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The new role of sustainable hydropower in flexible energy systems and its technical evolution through innovation and digitalization

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ABSTRACT

Hydropower has played an important role in Europe in recent decades, offering a unique combination of safe, low-cost, and clean power generation. Today, it is still one of the largest renewable energy sources (RES), accounting for about 35 % of RES electricity generation. However, grid stability is threatened by the increasing amount of undispatchable RES. Flexibility and dynamics such as energy storage and rapid response are urgently needed to achieve EU policy goals. In such a context, hydropower can play a key role, not only as a provider of regulated renewable energy but also due to its ability to balance a renewable energy system in the short term and the medium/long term by pumped storage technology. All these aspects underline the new role of hydropower, which aims to strengthen grid stability and power supply resilience and to enable higher penetration of volatile RES. In this context, the aim of this paper is to demonstrate the role of hydropower at the European level as well as the needs and opportunities of modernization to fully exploit its potential. In particular, this study provides, the assessment of the today flexibility offered by hydropower to the power system at the European level by leveraging a database of information collected through the participants to the working groups of the COST Action Pen@Hydropower which includes stakeholders in the hydropower sector of 34 European countries. The study confirms the key role of hydropower in future energy scenarios with 30 % of the flexibility demand at all time scales met by hydropower. Furthermore, the paper presents a review of the digitalization solutions and innovative technologies that support the growth of a new generation of sustainable hydropower together with the modernization opportunities for existing hydropower plants. The results of this work have practical implications for stakeholders in the hydropower sector and policymakers as it provides evidence at the European scale of the role of hydropower technology in balancing the power system and the need to have supportive frameworks and adequate markets to fully exploit the European hydropower potential to achieve the energy transition goals.

1. Introduction

Many countries in the world have introduced specific targets and financial incentives for further wind and solar power development, but few have policies to support the sustainability of existing hydropower plants and facilitate the addition of new ones. Hydropower is the most appropriate technology to provide future power systems with the emission-free flexibility they need. This new, crucial role that hydropower is expected to play in future power systems should be recognized by governments, energy stakeholders, and society, and reflected in long-term expansion targets and investment plans.

The sustainable use of water resources for hydropower to support this new role is the goal of initiatives and international associations, such as the Technology Cooperation Program on Hydropower of the

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International Energy Association [1], which is a working group of some member countries and organizations from Europe, the Americas, and Asia; the International Hydropower Association [2], whose members are hydropower developers, operators, and manufacturers from many countries around the world, and the Joint Research Program on Hydropower of the European Energy Research Alliance [3], which consists mainly of universities and research organizations in Europe.

In this sense, the main objective of the Pen@Hydropower Cost Action [4] is to build and establish a Pan-European network for sustainable, digitalised, and flexible hydropower to contribute to the Clean Energy Transition (CET) and climate change mitigation, and to promote the development of a sustainable society. Pen@Hydropower engages members on a more personal level and aims to create an interdisciplinary consortium that brings together researchers, scientists, and other stakeholders from engineering, social, economic, legal, and environmental sciences who will work towards the above goal through various activities. A key objective of the Action is to engage and build the capacity of many young researchers to bridge generations and prepare the hydropower experts of tomorrow.

To achieve this goal, there are some recognized challenges and identified barriers that need to be addressed and overcome. First, EU support for the scientific environment of hydropower is low. Over the past 15 years, only about 15 hydropower projects have been funded [5], and today only about 0.7 % of EU funding for RES development goes to hydropower to improve the performance, efficiency, and flexible operation of hydropower plants. As a result, there are few technological innovations to promote sustainability and resilient operation of old and new power plants. Pen@Hydropower addresses this with a twofold objective:

(1) *Research coordination* that includes a scientific support framework for hydropower producers and investors, a platform for collaboration among scientists and stakeholders from different disciplines, mapping of current EU legislation, market and CET scenarios, and identification of policy gaps and barriers to create a unique knowledge base currently lacking in the scientific community, and to develop a novel holistic scientific hydropower community strategy with new approaches to support sustainable development.
(2) *Capacity building* to expand the existing technical network by incorporating additional disciplines (engineering, ICT, environment and climate, hydrology, social, finance, etc.), promote the career development of young scientists through joint PhD programs, knowledge transfer, and training schools, and increase awareness - among policymakers and industry - of the importance of hydropower in the energy mix.

The Pen@Hydropower management committee consists of members from 34 European countries, including 21 Cost Inclusiveness Target Countries, and there are more than 260 members in the 5 working groups, ranging from young researchers and early career investigators (ECI) to experienced researchers. During the 4-year duration of the project, several funded activities are planned for researchers or innovators from all hydropower fields. Each year, a training school for PhD students and ECI is organized in different European regions to broaden their knowledge and deepen their teamwork in the field of hydropower. In 2023, the training school was organized in Timisoara, Romania, and in the year 2024, two training schools will be organised in Thessaloniki (Greece) and Porto (Portugal), all on the topic “Sustainable Hydropower” [6].

Researchers can also apply for short-term scientific missions to visit and work at a host institution in another country to gain new knowledge or access equipment or techniques not available at their home institution. In addition, the Action offers conference grants that enable young researchers to attend international conferences, as well as grants to attend high-level conferences to present their activities and results and to establish new contacts and potential future collaborations [7].

Considering the need to raise awareness about the capability of hydropower in supporting the power system in future scenarios and to increase the opportunities for this technology to improve its potential and achieve full exploitation, dedicated studies have been performed within Pen@Hydropower to create a robust database of information from several European countries representatives. These studies allow bridging the existing gap in the literature about the actual exploitation of the hydropower technology at the European scale and highlight todays and future needs for flexibility modernizations to raise technological competitiveness and sustainability which require adequate supporting frameworks from policies and governments. To this end, this article presents the investigations performed by the Pen@Hydropower working groups (WG), focusing on hydropower operations and technology developments: the WG1 on Hydropower’s role in flexible energy synergies and WG2 on Technological evolution through innovation & digitalization. The results provide for the first time a pan-European understanding of the hydropower technology status from a holistic perspective, exploiting information and data collected among stakeholders spread in 34 European countries.

Section 2 discusses the future flexibility requirements for power systems in different European countries with a time horizon from 2030 to 2050 and the contribution of hydropower to meet these needs. Section 3 presents a review of the technical innovations and digitalization technologies that can be exploited to modernize the existing hydropower power plant fleet and to design new plants so that they can more effectively support the power systems of the future. Section 4 identifies future developments and research fields of interest for hydropower development.

2. The flexibility of hydropower

It is well known that transitioning our energy system to one dominated by renewable energy sources is an increasing challenge [8]. This includes volatile renewable energy sources (VRE), which increase the demands on the system to balance supply and demand. For example, the increasing use of power converters to generate solar and wind energy is reducing grid inertia and challenging traditional approaches to limiting and restoring frequency. The Australian Energy Market Operator has found that a lack of frequency limiting by conventional power plants leads to difficulties in managing frequency and scheduling system reserves [9]. Similarly, the California Independent System Operator experienced a progressive degradation of its frequency containment and restoration performance: the frequency response measure decreased by 122 MW/0.1 Hz in 4 years [10].

In Europe, scenarios for 2030 show that for the effective management of large-scale VRE, flexibility on multiple time scales from short-term to seasonal, as shown in Fig. 1, is required.

In particular, the simulations projected the residual load curve in 2030 in the EU, which serves as a parameter for assessing flexibility requirements [12]. As can be seen in Fig. 2, the residual load curve has a peak in the morning and evening, which coincides with hours of increasing demand, and a significant drop in the midday when solar production increases. By measuring and predicting this parameter, the flexibility demand can be quantified in terms of energy per day, week, and month. Fig. 3 shows the daily flexibility demand per country in Europe in 2021, 2030, and 2050. The daily flexibility demand will reach 288 TWh in 2030 and will increase by an average of 133 % between 2021 and 2030 in all countries. Weekly and monthly flexibility needs are lower (258 TWh weekly and 173 TWh monthly), but they increase faster over the next decade: weekly flexibility is projected to increase by 166 % and monthly flexibility by 300 %. From these results, flexibility must be used in all areas of the power system, from power generation to stronger transmission and distribution systems to storage and more flexible demand.

With dispatchable power generation and high potential for storage

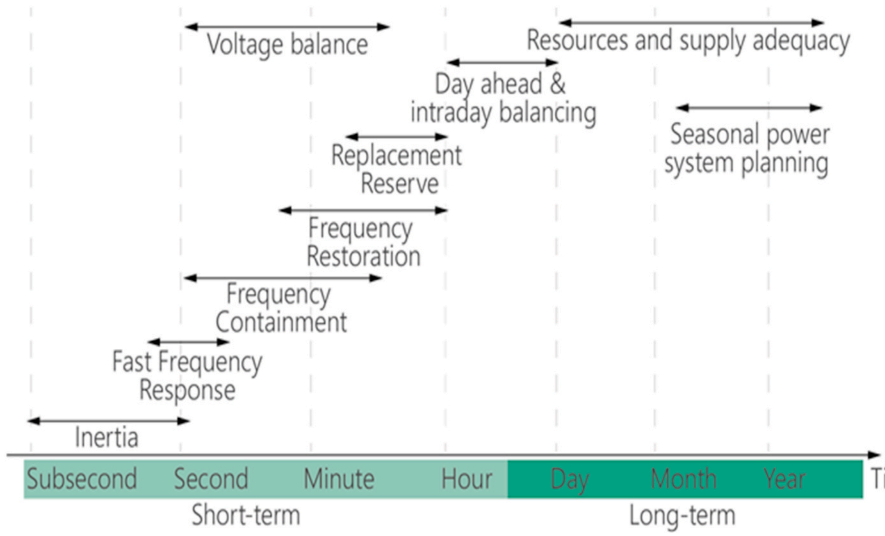

Fig. 1. Time horizon of the flexibility services that hydropower can provide. Adapted from Ref. [11].

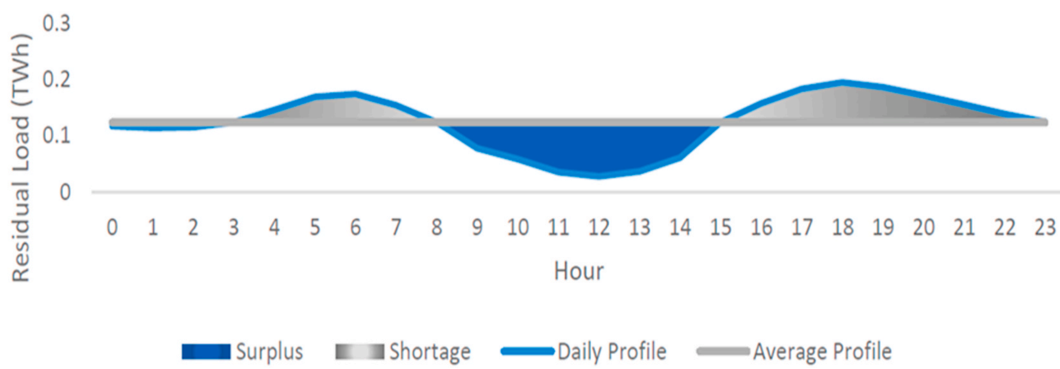

Fig. 2. Flexibility requirements based on hourly-averaged daily EU residual load curve in 2030 [11].

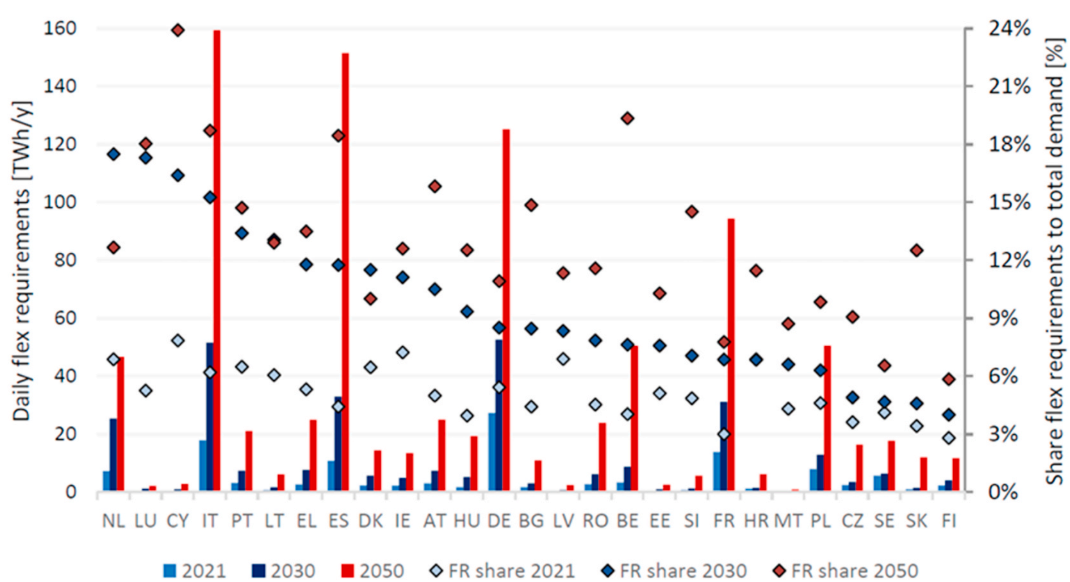

Fig. 3. Daily flexibility requirements in 2021, 2030, and 2050, ordered by 2030 flexibility requirements share to total demand [11].

capacity, hydropower is already providing these essential services to the grid. Even though the simulations predict a decrease in the share of hydropower in these services by 2050 (about −7 % for hydropower including pumped storage), this technology will be needed to meet the increasing demand, which will require higher flexibility of hydropower plant operation, higher availability, and higher electricity capacity and storage capacity of the hydropower fleet. In the 2030 scenario for the European Union, more than 30 % of the flexibility demand at all time scales will be met by hydropower.

A study conducted by the IEA [13] presents several case studies around the world in which hydropower contributes to power system flexibility by demonstrating its ability to support almost all the systems studied at different time horizons, from short-term grid services to long-term storage. The share of hydropower depends on the country, as

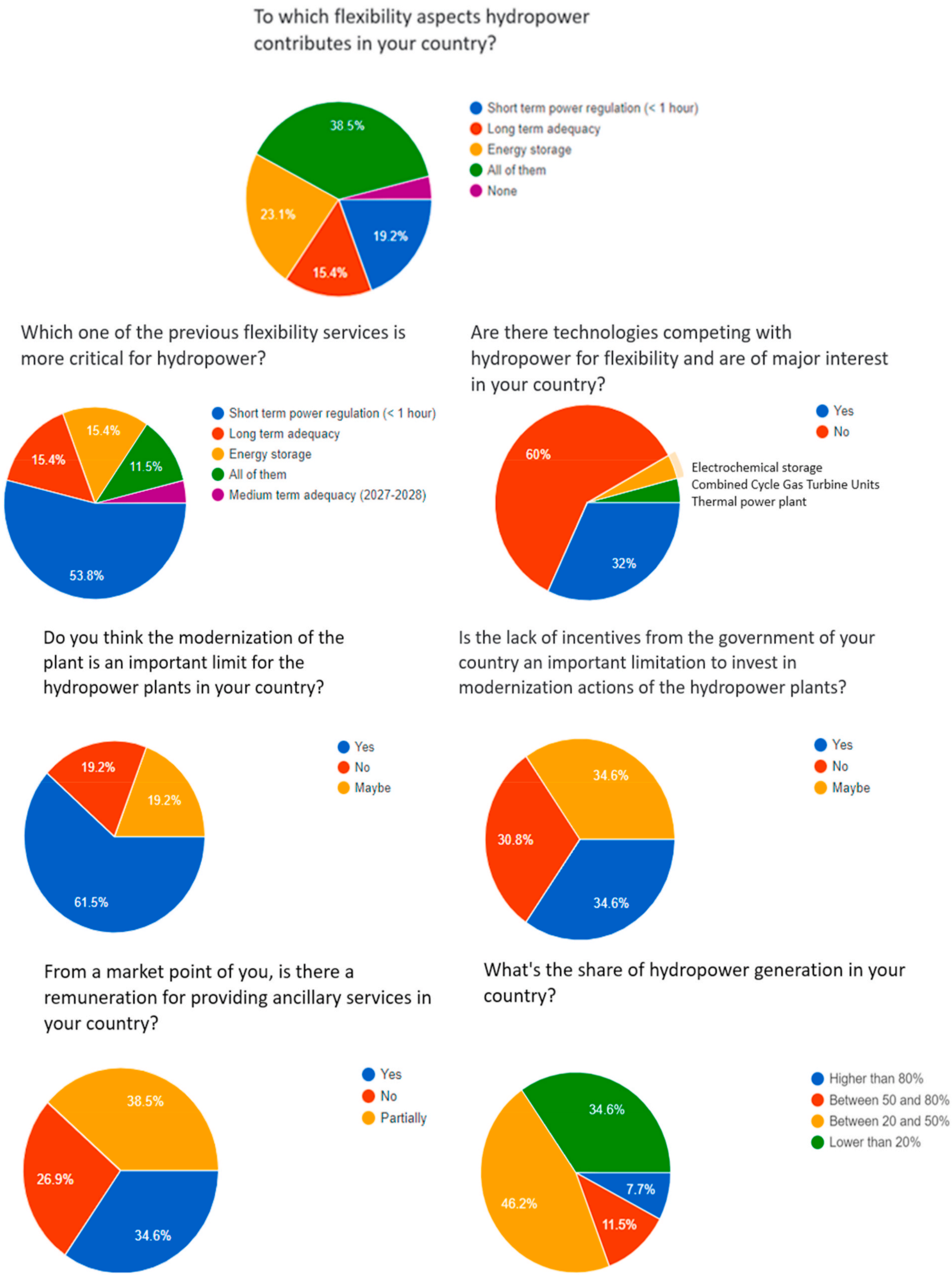

Fig. 4. Survey results based on 15 European countries participation.

it is a geographically limited resource. This also reflects a different market structure, which seems to be particularly pronounced in the countries where the share of hydropower is the highest, such as Norway and Switzerland, even for short-term sub-hourly services. An example from USA shows that dispatchable hydropower flexibility supports clean energy goals also economically by helping to keep system operating costs and consumer costs low [14].

Hydropower flexibility may also have an impact the hydraulic system and the environment, which has not to be disregarded. A study [15] identified and quantified the effects of different reservoir system attributes (among them the need to preserve reserves, lag times, the control of reservoirs controlled by other needs, operating policies, etc.) on hydropower flexibility. How integration of renewables affects aquatic ecosystems and increases cross-sectoral water conflicts was studied in Ref. [16]. For this an artificial intelligence-assisted multisector design framework was developed and applied for Volta River in Ghana. Results show how hydropower flexibility alone enables expanding intermittent renewables but increases flow variability by many times compared to state of the art fluctuations, with negative consequence on the river ecosystems and the agricultural sector revenues.

It is however a matter of fact of all these studies that hydropower is a key resource to enable the energy transition and achieve the 2030 and 2050 sustainability targets. Therefore, there are new opportunities for this technology in terms of market participation and further increasing its production. This requires, for example, an increasing share in the auxiliary services under the hour, by increasing the availability of balancing energy of the hydropower plant with multiple units, if available, both in generation and pumping mode. It must be pointed out that other storage solutions are available on the market for providing grid regulation services and there is not one single solution able to solve all the grid stability issues, but each has its own peculiarities. For example, in comparison with other grid solutions, such as battery storage energy systems, pumped-hydropower storage plants enable medium to long-term energy storage as well as significant power ramps (up and down). Moreover, in terms of industrial competitiveness and social benefits, several hydropower-related companies, capable of manufacturing mechanical, electrical equipment and civil engineering work, with zero need of critical raw materials, already exist in EU, bringing income to the European market, while also maintaining human engineering resources and expertise in EU.

2.1. Flexibility assessment

The importance of hydropower in the European energy landscape is reflected in the role of hydropower in providing flexibility to the power system. Within the Cost Action Pen@Hydropower WG 1 with more than 100 participants representing 19 European countries, a study has been carried out which provides an overview of hydropower contribution to the flexibility of the energy system on both the short and long-term services in Europe considering the countries members of this Cost Action. The study allows an understanding of the flexibility needs and hydropower role in different countries, the existing limitations, and possible solutions to overcome these barriers.

For this purpose, a survey has been tailored to investigate hydropower participation in different ancillary services and the current limitations and challenges faced by hydropower technologies. The results of the survey are illustrated in Fig. 4.

It appears clearly that in the 15 investigated countries hydropower has a pivotal role in providing flexibility in the short and long time-frame. However, there are several limitations especially due to the cost of flexibility which is not adequately remunerated. It appears that especially the short-term services are more challenging for the hydropower asset. One critical aspect is the impact on the flexibility and lifetime of hydropower equipment due to frequent start-stops and part-load operations. In fact, the increased number of transients and movements during off-design operations can lead to dynamical loads on hydro units, causing fatigue on mechanical components like wicket gates, runner blades, nozzles, servomotors, and bearings. This, in turn, reduces the overall lifetime of the equipment. As an example, Lithuania, with a high share of VRE sources, emphasizes the need for better solutions addressing part-load behavior, start-stop conditions, and fast changes in the system. Short-term power regulation becomes critical to prevent fatigue on hydro units, particularly in the context of frequent shifts in operation modes. In Spain, the importance of short-term power regulation services, including frequency containment reserves, automatic frequency restoration reserves, manual frequency restoration reserves, and replacement reserves, is highlighted. The removal of capacity payments has prompted a re-evaluation of regulatory frameworks for energy storage, with a focus on enhancing the short-term power regulation capabilities of hydropower plants. Spain currently operates 22 pumped-storage hydropower plants, contributing significantly to short-term power regulation. However, market conditions and regulatory uncertainties have hindered the investment in new pumped-storage projects, despite plans to commission an additional 3.5 GW by 2030.

The survey has shown that a significant expansion of renewable energy is planned in all European countries and that conventional hydropower could become a crucial tool for short-term electricity regulation beyond its traditional role as a basic power source. However, challenges related to plant fatigue, regulatory frameworks and climate impacts need to be addressed together to ensure the seamless integration of hydropower into the evolving energy landscape.

3. Technological evolution through innovation & digitalization

As the survey above shows, flexible operation is one of the challenges facing hydropower, and technological development to achieve this goal and others (e.g., related to increasing sustainability in terms of river hydraulics and ecology) must come through advances in digitalization and innovation. The Pen@Hydropower action has a working group WG2 on Technological evolution through innovation & digitalization dedicated to these aspects, to raise awareness of digitalization and other innovative technologies, sharing experiences between operators, manufacturers, and universities, and imagine the new generation of hydropower plants.

In the first grant period, one of the objectives of Pen@Hydropower was to identify trend technologies and the needs of the hydropower sector in terms of digitalization, flexibility, and efficiency. To this end, a survey was conducted to identify the current situation of members in their countries in terms of technological developments and common practices. This survey, described in detail below, can be considered representative of the European context and the different disciplines, as the Pen@Hydropower working group has 97 members from 27 different countries, whose expertise spans a wide spectrum that includes electrical, mechanical, environmental, computer science and civil engineering disciplines.

The WG2 holds regular meetings several times a year. Presentations and discussions delved into various groundbreaking developments and recent advances within the hydropower domain. These discussions and presentations encompassed topics like innovative turbine design, the impacts of digitalization on hydropower, anomaly detection using machine learning, monitoring the condition of rotating machinery, short-term scheduling of hydropower operations, the integration of hydropower into water-energy management systems, and the implementation of variable speed operations in hydropower plants.

Hydropower turbine design has seen many innovations aiming at improving efficiency, reducing environmental impact, and increasing flexibility. The implementation of digitalization technologies is, especially in the European Union, emerging as an effective strategy to support trade-offs among environmental, economic, and social aspects [17], fostering both the green and the digital transitions. Some of these innovations are fish-friendly turbines and installations [18], adjustable blades, low-head turbines, composite materials, artificial intelligence optimisation during CFD (Fig. 5) and active flow control [19].

Machine learning is a very useful tool to leverage big data and promote sustainability in energy, agriculture, conservation, and resilience [20]. Machine learning techniques are increasingly being applied to various aspects of hydropower plant operations, including anomaly detection in various subsystems [21]. Anomaly detection refers to identifying deviations or anomalies in data that may indicate equipment failure, suboptimal performance, or other problems requiring attention. In the application of machine learning for anomaly detection in hydropower systems, methodologies such as Adaptive Thresholding and Alarm Set-Point Adjustment are commonly employed. These techniques involve dynamically adjusting thresholds and alarm trigger points based on real-time data, enabling the detection of deviations from expected operational norms. Moreover, through the modeling of equipment states spanning from new to worn-out conditions, machine learning algorithms can accurately identify anomalies indicative of equipment malfunction or degradation using for example heatmaps (Fig. 6). This capability facilitates the early detection of potential issues, thereby allowing for timely intervention and the implementation of predictive maintenance strategies. Overall, the utilization of machine learning in anomaly detection for hydropower systems enhances operational efficiency and supports proactive maintenance planning by enabling the timely identification and mitigation of equipment anomalies [22].

As frequently discussed in Pen@Hydropower WG2 meetings, condition monitoring of rotating machinery in hydropower involves the systematic monitoring of various parameters to assess the health and performance of the equipment. This is typically achieved through sensor deployment, data acquisition, simulations, among them rotor modal testing and modal simulations [24]), signal processing, fault detection algorithms, diagnostic analysis, and maintenance scheduling.

Hydropower applications play a crucial role in the Water-Energy nexus, which refers to the interconnected relationship between water resources management and energy production. Hydropower applications leverage water resources, such as rivers, reservoirs, and dams, to generate electricity through the conversion of hydraulic energy into mechanical energy using turbines and generators. In addition to energy production, hydropower applications are integral to water resource management by regulating water flow and providing water storage capacity. Reservoirs created by hydropower dams serve multiple purposes, including flood control, irrigation, water supply, and recreational activities. Hydropower applications offer opportunities for sustainable water-energy management by reducing reliance on fossil fuels and mitigating greenhouse gas emissions by utilizing energy recovery opportunities by means of a turbine in drinking water systems [25].

Variable speed operation in hydropower refers to the ability of hydropower turbines to adjust their rotational speed to match varying flow conditions and optimize energy generation. Conventional hydropower turbines operate at a fixed rotation speed determined by the frequency of the electrical grid to which they are connected. However, in variable speed operation, the rotation speed of the turbine can be adjusted independently of the grid frequency, allowing more flexible control of power output. Variable speed operation allows hydropower turbines to adapt to changing flow conditions in rivers or reservoirs. By adjusting the turbine speed to match the available water flow, the turbine can operate at its most efficient point, maximizing energy capture and overall power generation. Geometry optimisation steps are shown in Fig. 7.

The importance of the above studies was in Pen@Hydropower WP2 stressed also with surveys and questionnaires. These were conducted to monitor the current situation and future in all members' countries considering the latest technologies in the hydropower sector.

3.1. Survey methodology

Surveys were used to gather information from respondents to answer research questions. A conceptual framework consisting of innovative technologies and digitalization in hydropower was selected. Many of the questions were prepared as closed-ended and only a few were asked as open-ended questions. The choices in closed-ended questions are determined based on the experience of the preparers. The questionnaire was validated through sharing the questionnaire with the experts in the Pen@Hydropower before publishing the questionnaire. The questions in the survey were created to understand the technological level of hydropower plants in the different European countries and to identify what technological advances the new investments in hydropower plants should include. During one of the regular meetings of the WG1, the questionnaire was explained to members of the group and the questionnaire link was shared with the members. The structure of the questionnaire was optimized to facilitate completion by members from different disciplines. The final form of the questionnaire is shown in Fig. 8, and its explanation with the survey results is given in the following section.

3.2. Results and discussions

Unmanned operation increases operational efficiency in hydropower plants and protects plant operations from human error, but it also requires an advanced control system that collects all sensor data on site. It also requires a communication infrastructure with a reliable communication protocol. The control algorithms of the hydropower plant should be sophisticated enough to allow the control system to operate the plant satisfactorily even when there is no operator on site.

The first question analyses the prevalence of unmanned operation of hydropower plants in Europe. The respondents are experts and academicians who give consultancy to plant owners and operators in their countries such that they are aware of the general situation in their countries. The results are shown in Fig. 9. 60 % of the respondents indicate that at least 50 % of the power plants in their country are operated unmanned. On the other hand, 30 % of the respondents indicate that at most 10 % of the power plants in their country are operated unmanned. This question shows that the unmanned operation of the hydropower plants is quite high among the participants.

Unmanned operation requires that the facility's communications infrastructure and other control algorithms are set up accordingly. Supervisory Control and Data Acquisition (SCADA) systems are used to collect information from sensors in the plant, log that information,

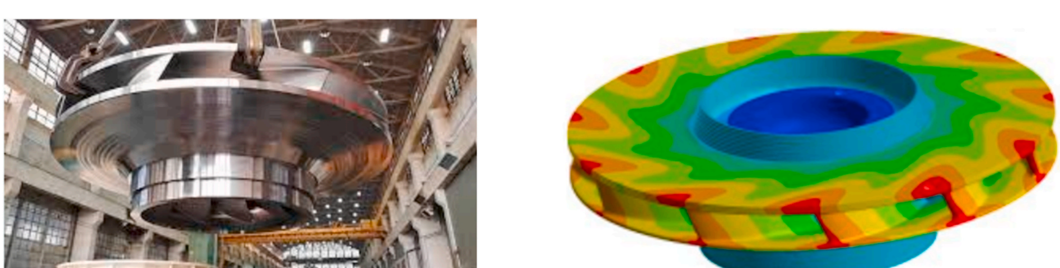

Fig. 5. Discussions in WG2 meetings have exposed the role of CFD optimisation in the turbine design featuring improved flexibility.

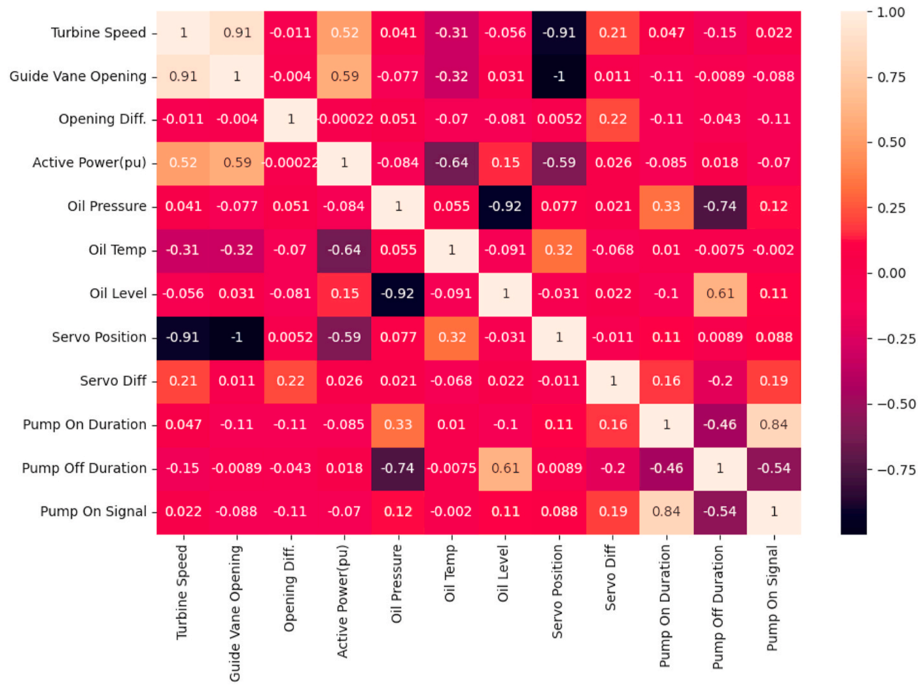

Fig. 6. Heatmap showing the correlation between parameters in the training dataset for anomaly detection in high-pressurized oil system [23].

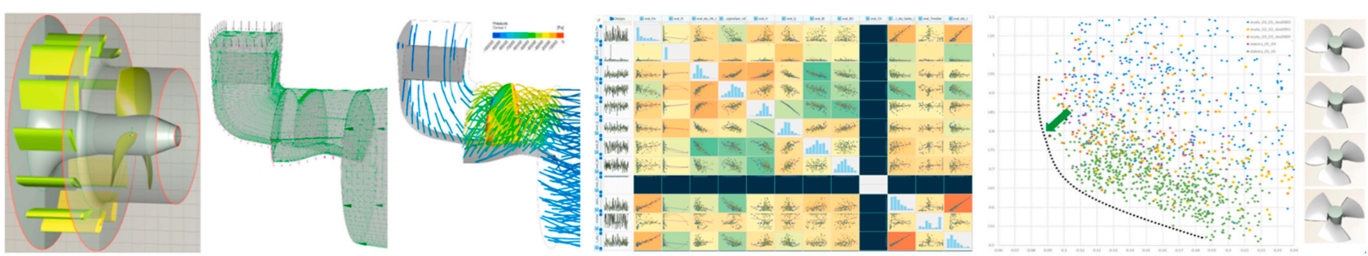

Fig. 7. Geometry optimisation for variable speed operation [26] for variable speed optimisation should be software connected. Optimisation procedure includes (1) selection of parametric models of geometry, (2) fluid flow analysis, (3) sensitivity analysis and (4) optimisation using a multi-objective genetic algorithm.

visualize it based on trends, and list it as alarms and events. The operator monitors and controls the plant remotely or on-site via man-machine interfaces. Regarding this aspect, it appears that the majority of hydropower plants have modern SCADA systems, as shown by the results in Fig. 10, which perfectly reflect the results of the first question (Fig. 8): 60 % of the respondents say that at least half of the power plants in their country have modern SCADA systems, while 10 % of the respondents say that up to 25 % of the hydropower plants in their country have modern SCADA systems. These results show that most hydropower plants are unmanned and have modern control systems. This situation will allow the hydropower industry and developers to access historical data in a structural way.

A pumped storage power plant is an efficient way to store electrical energy by pumping water to a higher reservoir when demand is low and by generating power to a lower reservoir during peak periods when demand is high. The next question asks about the presence of pumped storage power plants and the results are shown in Fig. 11. 20 % of the respondents have more than 20 pumped storage power plants in their country. On the other hand, 40 % of the respondents have 1 to 5 pumped storage power plants in their country and 20 % of the respondents have none. This question shows that the number of pumped storage power plants is variable and there is no common installation in the different countries when looking at the numbers.

Regarding the interaction between hydropower plants and the environment, new approaches have been developed in recent years to ensure accurate and rapid monitoring of fish. The use of digital tools combined with machine learning and artificial intelligence algorithms (e.g. convolutional neural networks) for automatic image-based detection and classification of species in different environments has been a breakthrough. Deep neural networks have already been successfully applied in various fields for fish monitoring [27]. In addition to image-based detection systems, molecular techniques such as environmental DNA have emerged as a tool for monitoring various aquatic species, particularly fish [28]. For example, a single eDNA study at the Spjutmo hydropower plant (Sweden) detected twice as many fish species as several electrofishing studies [29].

Fish-friendliness is a must for sustainable hydropower. To this end, there are many ways to provide fish safety, including fish passages, turbine designs, and fish tracking. When asked about the fish-friendliness of hydropower plants in their country, most of the respondents confirmed the presence of a fish passage in their country's hydropower plants. Few of them also indicated that the turbine design is fish-friendly, and only a small proportion of respondents indicated that the hydropower in their country is not fish-friendly. It can be concluded that most of the hydropower plants care about fish passage.

Regarding the presence of variable speed operation, which is

Participant's Information • Name • Surname • Country	Presence of any hydropower plants in the drinking water supply system for pressure energy recovery or any projects related to hydropower plants in the drinking water supply system • Yes/No
Unmanned Operation of Hydropower Plants • 0% • Below 10% • 10% to 25% • 25% to 50% • Above 50%	If yes, typical output of recovery units? • Below 10 kW • 11-100 kW • 101 – 500 kW • more than 500 kW
Presence of Modern SCADA Systems • 0% • Below 10% • 10% to 25% • 25% to 50% • Above 50%	The average age of hydropower plants • 0-10 • 11-20 • 21-35 • 36-50 • Older than 50
Number of pumped storage hydropower plants • 0 • 1-5 • 6-10 • 11-20 • Above 20	The percentage of the hydropower plants that have technical documents in digital media • 0% • Below 10% • 10% to 25% • 25% to 50% • Above 50% •
Fish friendliness of hydropower plants • There exist fish passages • The turbine design is fish friendly • Not fish friendly	Presence of any recent hydropower installations or major hydropower refurbishments, any installation of significant technological innovations, or adopting up-to-date digitalization approaches.
Presence of variable speed operated hydropower plant or any project on variable speed operation • Yes/No	Any (realistic) plans for building new hydropower in the near future, any plans to adopt digitalization approaches or any major technological innovations.

Fig. 8. Questionnaire structure.

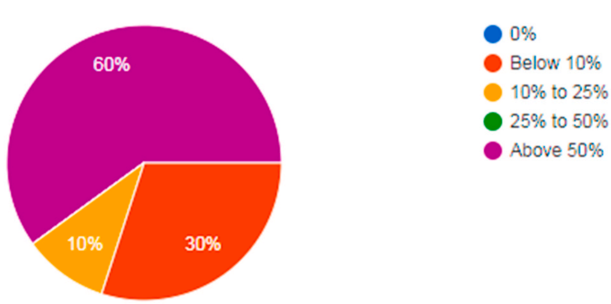

Fig. 9. Distribution of unmanned operated hydropower plants.

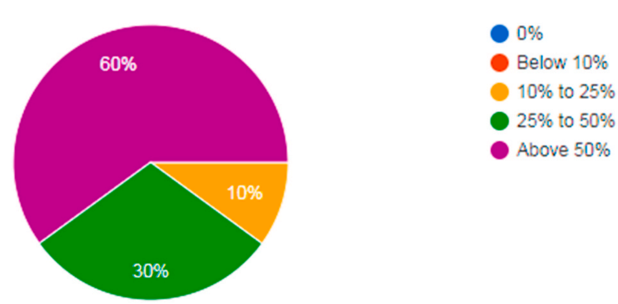

Fig. 10. Presence of modern SCADA systems in hydropower plants.

extremely efficient in pumping mode, it was found that this is common throughout Europe. 60 % of the respondents confirmed the introduction of variable speed operation in their country. The use of variable speed turbines is not very common in the hydropower industry in Europe.

Hydropower in the drinking water system is an untapped potential for green and sustainable cities. In the questionnaire, respondents are asked about the existence of hydropower plants in the drinking water supply for the recovery of pressurized energy or about the existence of

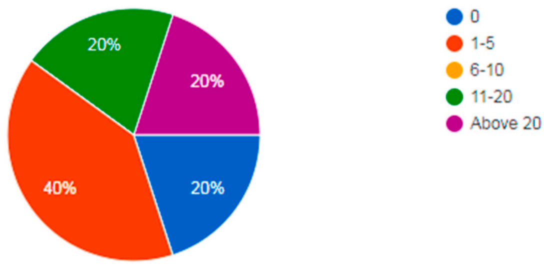

Fig. 11. Number of pumped storage hydropower plants.

projects related to hydropower plants in the drinking water supply. 90 % of respondents indicate that there is a hydropower plant in the drinking water system in their country. As can be seen in Fig. 12, the typical capacity of recovery plants ranges from 11 to 100 kW. This suggests that while most countries have hydropower facilities in their drinking water systems, the potential of hydropower in the drinking water system needs to be explored more thoroughly.

The average age of the hydropower plant fleet can indicate the future potential for refurbishment in a country. When power plants are modernized, new technologies can be easily adapted and integrated into the newly modernized system. The results summarized in Fig. 13 show that for 50 % of the respondents, the power plants in their country are on average between 21 and 35 years old, while for 20 % they are over 50 years old. 30 % of the respondents indicate that the average age of the hydropower plants in their country is between 36 and 50 years. These results show that the hydropower fleet in Europe is quite old, and the hydropower industry should develop new solutions based on innovation and digitalization for refurbishment.

In the context of digitization, technical documents are stored and organised on digital media to digitise them. The last question asks respondents how much of the technical documents in their countries' hydropower plants are stored in digital media. As shown in Fig. 14, 40 % indicate that more than 50 % of the technical documents of the hydropower plants in their countries are stored on digital media. On the other hand, 30 % of the respondents indicate that this rate is less than 10 %. This confirms that the hydropower industry and developers need to spend more time to digitise the technical documents for technological progress, such as the digital twin.

In the open-ended questions, respondents refer to major modernization works, including hydropower plants with an installed capacity of more than 500 MW. There are some power plants that are being renovated to make them compatible with variable speed control.

4. How to continue?

The imperative to enhance production and utilization of energy from renewable sources, as stipulated by the objectives of the EU Renewable Energy Directive, represents a crucial measure towards mitigating greenhouse gas emissions and bolstering energy security. Concurrently, countries are obligated to implement water, nature, and other environmental regulations, with the EU Water Framework Directive serving as the principal instrument for water policy by delineating water protection targets harmonized with economic interests.

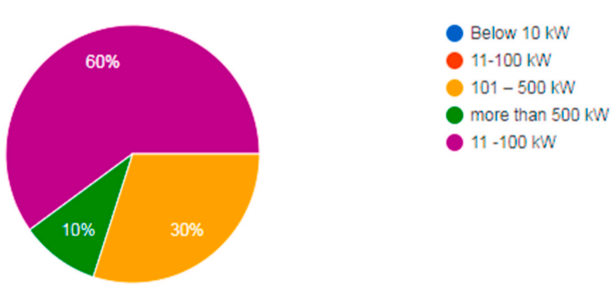

Fig. 12. Typical outputs of recovery units.

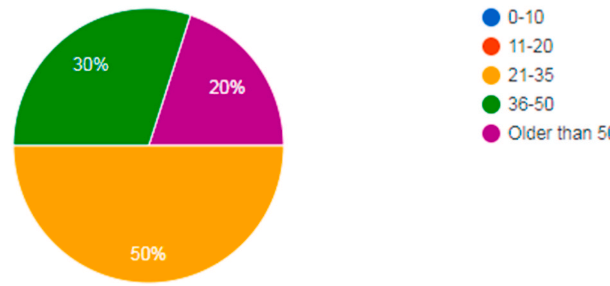

Fig. 13. Average age of hydropower plants.

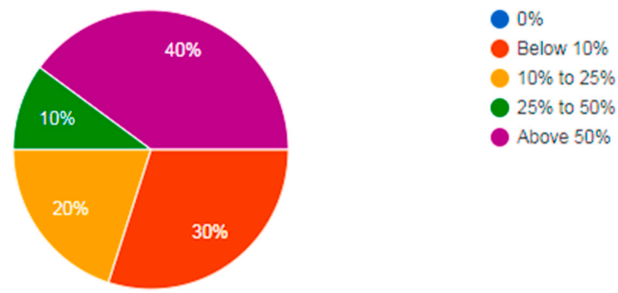

Fig. 14. Technical documents in digital media.

Hydropower has been recognized as a primary contributor to hydromorphological alterations, loss of connectivity, and significant adverse effects on habitats, particularly fish populations. Therefore, each hydropower plant refurbishment must assess and improve the status of river stretches or water bodies concerning deviations from type-specific natural conditions in terms of hydrology, morphology, biological and sediment continuity, as well as biological communities. In the flexibility assessment, the specific ecological structure and function of the river stretch, evaluated at the catchment/sub-basin level, should be examined, particularly regarding habitats for sensitive or valuable fish species and other biological quality elements within the riverine ecology, such as red-listed species.

Additionally, refurbishments should consider social aspects. The landscape's aesthetic values, high architectural and historical quality, and recreational value, including tourism and recreational uses such as cycling paths, camping sites, and canoeing, must be respected. Cultural heritage, including historical buildings and villages or towns, should also be preserved. In the EU, the displacement of communities is less pertinent compared to other regions of the world.

Through networking among members and allocations of grants (short-term scientific missions, inclusive target countries conference grants, virtual mobility grants, etc.) Pen@Hydropower action is participating in further hydropower research and development. Pen@-Hydropower action has identified fields, where further networking is needed in the nearest future. This includes, but is not limited to:

(1) *Storage needs of future electricity systems and the role of hydropower as a contributor to energy system resilience.* The increasing use of intermittent renewable energy sources in future electricity systems necessitates significant energy storage capacity. Specifically, large hydro-pumped storage units capable of storing energy for extended periods (from several hours to days) are essential. However, the relation to battery storage will indicate the needed capacity and future utilization modes of hydro-pumped storage plants.
(2) *Recognizing and addressing digitalization barriers for hydropower plant refurbishment.* To explore the benefits of digitalization in

hydropower refurbishing, barriers to digitalization must be assessed while considering the assessment of different scales of hydropower plants targeted for refurbishment and identifying specific equipment or systems in need of attention. Key challenges include the need to standardize data models, cybersecurity concerns, and economic implications. The data model's standardisation is needed for effective comparison and benchmarking of hydropower plants, addressing limitations in data storage and the three Vs (veracity, volume, velocity). Cybersecurity concerns are associated with integrating data from multiple hydropower plants and handling the increasing volume and variety of data resulting from the introduction of novel sensing and instrumentation technologies. Evaluating the economic implications of implementing digitalization in refurbishment processes should be performed given the increasing demands on hydropower to reduce costs and increase efficiency while lacking general governmental support.

(3) *The effect of hydropower on the continuity of underwater life.* Identification and categorization of the local environmental impacts of European hydropower in regulated rivers under current and future (climate change-affected) scenarios, along with mitigation methods, should be performed. Special emphasis should be placed on the continuity of sediment transport versus the continuity of underwater life, and for this field measurements and hydraulic modeling may be needed for selected use cases in addition to already existing (but few) case studies and relevant European data. There is also a need for a comprehensive summary and the common European perspective on the effect of hydropower on the continuity of underwater life.

(4) *The role of hydropower in the EU energy transition.* The primary goal is an analysis of electricity generation trends within the EU over recent decades. This should encompass various forms of generation, including dispatchable, non-dispatchable, and distributed generation, among others. By doing so, one should evaluate the evolving role of hydropower within the EU context, particularly in comparison to other renewable energy sources. Furthermore, the analysis should not only consider the overall EU perspective but should also delve into regional variations across Eastern Europe, Northern Europe, Western Europe, and Southern Europe. By examining these diverse regions, insights into how the role of hydropower differs across the continent in comparison to other renewables should be established. Such a comprehensive approach should provide a nuanced understanding of the dynamics shaping the energy landscape within the EU and its various subregions.

(5) *The future of hydropower couplings.* The in-depth understanding of the prospects for hydropower couplings is needed. An investigation should entail an in-depth analysis of the requirements and simulations associated with coupling hydropower to various systems, including energy storage, power-to-fuel, power-to-gas, and other energy conversion methods. Moreover, the examination should encompass the exploration of hybridization options, such as integrating hydropower with photovoltaic systems, wind power, and other renewable energy sources. By thoroughly describing the anticipated requirements and simulations for these hydropower couplings, as well as exploring potential hybridization options, valuable insights into the evolving landscape of renewable energy integration will be provided, also contributing to the advancement of sustainable energy solutions and decision-making processes concerning the future of hydropower utilization.

(6) *Transboundary dimensions of hydropower sustainability standard.* This research aims to contribute valuable insights to the ongoing dialogue surrounding sustainable energy development, promoting international collaboration for the responsible use of hydropower resources across borders. It also seeks to identify stakeholders currently absent from existing standards. The initiative focuses on assessing the environmental, social, and economic impacts of hydropower projects, particularly considering their cross-border implications. This entails a thorough examination of the Hydropower Sustainability Standard, with an emphasis on its transboundary dimension, recognizing that rivers and water resources often cross political boundaries. Key objectives include evaluating the current standard, pinpointing areas for enhancement, and investigating the environmental impacts of hydropower projects, particularly in terms of their transboundary effects. Social and economic aspects should not be neglected, considering the well-being of communities on both sides of international borders. Furthermore, the best practices for transboundary cooperation and conflict resolution in the context of hydropower development should be found, ultimately providing recommendations for refining, and implementing sustainable hydropower practices with a transboundary perspective.

5. Conclusions

This paper presents the results of the first activities carried out in the framework of PEN @Hydropower. The Pen@Hydropower action laid the foundation for a pan-European collaborative platform of scientists and stakeholders from different disciplines, whose initial goal was to map the current state of the hydropower sector in Europe. By leveraging the unique point of view provided by hydropower stakeholders, coming from 34 different European countries, this study demonstrated that the key requirements for the successful implementation of the zero-emission energy scenario are flexibility and digitalization. They should be implemented in all areas of the energy system, from power generation to stronger transmission and distribution systems, storage, and more flexible demand.

The flexibility development should address storage needs of future electricity systems and the role of hydropower as a contributor to energy system resilience. The impacts to the environment, among them the hydropeaking and the effect of hydropower on the continuity of underwater life, must be adressed, and where possible transboundary dimensions of hydropower sustainability standard should be considered. Hydropower shouldn't be viewed as the sole contributor to flexibility, we see further development potential through various energy couplings.

The flexibility development must occur through advances in digitization and innovation, the mapping of which was the second short-term goal of Pen@Hydropower. The European hydropower sector exhibits a good level of digitalization, but this is not fully exploited. The latest technological solutions do not seem to have been uniformly adopted across European countries, confirming the need for knowledge transfer between stakeholders. For instance, the unmanned operation of hydropower plants must be improved, as must be the number of pumped storage type hydropower plants be increaed. Moreover, the fleet is quite old, which offers a great opportunity for promoting innovative refurbishment strategies to increase the sustainability of hydropower worldwide.

By focusing on the above key areas, Pen@Hydropower action aims to contribute significantly to advancing sustainable hydropower solutions, fostering international collaboration, and promoting responsible hydropower development across borders.

CRediT authorship contribution statement

Elena Vagnoni: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Dogan Gezer:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Ioannis Anagnostopoulos:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Giovanna Cavazzini:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Eduard Doujak:** Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition. **Marko Hočevar:** Writing – review & editing, Writing – original draft, Conceptualization. **Pavel Rudolf:** Writing – original draft, Supervision, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Elena Vagnoni reports financial support was provided by European Commission. Dogan Gezer reports financial support was provided by European Commission. Giovanna Cavazzini reports financial support was provided by European Commission. Ioannis Anagnostopoulos reports financial support was provided by European Commission. Pavel Rudolf reports financial support was provided by European Commission. Eduard Doujak reports financial support was provided by European Commission. Marko Hocevar reports financial support was provided by European Commission. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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