD simulations are also used to study the influence of the changes of internal flow to the external characteristics during transient processes. Moreover, most of the transient processes are associated with significant discharge changes, causing water hammer waves, travelling back and forth through the whole piping system. These compressible effects introduce additional dynamics in transient processes and complexity to the simulations.

Simulations of the transient processes calculate the flow in the turbine (from the inlet of the spiral case to the exit of the draft tube) with 3D unsteady CFD analysis and the flow in the rest of the hydraulic system with a simplified 1D model that models the water hammer waves in the piping system, surge tank, valves etc. The coupling is realised by partly overlapping the 1-D and 3-D parts while guide vane closure/opening is treated by a moving dynamic mesh method.

Time-varying boundary conditions according to on-site measurements are crucial for the accurate prediction of transient pressure fluctuations. In the event that experimental data are unavailable, boundary conditions are taken from 1-D hydroacoustic simulations, imposing machine speed, flow rate and for the load-rejection case also the guide vane position. In case of pump-turbines, the computations extend through the *S*-shaped region of the machine in the turbine-brake and reverse pump domains, showing that such computations can be performed on a more regular base, although they are quite time-consuming.

A better understanding of transient operating conditions of hydro turbines may lead to further improvements of hydraulic and mechanical designs, machine stability, and reliability. Findings would indicate problematic regions in terms of structural load or load changes. This would allow improving the turbine start procedure in order to reduce stress and increase lifespan. Cavitation, in particular, would also be worth including in the simulations since it seems to play an important role during the start-up and runaway processes.

4. Digitalisation of hydropower operation

Most of the hydropower plants were designed decades ago, to work in conditions different from those required to them today. The massive penetration of solar and wind intermittent generation yields new conditions for the electrical power system (EPS), putting at risk its stability by a lack of inertia. Therefore, a key challenge for modern hydropower plants is to enhance drastically their flexibility by providing storage capacity and advanced system services that need to be further developed to support the integration of variable renewable energy (VRE). However, hydropower plant units actually experience hydrodynamic phenomena (see §1–2) that limit their flexibility.

The objective is, therefore, to gather and elaborate real-world (big) data on the actual working conditions of the turbines to enhance the capacity of hydropower plants to provide advanced grid supporting services, without compromising their safety and reliability. The objective of the emerging technology presented herein is to support hydropower plants to fulfil the future EPS requirements, by enabling fast frequency containment reserve (FCR), frequency restoration reserve (FRR) and black start in emergencies. This novel concept has not been studied so far and builds on the knowledge acquired in terms of recent research projects [4] where an extensive series of testing and experiments analysed the phenomena that need to be monitored and controlled.

Such a technological advance would build on the so-called digitalisation of hydropower, which will transform the way projects are designed, developed/upgraded, operated and maintained. Existing hydropower facilities were in many cases constructed several decades ago. Accordingly, the degree of digitalisation of their equipment is low compared to that of the O&M components and systems of modern RES e.g. wind turbines. The rehabilitation and upgrading of the existing fleet offer the opportunity to digitise the way hydropower equipment operates. Apart from the prolongation of the lifetime and addressing cyber-security risks, rehabilitation and digitalisation involve increasing the overall efficiency and, thus, the produced energy. Current estimations show that the digitalisation of the world's 1225 GW installed hydropower capacity could increase by 42 TWh the annual production [60], which is equal to USD 5 billion in annual operational savings and significant reduction of greenhouse gas emissions.

The aforementioned enhanced services to the grid will be achieved by increasing the operating range of turbines to enhance the operational flexibility of hydropower plants. Digitalisation will enable reducing drastically the response time of generating units or reversible pump-turbines. It will also allow assessing the economic impact of offering additional reserve flexibility. Overall, it still supports high-level safety and reliability standards for the hydropower plants.

The requirements for extended operating range and fast dynamics are stressing tremendously both the reliability and safety of the hydropower plants; unexpected outage being at risk. Therefore, only a disruptive approach could breakthrough this risk by linking physical engineering and data science to develop and validate turbine and systems digital avatar for harnessing the dynamics of the hydropower plant. The objective is to develop methods and tools for creating the "Digital Avatar" of hydropower plant dynamics and, therefore, enabling enhanced services to the grid. A multidisciplinary approach covering hydraulic machinery, EPS and its associated control and components fatigue modelling is required for the development of the Digital Avatar of hydropower plant dynamics (Fig. 2).

State of the art methodology for engineering and operating hydroelectric units includes advanced electromagnetic, flow and structural numerical simulations of the different hydraulic, mechanical and electrical components of the machine, [97,98]. Furthermore, extensive tests are performed to validate the aforementioned numerical simulations and, then, to secure the installation and operation of the units for reliable commercial operation. Therefore, gathering all the corresponding information into a comprehensive set of data enables to develop a digital avatar of the unit made available for supporting the flexible unit operation. In particular, the impact of transient operations such as start-stop can be assessed in terms of stresses, wear and tears and structural fatigue of the hydroelectric units.

Therefore hydroelectric infrastructure may become more compliant to changing and dynamic context conditions (climate, market and environmental safeguards) by introducing new design and operational paradigms (renewal, development). Current TRL is estimated at level 3 but the methods and tools to be developed are based on the latest findings and ongoing R&D. The tools and methods to be developed are expected to mitigate the risks for the next technology development stages of hydro units. As the extension of the operating range may entail additional stresses on the electromechanical equipment, the digital avatar of the hydropower generation system including turbine, generator and control, avoids said stresses by accurately and safely mimicking the dynamic behaviour of the equipment [99]. The advanced tools used include data analysis, advanced modelling, lifetime prediction and methods for predictive maintenance [100] or condition monitoring [101,102]. Such tools will further contribute to increasing the robustness and reliability of the path towards the next technological stages. Furthermore, the hydro technology performance will be further increased because digitalisation will enable new features to the hydropower plant, namely enhanced flexibility, which, therefore, will enhance the role of hydropower for wind and photovoltaic energy integration and for the stability of the electrical system.

Further to the Hydro Equipment Technology Road-map edited in 2013 by the former Hydro Equipment Association [103], the concept of a digital turbine has received increased attention and been extensively publicised [104]. However, very little has been really achieved so far to solve the scientific challenges of modelling and controlling the flow phenomena [14,105] experienced by the hydraulic units from still up to

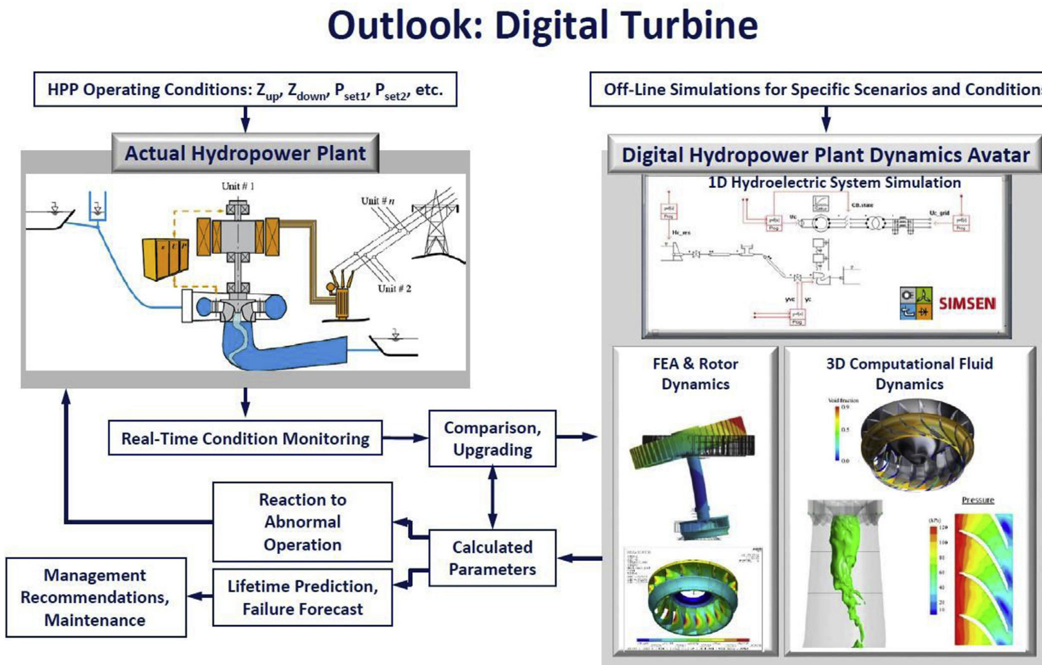

Fig. 2. Information flow & exchange of a Digital Avatar for hydropower plant dynamics. Source: authors' compilation.

full load operating range. In particular, recent knowledge advances in modelling and controlling turbines flow instabilities [66,106] and cavitation [107], pave the way to future technology development to enhance the operating range of hydro units. The European research project HYPERBOLE [4] is worth to be mentioned with respect to the assessment methodology of the turbine operating stability at off-design operating conditions. In particular, the prediction of the stability of Francis turbine based on modelling and reduced scale model tests has been validated [108–110].

In the case of reversible pump-turbine units, which are key components for the grid stability, it has been recently demonstrated [111], that the time to change from the pumping operation mode to generating mode can be drastically reduced to make this technology complying with the new grid specifications.

The ultimate aim is to develop a technology that allows the production of dispatchable hydropower in a changing context. This would allow an operation that provides inertia to the EPS and allows a higher penetration of RES. Advanced monitoring would also provide advanced levels of safety that are currently not available. The proposed technological development can also be applied in existing stations, transforming their modus operandi. Naturally, the technology needs to be transformed into tailor-made models that adapt to the particular characteristics of each power station. Additional research and development (R&D) challenges include the cost parameter as well as the necessity to render water and energy storage at different scales compatible with environmental safeguards.

5. Current controlled segmented generator rotors to reduce vibrations and add rotordynamic control

Frequent start and stops required to provide secondary regulation result in additional wear on the energy conversion components. Traditionally, inspections indicated to the maintenance engineer about the need to conduct maintenance works. Currently, condition monitoring is intended to provide information about the state of the components. The next step that is being attempted is condition-based maintenance. At the same time, sensors, data collection and data analysis (see §3) are becoming ever more available and cost-effective. Every large-scale hydropower unit is equipped with vibration, temperature, voltage and current sensors. Quite often, though, such sensors are only used for system protection and tripping of the unit.

The provided benefit would be increased if the components could sense the status of the unit *and* actively. Thus, not only the components would report but they would also counteract e.g. the vibrations. In that way, the system would provide some form of self-healing capability during emerging problems. Segmented rotors [112] and current-controlled rotor magnetization equipment has the potential of providing such a tool for generator air gap unbalances.

Normally, an active system requires additional actuators, but in the case of the segmented —or split— rotor (Fig. 3) the existing poles are used as the actuators. However, additional components are needed in the magnetization equipment in order to control the current. The idea is closely related to self-bearing machines where the radial force is controlled in the electrical machine from the stator side [113,114]. Here, the control is moved to the rotor instead and the circuit adapted to achieve the control.

The system can also be thought of as a magnetic balancing system that evens out disturbances in the air gap flux density. As has been shown, the system reduces extra losses and voltage harmonics and vibration levels as well. It is a lifetime extender since it has the potential to remove fatigue loads on the rotor and stator during operation.

Modern power electronics with current-controlled power supplies provide new opportunities for the control of electrical machines. The idea of a segmented rotor could be combined with novel ideas on excitation [115,116] to open-up possibilities for reduced investment cost and maintenance.

The most obvious use of a segmented rotor system is to reduce unwanted forces as they occur inside the generator. However, since it is a controllable force it can also be used to affect the rotordynamics of the shaft. In Fig. 4 a simulation of a Jeffcott rotor with an electrical machine inside is simulated with and without the added damping from the split rotor system. The rotor starts-off excentric and as the rotor spins it will whirl in the journal bearings.

If the damping is low, the whirling motion will persist. Adding damping would change the situation. This could be of interest in vertical machines where the stiffness of the journal bearings is quite low in the centred position of the shaft. Possibility to add a constant radial force would force the bearings to find a stable operating point. All

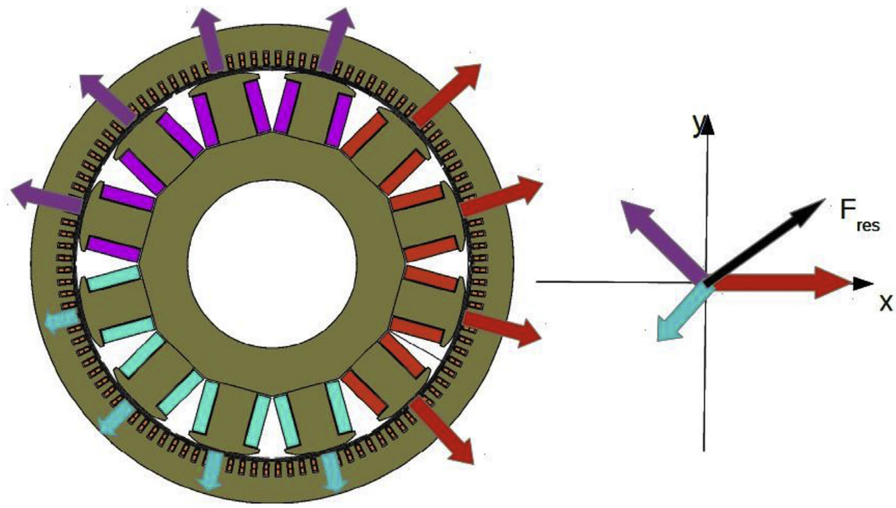

Fig. 3. Segmenting of the rotor field winding into 3 segments for a 12 pole machine. The segments have individually controlled magnetization currents indicated by different colours, with different amplitudes of field current. Depending on shape deviations, or motion, the amplitude is different and that balances the magnetic field, or gives the option to create a net force vector in any direction. Source: authors' compilation. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

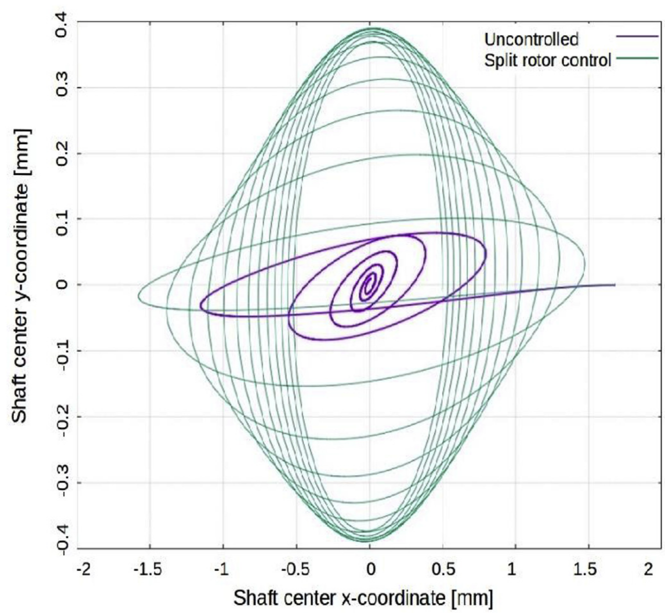

Fig. 4. Simulation of the whirling motion of a shaft supported by two bearings with low damping. The figure shows the centre of mass in a xy-coordinate system in mm. The green line corresponds to the undamped motion and the blue where damping is added from the split rotor system. Source: authors' compilation. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

active systems require some form of sensors, in the case shown above position sensors, strain gauges and flux sensors have been used to create the control signal. However, it is possible to use sensor-less control to remove dependence on sensors with a small loss of possible control features. Power electronic converters open up new possibilities for electrical machines. There is more to discover and it is expected that new ideas will enhance the coupling of electrical machines with power electronics.

6. Variable speed hydropower generation

The operating conditions of a hydropower plant can be highly variable. Variations in the operating conditions of the hydropower plant contribute to reduce the plant's global efficiency and may result in flow instabilities, cavitation etc. that reduce the lifetime of hydropower units. By varying the rotational speed of the hydropower plant's units with respect to their synchronous speed, the plant can better adapt to the to the hydrological regime of the river, thereby increasing the plant's global efficiency and the units' lifetime, and can also increase its contribution to the EPS ancillary services.

The above-mentioned speed variation is possible thanks to the use of power electronic converters, in either of the two following ways: converter-fed synchronous machine (Fig. 5a) and doubly-fed induction machine (Fig. 5b). In the current context of increasing penetration of non-synchronous VRE, variable speed hydropower units offer some important advantages for the operation of the power system, namely: better active and reactive power control, larger spinning reserve capacity. Variable speed pumped storage units are able to control both active and reactive power in pump mode, as well as start-up in pump mode and change the operation mode in a time shorter than conventional pumped-storage units.

a) Converter-fed synchronous machine.

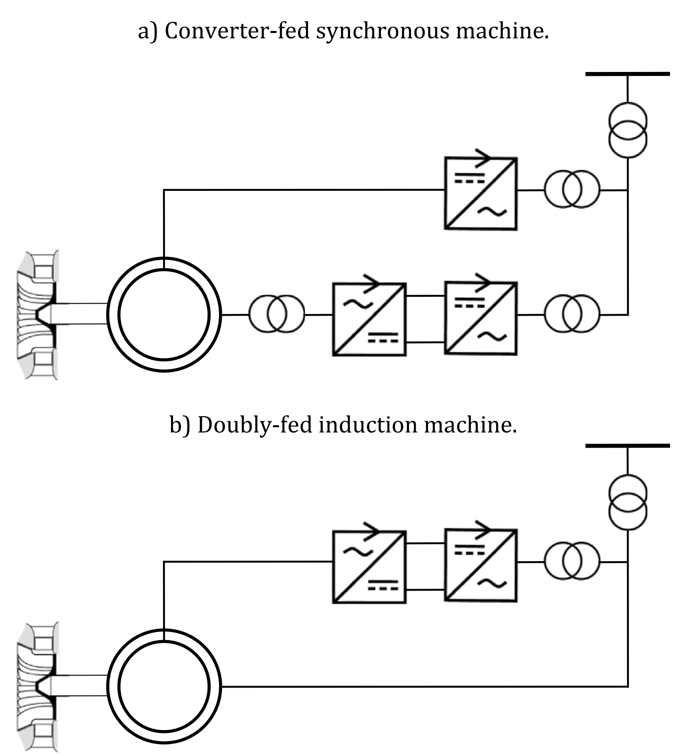

Fig. 5. Unit configurations for variable speed operation. Source: authors' compilation.

b) Doubly-fed induction machine.

Fig. 6 contributes to understanding the advantages of using variable speed Francis turbines. The figure shows the efficiency hill chart of a Francis as a function of the unit speed n_{11} and the unit flow q_{11}, which depend on the rotational speed n, the flow released through the turbine q, the net head h and the turbine diameter D, as described in equations (1) and (2), respectively. The area within the red curve represents the recommended operating range of the turbine. Blue and black solid lines represent unit speed and unit flow for two different gross heads (h1, h2) at synchronous speed (150 rpm), whereas blue and black dashed lines represent unit speed and unit flow for the same water levels in the reservoir at 118.5 and 158.5 rpm, respectively. In both cases (h1 and h2), the turbine efficiency increases in all operating points thanks to varying the rotational speed. In the first case (h1), varying the rotational speed of the turbine also allows the unit to operate with a gross head lower than the minimum recommended for fixed speed operation, and in the second case (h2), it allows enlarging the range of operating flows for a given gross head.

$$n_{11} = \frac{nD}{\sqrt{h}} \tag{1}$$

$$q_{11} = \frac{q}{D^2\sqrt{h}} \tag{2}$$

Fig. 7 contributes to understanding the advantages of using variable speed pump-turbines in pump mode. Blue and black solid lines represent, respectively, pressure head-flow and hydraulic power-flow curves of a Francis pump-turbine operating in pump mode, for different rotational speeds (from 0.90 to 1.02 p.u.). The green solid line represents the pressure head-flow curve of the power plant's conduits for a given gross head. As can be seen in the Figure, at synchronous speed, the pump-turbine has a unique operating point (p_{syn}). Varying the rotational speed allows the unit to modify the hydraulic power transferred to the fluid from p_{min} to p_{max}, and therefore the electrical power is taken from the grid.

Variable speed hydropower generation began receiving attention in the scientific in the 1980s. Gish et al. (1981) studied the possibility of using doubly-fed induction machines (DFIM) in hydropower plants [117]. Using fully-fed synchronous machines was already at that time technically feasible [118], but not economically.

In the second half of the eighties of the past century several engineers working for Hitachi Ltd. got several patents for diverse pieces of equipment and control systems for variable speed hydropower generation and pumping [121–123]. The first variable speed pumped-storage unit was commissioned in Japan in 1987 by KEPCO (Kansai Electric Power COmpany) [124,126]. Three years later TEPCO (Tokio Electric Power COmpany) commissioned the second variable speed pumped-storage unit in Yagisawa pumped-storage plant (PSPP.

A few more variable speed pumped-storage units have been commissioned in Japan since then, namely [128–134] [1]: two 400-MW units at Okhawachi PSPP, one 100-MW unit at Takami PSPP, one 300-MW unit at Shiobara PSPP, one 300-MW unit at Okukiyotsu, one 30-MW unit at Yanbaru PSPP; four 340-MW units at Omarugawa PSPP; and one 400-MW unit at Kazunogawa PSPP.

The main motivation to commission variable speed pumped-storage units in Japan has so far been the high penetration of nuclear generation. It adds some difficulty to the power system operation, particularly during off-peak demand hours when it's necessary to schedule an excessive number of thermal generating units to guarantee adequate frequency control [135].

In China, the first (and only so far) variable speed pumped-storage unit was commissioned in 1989 as part of the Panjiakou PSPP [136]. The unit is equipped with a fully-fed synchronous machine, being the first of its kind at that time. The motivation to install the variable speed unit of Panjiakou was the large variation in the plant's operating conditions, particularly in the water level of the upper reservoir [137,138].

[1] The installed power capacity and year of commissioning of the above-mentioned units slightly vary across the cited references.

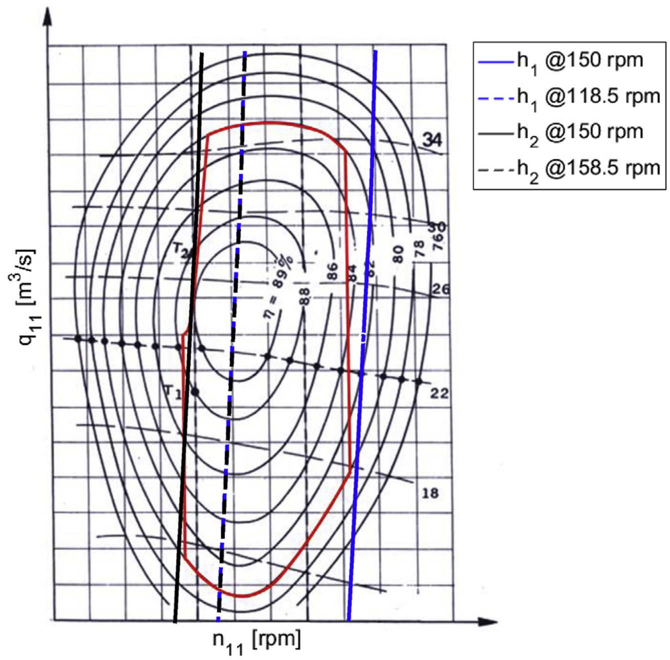

Fig. 6. Advantages of variable speed operation for a Francis turbine. Source: authors' compilation.

In the 1990s and the early 2000s, several projects were undertaken to demonstrate the feasibility of variable speed operation in small hydropower plants, some of which are listed next:

- the 378-kW variable speed Kaplan tubular turbine with fixed guide vanes, installed in Ingelfigen small hydro to deal with the head variation [139];
- the 60-kW variable speed PAT (Pump operated As Turbine) installed in the drinking water network of Sion, Switzerland, for pressure control [139];
- the replacement of the salient pole rotor a 10-MW unit of Compuerto hydro plant with a three-phase wound rotor fed by a cycloconverter [140];
- the addition of a 21.3-MW frequency converter to Forbach PSPP to let one of the pump-turbine units operate at a variable speed [141];
- the 50-kW variable speed hydropower unit with permanent magnet excitation installed to control the water level in a small pond in the river Tirva, Finland [142].

However, it was not until 2004 that the first large variable speed hydropower units were commissioned in Europe when Goldisthal PSPP began operation. Goldisthal is equipped with four 265-MW pumped-storage units, two of which are connected to the grid through a DFIM. Goldisthal's variable speed units operate an average of 19 h a day providing frequency containment and restoration reserves [143].

Since then, three new variable speed PSPPs have been commissioned in Europe, all of them equipped with Francis pump-turbines and DFIMs, namely: Avče, in Slovenia, with an installed power capacity of 180 MW (1 × 180 MW) [144,145]; Linthal, in Switzerland, with an installed power capacity of 1000 MW (4 × 250 MW) [146,147]; and Frades II, in Portugal, with an installed power capacity of 780 MW (2 × 390 MW) [144,148]. In addition, it's worth mentioning the refurbishment project of Grimsel II PSPP, in Switzerland. Grimsel II PSPP is equipped with 4 horizontal-axis ternary units, each with a Francis turbine and a radial pump and an installed power capacity of 80/

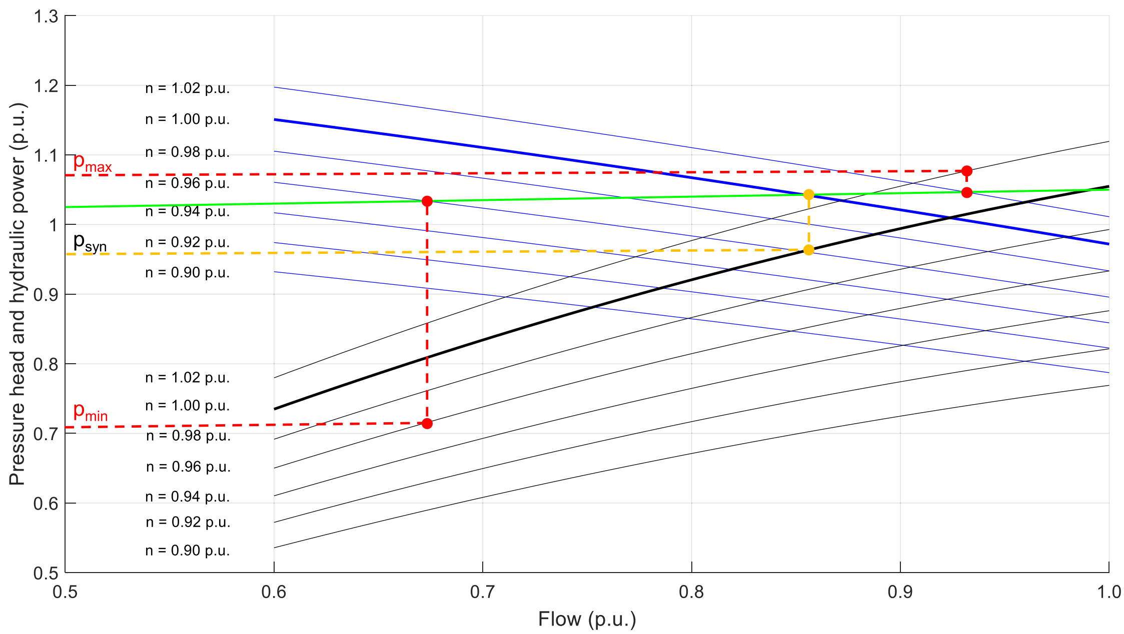

Fig. 7. Advantages of variable speed operation for a centrifugal pump. Source: authors' compilation.

90 MW in turbine/pump mode. One of the units was equipped with a 100-MW frequency converter (world's record for this type of application) in May 2013 and is since then operating at variable speed in pump mode (the converter is bypassed in turbine mode) [149].

Three more variable speed PSPPs will likely begin operation in the following three years, namely: Nant de Drance PSPP, in Switzerland, will be equipped with six 150-MW pump-turbines, each coupled to a DFIM [146,150]; Fengning PSPP, in China, will be equipped by twelve 300-MW pump-turbines (six units are already in operation), two of which will be coupled to a DFIM [151]; and Tehri PSPP, in India, will be equipped with 4250-MW pump-turbines, each coupled to a DFIM [152]. In addition, two old 303-MW pumped-storage units of Okutataragi PSPP, in Japan, are being upgraded for variable speed operation and will begin operation soon [124,153]. The old pump-turbine runner will be replaced with a new one specifically designed for variable speed operation, and the old synchronous machine will be replaced with a DFIM [154].

As can be deduced from the above summary, variable speed hydropower generation has already reached the highest possible TRL. There are, however, only a few variable speed hydropower units (most of which are pumped-storage units) in operation all over the world. The reasons for the slow pace of installation of variable speed hydropower units are of diverse nature. Some of these reasons are the following:

– -It usually takes a long time from the conception of a hydropower project to the commissioning of the hydropower plant, in part due to complex administrative procedures [155].
- New hydropower developments often raise a wide range of environmental concerns [156].
- The extra revenue a variable speed hydropower plant can gain in the electricity and ancillary services markets is not always worth the extra cost necessary for the plant to operate at variable speed [157]. This extra cost was estimated in Ref. [158] to range from 7% to 15% of the investment cost of a fixed speed hydropower plant.
- In some countries, there is no sufficient regulatory certainty for investments in hydropower [159].

Despite the foregoing, there are still some technological challenges left that, once overcome, might contribute to enlarge the above-mentioned advantages of variable speed hydropower generation. Two important challenges are [147]:

- Enlarge the stable operating range of hydraulic machines in order to take full advantage of variable speed operation.
- Enhance the insulation system of converter-fed machines.

7. Novel concepts in hydroelectric energy storage

The increasing penetration of variable renewable energy (VRE) in the electrical power system (EPS) is boosting the innovation in energy storage. Even though PSPP is a mature storage technology, it continues to evolve [160] to respond to the faster and more frequent mode transition requirements i.e. from pump to turbine and vice versa. As for other more recent energy storage technologies, VRE is acting as the main driver for such an evolution. This section summarizes the state-of-the-art of two emerging PSPP technologies which, in the authors' opinion, have significant potential.

7.1. Coordinated operation of fast energy storage systems and hydropower

Renewable generation is usually connected to the grid through power converters (i.e. non-synchronous). Non-synchronous generation is usually not required to provide synthetic inertia or load-frequency control. Therefore, for a given demand load in a given power system, the larger the instantaneous penetration of non-synchronous generation, the lower the synchronous inertia provided by conventional synchronous generation and the larger the rate of change of frequency and the frequency deviations (in absolute value) under contingency events [161–165].

Hydropower turbines currently provide inertial response and are well suited to provide load-frequency control as established in Ref. [166]. However, when the system inertia is low, fast-acting frequency responsive units are needed to maintain the system frequency within the standard frequency range [167,168].

The coordinated operation of fast energy storage systems (i.e. inverter-coupled) and hydropower would allow a better frequency control in the electrical power system, with lower wear and tear of the hydropower units. Among the various existing inverter-coupled energy storage technologies, flywheels and supercapacitors are probably the ones that are best suited for frequency control applications. Both are

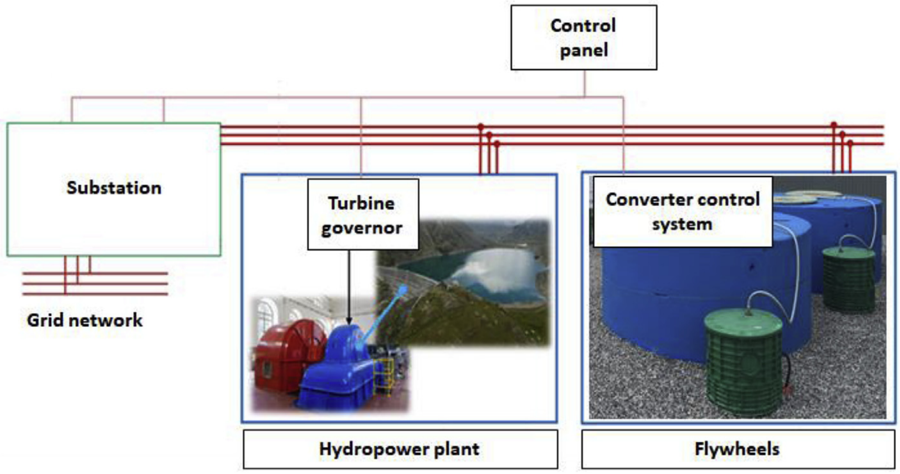

Fig. 8. Potential layout of a hybrid flywheel/hydropower system. Source: authors' compilation.

able to withstand a large number of continuous charge-discharge cycles, but usually, have a small energy storage capacity and can, therefore, control their active power output/input for a small amount of time (from a few seconds to a few minutes) [169]. Hydropower generation has, in turn, lower frequency response but can usually control its active power output for a longer time (from a few hours to a few days, or even longer). Flywheels and supercapacitors can be easily integrated into existing hydropower plants and fully operational in a very short time (few months). Their integration in existing hydropower plants might provide additional benefits to the voltage control in the vicinity of the power plant. It would be also possible to coordinate the operation of existing hydropower plants with a fast energy storage system connected to the transmission power system in another network node, or even with a set of them geographically distributed. A potential layout of the hybrid system can be seen in Fig. 8.

The coordination of fast energy storage systems and hydropower has not yet been demonstrated in an operational environment. The technology was partially brought to a TRL 4 by a research team of the Pacific Northwest National Laboratory (PNNL), as a result of a research project titled "Wide-area energy storage and management system to balance intermittent resources in the Bonneville Power Administration and California ISO control areas".

Phase–1 of the project [170] included the development of a control algorithm for an aggregate regulating unit, comprising a hydropower unit and a flywheel, to follow the area control error (ACE) signal. The control algorithm was tested by means of computer simulations. The results of the simulations showed that the aggregate regulating unit may provide a robust and accurate ACE signal tracking, and that the flywheel may help to keep the hydro unit operating point close to the best efficiency, while the hydro unit may help to hold the flywheel's state of charge (SOC) within the desired range.

In Phase–2 of the project, the PNNL successfully tested the control algorithm with a 25-kWh, 100-kW flywheel provided by Beacon Power by means of hardware-in-the-loop simulations [171,172]. Based on the concept, an improved version of the control algorithm [173] and a patent [174] were published.

The contribution of a flywheel energy storage system to the frequency control of El Hierro wind-hydropower system was addressed in Ref. [175]. Different control strategies were tested by means of computer simulations. In order to properly distribute the frequency regulation effort between the flywheels and the hydropower units, different control dead-bands were assigned to each technology. The results presented in Ref. [175] point out that, in El Hierro power system, a flywheel energy storage system with a power rating of 3% of that of the pumped-storage power plant can help significantly reduce the amplitude of frequency oscillations caused by the variability of wind power production, and thus to integrate more wind power in the electrical power system.

The coordination of a supercapacitor energy storage plant and a run-of-the-river hydropower plant equipped with a doubly-fed induction generator to provide frequency regulation was studied in Ref. [176]. The supercapacitor energy storage plant was assumed to provide a virtual inertial response, whereas the hydropower plant was assumed to provide frequency regulation. The results presented in the paper demonstrated the benefits, in terms of frequency quality, that providing an inertial response with fast-acting energy storage systems and frequency regulation with medium-fast generation units can bring to the EPS. The virtual inertial response provided by fast-acting energy storage systems helps reduce (in absolute values) the system rate of change of frequency). Thus, medium-fast generation units are able to contain the frequency deviation within a narrower band.

The power generation system of Flores Island, in the Azores Archipelago, is composed of 4 small hydropower units, 2 wind and 4 diesel generators, and a flywheel [177]. Even though to our knowledge there is no explicit coordination between the hydropower units and the flywheel, we believe it's worth mentioning such a unique power generation system.

The International Hydropower Association (IHA) estimates that the world's total installed hydropower capacity (including pumped-storage) was 1267 GW at the end of 2017 [178]. Assuming that each existing hydropower and pumped-storage plant (PSPP) were complemented by fast energy storage with e.g. 5% of the installed hydropower capacity, new 65 GW of fast energy storage systems, distributed among several thousand projects, would have to be manufactured, installed and commissioned worldwide. This would definitely contribute to creating appealing market opportunities for, and to strengthen the competitiveness of a wide number of agents.

7.2. Underwater pumped-hydro energy storage

An important limitation of PHES is that it can only be developed in geographically suitable locations. The underwater pumped hydro energy storage (UPHES) is a novel pumped storage concept in which the upper reservoir is the sea itself and the lower reservoir is a hollow deposit (or a set of) located at the seabed. The seawater entering the deposit drives a turbine and generates electricity. The deposit is emptied by pumping the water back to the sea, thus storing part of the electricity consumed in the form of potential energy. The concept was devised with the aim to enlarge the number of potential locations for PSPP. The operating principle of UPHES is summarised in Fig. 9.

The technical viability of UPHES was analysed for the first time by a research team from the Massachusetts Institute of Technology (MIT)

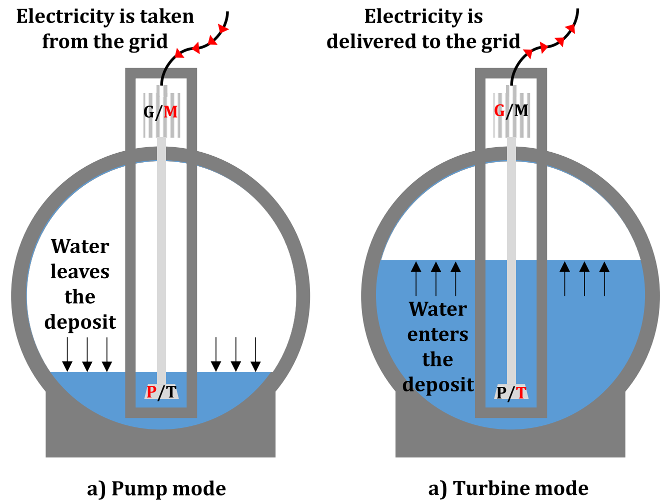

Fig. 9. Operating principle of UPHES. Source: authors' compilation.

between 2008 and 2011 [179]. For this purpose, the research team built a concrete spherical deposit with an inner diameter of 75 cm, equipped with a micropump and a microturbine of approximately 125 and 400 W, respectively. The test unit was successfully tested both in turbine and pump mode with and without a vent line (i.e. a pipe from inside to outside the sphere aimed to keep the pressure inside the sphere near the atmospheric pressure). The tests showed that without the vent line the energy stored per volume capacity and the power output of both the turbine and the pump increase. However, the power output significantly varies with the internal pressure. Spain was identified in Ref. [179] as the location with the largest suitable area for installing UPHES.

The UPHES concept has recently been brought to a TRL 5/6 under the framework of the Storing Energy at the Sea (StEnSea) project [180]. The techno-economic viability of UPHES was addressed in the first phase of the StEnSea project. Main design parameters of the system were defined from the results of the techno-economic viability study, namely: material, location, shape, size and installed power capacity of each deposit. The conditions for potential sites were described in Ref. [181] and include a water depth ranging from 600 to 800 m, a slope of the seabed not greater than 1°, and a distance to the electrical grid/maintenance bases/installation bases lower than 100/100/500 km. A smaller feed pump was also proposed to be used instead of the vent line to avoid cavitation in pump mode [182]. Unfortunately, the results of the techno-economic viability study demonstrated that the price arbitrage in the German spot electricity market does not guarantee the economic feasibility of UPHES.

According to Ref. [182], the potential available energy storage capacity (technical) in the top 10 countries in Europe/worldwide is 166.2/817.3 TWh. Spain and Italy are the two European countries with the highest potential. In the second phase of StEnSea, a 1:10 scale model was installed at 100 m depth in the Konstanz Lake. It was successfully tested for a 4-week period at the end of 2016 [183].

In addition to the above-mentioned research projects, it is worth mentioning the research carried out at Chalmers University of Technology [184] and the Technical University of Madrid [185]. Assessing the economic viability of UPHES in Denmark [184] showed that the price arbitrage in the spot electricity market does not guarantee the economic feasibility of UPHES. The research presented in Ref. [185] took a step ahead of [184], and assessed the economic viability of UPHES in Spain, considering the participation of the system in both the spot electricity and the frequency containment reserve markets resulting in similar conclusions as those in Refs. [181,184]: the current market conditions in Spain render the investment in UPHES infeasible.

The analysis of [185] followed the methodology used in Ref. [186] to calculate the levelised cost of energy (LCOE) delivered by UPHES and the net levelised cost of storage (LCOS) and concluded that UPHES is fully competitive with compressed air energy storage (CAES) and conventional PSPP.

8. Technology development in small-scale hydropower

The development of new large-scale hydropower plants is challenging mainly, due to the environmental impacts of dam construction that hinder their licensing. Small-scale hydropower is generally more eco-friendly and can potentially offer an alternative clean energy solution in the variable electricity market. The current policy and operational framework for small hydro do not guarantee viable economic terms with favourable payback period [187]. Optimised operation and control technologies [188] and combined installations-operation with other energy technologies such as PV [189] could also increase its profitability.

Small-hydro plays an important role in mini-grid and rural electrification strategies, particularly important in developing countries mini-grids [191,192] support economic activities in remote areas [188,189].

8.1. Novel designs of gravity hydraulic machines

In the micro hydropower field, there is an unexploited potential with low head differences (few meters) available in rivers, irrigation canals and at old mill sites [193,194]. Existing technologies are not always cost-effective at such scales [195,196], especially for power output below 50 kW. Recent advances in gravity hydropower converters (hydrodynamic screws and gravity water wheels) have improved their cost-effectiveness; their environmental impacts, especially on fish populations, are minimal [197] and their efficiency is attractive.

Gravity water wheels have been extensively tested in terms of recent scientific projects [198,199]. They are distinguished into (i) overshot [200]; (ii) breastshot [201] (iii) and undershot water wheels, depending on the head differences and the maximum flow rate per metre width [194]. Maximum hydraulic efficiency of gravity machines may exceed 80% [202] but typical values of global efficiency range at 50–70%. Water wheels cost is 33–60% of that of Kaplan turbines, and lower than that of hydrodynamic screws [197]. Water wheels are advantageous when it is possible to revamp existing civil structures such as old water mills, becoming attractive educational, tourist and recreational locations.

The power take-off (PTO) system is as an important aspect to be improved. The rotational speed of water wheels is generally low and requires a gearbox to match the generator frequency. This results in a very expensive PTO. Preliminary works have been conducted to overcome this deficit, by testing a new transmission system [203], because permanent magnet generators could be used in these situations, but they require reasonably complex power electronics [204]. An additional approach tested the use of adjustable inflow structures that can be managed as a function of the flow rate. Some studies have already been carried out for gravity water wheels [194,205]. Such approaches were tested in the laboratory [201] where a model of an existing breastshot water wheel (Fig. 10) was tested at a 1:2 scale (Froude similarity).

New water wheels in development, still at the prototype stage, include the hydrostatic pressure machine (HPM) and the turbine water wheel (TWW). The HPM is a water wheel that can be used in flowing water, without any canal drop, achieving a hydraulic efficiency of 60–65%. The HPM generates an increase in the upstream water depth. This creates a hydrostatic force on the blades that compensates for the low levels of kinetic energy [206,207].

The TWW represents a water wheel that can be used for the head differences of an overshot water wheel (up to 6 m) and flow rates of an

Fig. 10. Breastshot water wheel in Verolengo, Italy and its laboratory 1:2 model [201]. Source: authors' compilation.

undershot water wheel (few m^3s^{-1}). Preliminary experiments have been conducted with a small-scale prototype (30 cm wheel diameter, scale < 1:10), indicating a current TRL 4 [208].

8.2. Advanced design and operation of pumps as turbines

Pump as turbines (PAT) are hydraulic pumps operating in reverse mode as turbines, thus producing energy rather than consuming it by means of a connected induction motor working as generator [209]. In Fig. 11 is displayed a standard centrifugal PAT linked to a torque meter and induction generator. Hydraulic pumps are mass-produced globally and the main advantages of their application as turbines include compact dimensions, short delivery time, easy maintenance and availability of spare parts, and reduced installation cost [210–214].

With respect to conventional turbines, the cost is 5–10 times lower [215]. This is particularly significant in the context of micro hydropower schemes having installed power less than 100 kW where typically the 35% of the total scheme cost corresponds to the purchase of the turbo-generator unit [216,217]. At the same time, though, the use of PATs brings about a few drawbacks:

vii. lower peak hydraulic efficiency with respect to a conventional turbine;
ix. a general lack of performance data provided by the manufacturers;
x. design uncertainties and associated risks for designers and users;
xi. the lack of in-built regulation devices (e.g. wicket gates, movable-pitch blades) commonly results in poor part-load performances.

Despite the benefits associated with the use of PATs, their share in the hydro turbine market until now has been negligible. This is partially attributable to the lack of knowledge or interest on the topic from pump manufacturers and hydropower consulting firms (point ii), and partially to the few technical challenges yet to be addressed regarding the PAT design and operation (part iii). Indeed, the current technology readiness level of PAT technology is estimated at TRL–4 due to limited knowledge on the design and operation characteristics of reversed pumps [218].

So far, existing PAT-based schemes typically feature a nominal power below 20 kW even though a few examples of larger installations exist [219]. The most outstanding field of application of PATs is powering off-grid rural electrification projects in remote areas, where local hydro turbine suppliers are not available [209,220,221] and energy recovery in pressurised water networks [222].

The main research directions on the topic of PATs can be grouped into 4 topics:

a. The first aims for improved performance prediction of PATs and reduced design uncertainties by reliably predicting the characteristic curves of any machine with respect to their known behaviour as pumps. The main efforts point towards the development of numerical methods based on empirical data from tested pumps/PATs or the refinement and validation of CFD models [223–227].
b. A second topic aims at improved control of PAT installations under variable flow and head conditions, typical in drinking and irrigation water networks. Such methods rely either on mechanical devices as automated valves and hydraulic bypass ducts (hydraulic regulation), on the adoption of a variable-speed drive (electric regulation) or on a combination of both (hydraulic-electric regulation) [228–230]. Intermittent Operations is an investigated design solution [130] with a limited application in hydro schemes [222].
c. PAT geometry modification in order to improve the performance of a pump when used as the turbine is a third thematic area. This includes measures such as inlet impeller rounding and suction eye

Fig. 11. Hydraulic test rig to evaluate the performance of Pumps as Turbines at Trinity College Dublin under the Dwr Uisce project: a) view of the assembled turbine, inline torque meter and induction generator; b) overall view with a flow meter, control valve and pressure reading gauges. Source: authors' compilation.

enlargement [231];

d. In a fourth thematic area PATs are coupled with innovative generator types and configurations other than induction alternators, such as permanent magnet or self-excited induction generator machines [232].

The ultimate goal is to produce a design methodology ultimately leading to a wider application of such units to tap a significant potential otherwise dissipated. To address the lack of performance data, a recent study proposes a statistical method to obtain the turbine mode characteristics from the pump manufacturer data [233]. Besides the academic environment, examples of commercial R&D activities include solutions for PAT utilisation in water networks developed by EPFL/HES Wallis in terms of the DuoTurbo project [234] Tecnoturbines in the EU [235], Rentricity in the US [236] and a modular PAT-based turnkey containerised powerhouse [237].

8.3. Assessment of hydropower potential in existing infrastructure

Untapped hydro potential lies in existing small dams developed in rural-agricultural areas to meet various needs not related to energy production such as irrigation, drinking water supply [190] or flood mitigation [238]. Dam construction and the required civil works constitute up to 60% of the capital cost of new hydro [238]. Accordingly, the transformation of such dams to hydroelectric facilities, when possible, typically involves a fraction of the total cost and time.

The first large-scale assessment of such potential was conducted in the U.S [239]. and the influential analysis revealed that the transformation of the U.S. non-powered dams (NPDs) could add up to 12 GW of hydropower capacity. The analysis in Ref. [240] estimated the potential in NPDs of sub-Saharan Africa states at 243.5 MW. To date, a similar analysis has not been performed for large parts of the world hampering the identification of the first-rate advantageous NPDs.

9. Fish-friendly hydropower

The environmental and ecological characteristics of hydropower plants have been the objective of several research projects. The objective of these projects has been the fish population, the design of fish-friendly turbines and the development of water-lubricated bearings in turbines to mitigate water pollution risk. Research activities related to water-related challenges such as securing the required environmental flows to enable ecological conservation and the water-energy-ecosystem nexus interactions exceed the scope of the present article as they are not of purely technological nature.

Although hydropower is the largest source of clean electricity, hydro plants may generate adverse effects on ecosystems. Allowing fish migration is of primary importance in ecosystem preservation, especially during the spawning and migrating bio-period. Aiming at minimizing turbine-induced mortality of downstream migrating fish populations, an eco-hydraulics approach is adopted in hydropower plants' design. Contrary to the conventional turbines, low head gravity turbines (water wheels, hydrodynamic screws) are considered fish-friendly. However, these turbines can be only employed at very low head sites. Therefore, two strategies have been developed for high head hydropower: fish passage facilities and fish-friendly turbines.

9.1. Fish passages

Fish passages are hydraulic structures that allow the upstream and downstream migration of fish when a dam impedes their migration [241]. Their application already dates a few decades in the past [242] and is considered a technologically mature sub-system. Classical examples of fish passages are vertical slot fish ladders [243] consisting of a channel with typical bed slope between 5% and 10%, with pools separated by transversal baffles. However, fish ladders are not suitable for downstream fish migration, because fish tend to follow the main river flow i.e. the flow running through the turbine.

Despite the high TRL of fish passages, recent analyses show that most of them are not eco-efficient. In many cases, the river species are not able to use them [241, 244]. The interaction between fish populations and the passages is a complex phenomenon and optimal designs should consider fish behaviour and fish reaction to external stimuli coming from the turbulent and hydraulic flow field [245,246]. From an engineering point of view, it is still needed to better understand the optimal design of fish passage in relation to swimming ability of fish and determine the most suitable locations to install their inlet/outlet.

Fish passages adopted for the downstream migration is generally different from the fish ladder used for the upstream one. Accordingly, screens are placed before the turbine to prevent fish entrance and to divert them towards the passage. Such screens induce head losses, i.e. a reduction in the power output of the hydro plant. The authors in Ref. [244] underline the need to conduct in-depth investigations on the complex interaction between fish and such structures.

Recent scientific efforts have also focused on understanding the relationships between turbulent hydraulic environments and animal behaviour in the fishways to improve attraction, approach, entry and passage for multiple species [247].

9.2. Fish-friendly turbine design

In order to overcome the limitations of fish passages, recent R&D efforts have focused on the development of fish-friendly turbines for relatively higher head hydro stations. Accordingly, the Alden turbine and the Minimum Gap Runner turbine have been introduced. The Alden turbine specifically works with head differences of up to 25 m.

The Alden turbine is a relatively new design for a fish-friendly turbine. It has only three blades to reduce fish mortality wrapped around the shaft that rotates around a vertical axis. It also features a slower rotational speed (120 rpm in the model) compared to conventional turbine technologies. The Alden turbine was initially conceptualised and tested using CFD and experiments at a pilot scale in the Alden research laboratory [248]. A physical model (scale 1:8.71) has been developed and tested. The results indicate that the commercially is expected to allow maximum hydraulic efficiency of 93.6% and fish passage survival rates of 98% or greater for fish less than 20 cm [249].

The Minimum Gap Runner turbine (MGR) is a modification of the Kaplan turbine. Its design reduces the gaps between the adjustable runner blade and the hub as well as and between the blades and the discharge ring. These modifications resulted in decreased fish injury and mortality and improved turbine efficiency [249].

10. Conclusions

The present article collects information on the challenges, innovation trends and emerging hydropower technologies. It mainly covers European research projects related to various aspects of hydropower. Hydropower facilities are complex systems that employ a wide spectrum of methods and (sub-)technologies bridging knowledge of different scientific disciplines. This work is an attempt to analyse these aspects in an integrated manner. Accordingly, it covers typical mechanical technology research related to hydropower components also presenting the progress of experimental and laboratory applications. It also includes aspects related to the generators and the electrical equipment, a vital element of hydroelectric stations. The emerging need to digitalise hydropower design and operation is also presented. The digital transformation of hydropower is expected to revolutionise the way new and existing hydro stations operate especially given the fact that, so far, the hydropower field –a relatively conservative sector– has not adopted the latest advances of the information technology (IT) sector. Novel concepts in hydropower energy storage and hybrid operations that include radically new designs have also been presented.

However, hydropower R&D also focuses on improvements and adaptations in technologies that exist for a long time. This is the case on research related to small-scale hydropower; further improvements will allow increased efficiencies, economic viability and reduced environmental intervention and impact.

As far as hydropower components are concerned, it is expected that advances and breakthroughs in the IT and automation will shape hydropower's future. In that direction, the management of hydropower plants already looks towards advanced automation and control capabilities. Due to the reshaped European electricity markets and their ongoing liberalization, hydropower operation needs to consider different markets (i.e., spot, balancing, frequency reserve) in its scheduling. This involves significant computational burden and big data analytics, a common challenge of many sectors. This includes (near) real-time simulations and modelling to respond to specific ancillary service requests. The use of sophisticated algorithms, simulation and optimization techniques is also expected to become a regular feature in the operation of the hydropower fleet. Digitalisation will provide the mean to hydro stations to align with the future requirement of the climate policies and the electricity markets.

Future technological advances in environmental sciences will have a direct impact on the way the ecological impact of existing and new hydropower sections is assessed. The present analysis focused exclusively in the energy-related technological aspects and did not cover research activities related to water and environment issues. Important challenges such as sediment transport, ecological flow regimes, impact on water temperature currently hinder or put limitations on new hydropower construction. Hydropower, thus, faces a certain number of environmental constraints that aim at the preservation and restoration of the biodiversity of river ecosystems. Defining advanced, more accurate methodologies to assess the environmental impacts (e.g. in the case of environmental flows) is an important step to reach an environmental friendlier operation of hydropower. A better understanding of the hydro's interaction with the ecosystems achieved through research activities in the water and environment fields may help address some of the constraints and – at least partially– support the mitigation of environmental impacts on. Such practices also extend to the construction and tunnelling fields. Advanced construction and drilling methods can also mitigate the environmental and social impacts of hydropower and particularly the part related to the civil works (e.g. lifecycle GHG emissions).

At the same time, the future evolution of the hydropower sector will need to take advantage of advances in climate and environmental sciences. The sector can benefit from advances in hydrology data collection and analysis of river basins. According to IRENA [250], the global technical hydropower potential is at 15,955 TWh/year. Considering that the global generation in 2018 was 4200 TWh [251], there a significant amount of it remains untapped.

Breakthroughs in the estimations of water travel time, groundwater infiltration and evaporation can have a direct impact on hydropower scheduling. Climatic conditions and their possible changes in the short-, medium- and long-term are also crucial. Future water availability is a decisive parameter for the economic viability of a hydropower station. Thus, advances in the detail, the refinement and the accuracy of climatic projections will also benefit hydropower. Reducing or partially removing uncertainties is very important, especially since hydropower is a capital-intensive technology that requires a large majority of the investment up front.

It is, thus, clear that the future role of hydropower is not only dependent on the technological advancements that are covered in the present analysis. Knowledge breakthroughs in other scientific disciplines are also important and can potentially enable improved services. The availability of a portfolio of different, advanced technologies would certainly create solutions for an increased number of applications.

Disclaimer

The views expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission.

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