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

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Abstract:

Hydropower (HP) 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 and its share is estimated to reach 50% by 2025. However, grid stability is threatened by the increasing amount of unregulated energy (wind and solar). Flexibility and dynamics such as energy storage and rapid response are urgently needed to achieve EU policy goals. In such a context, HP 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 (seconds to minutes) and in the medium/long term (months or even years) through the use of 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.

The study provides an overview of the preliminary results obtained by the working groups of the COST Pen@hydropower action. In particular, it presents a first assessment of the flexibility offered by hydropower today at the European level, focusing on different geographical areas, and confirms the key role of hydropower in future scenarios (30% of the flexibility demand at all time scales met by hydropower). An overview of the digitalization solutions and innovative technologies that support the growth of a new generation of sustainable hydropower and the modernization of existing hydropower plants is also provided.

Keywords:

Hydropower; Energy; Sustainability; Flexibility; Digitalization.

1. Introduction

Many countries in the world have introduced specific installation targets and financial incentives for further wind and solar power development, but few have policies to support the sustainability of existing and facilitate the addition of new hydropower plants (HPPs). However, hydropower is the most appropriate technology to provide the future power systems at RES 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 some initiatives and international associations, such as the Technology Cooperation Program on Hydropower of the 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, digitalized and flexible hydropower in order to contribute to the Clean

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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 HP is low. Over the past 15 years, only about 15 HP projects have been funded [5], and today only about 0.7% of EU funding for RES development goes to HP to improve the performance, efficiency, and flexible operation of hydropower plants, to support the use of other RES and electricity storage, and to address important environmental issues related to river hydraulics and ecology. As a result, there are few technological innovations to promote sustainability and resilient operation of old and new power plants to meet the increasing demands of power systems and environmental and social requirements.:

– Research coordination objectives that include a scientific support framework for HP 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 HP community strategy with new approaches to support sustainable development.

– Capacity building objectives to expand the existing technical network by incorporating additional disciplines (engineering, ICT, environment and climate, hydrology, social, finance, etc.), promote career development of young scientists through joint PhD programs, knowledge transfer, and training schools, and increase awareness among policy makers and industry of the importance of HP in the energy mix.

The Pen@Hydropower management committee consists of members from 33 European countries, including 20 COST Inclusiveness Target Countries (ITC), and there are more than 160 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 fields HP. Each year, a training school for PhD students and ECI will be organized in different European regions to broaden their knowledge and deepen their teamwork in the field of hydropower. This year, the training school will be organized in Timisoara, Romania (May 9-12, 2023), on the topic of "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 under this Action and to establish new contacts and potential future collaborations [7].

This article presents some initial results of the Pen@Hydropower working groups since the launch in September 2022. These results provide for the first time a pan-European overview of the hydropower technology status from an holistic perspective, exploiting information and data collected among stakeholders spread in several different 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 then presents some technical innovations and digitization technology that can be used to modernize the existing HP power plant fleet and to design new plants so that they can more effectively support the power systems of the future.

2. The flexibility of hydropower in the European context

It is well known that transitioning our energy system to one dominated by renewable energy sources is an increasing challenge. 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 (AEMO) has found that a lack of frequency limiting by conventional power plants leads to difficulties in managing frequency and scheduling system reserves [8]. Similarly, the California Independent System Operator (CAISO) experienced a progressive degradation of its frequency containment and restoration performance: the frequency response measure (FRM) decreased by 122 MW /0.1 Hz in 4 years [9].

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

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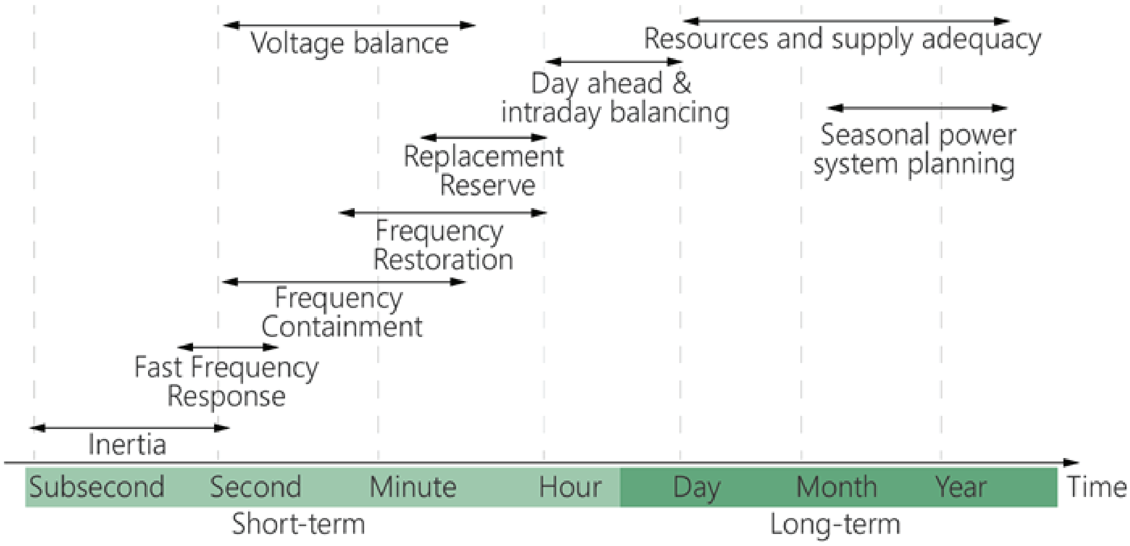

Figure. 1. Time-horizon of the flexibility services that hydropower can provide. Adapted from IEA [10].

In particular, the simulations projected the residual load curve in 2030 in the European Union (EU), which serves as a parameter for assessing flexibility requirements [11]. As can be seen in Figure 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. Figure 3 shows the daily flexibility demand per country in Europe in 2021, 2030, and 2050. The daily flexibility demand will be 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 on a weekly basis and 173 TWh on a monthly basis), but they increase faster over the next decade: weekly flexibility is projected to increase by 166% and monthly flexibility by 300%. From these results, it is clear that 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.

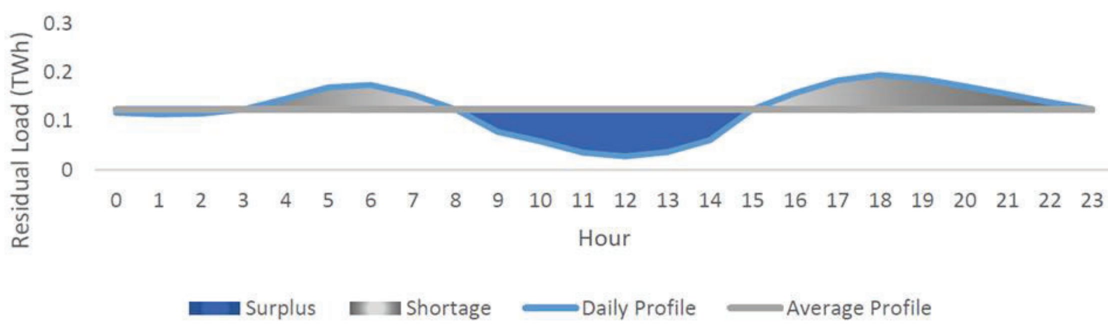

Figure. 2. Flexibility requirements based on hourly-averaged daily EU residual load curve in 2030 (Source: Joint Research Centre [11])

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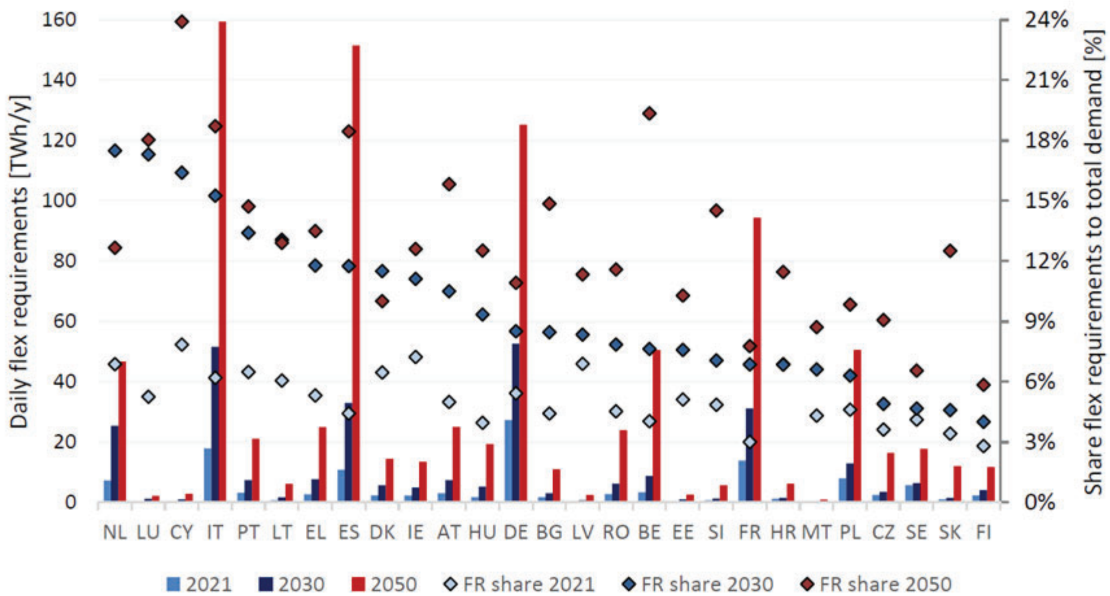

Figure. 3. Daily flexibility requirements in 2021, 2030 and 2050, ordered by 2030 flexibility requirements share to total demand (Source: Joint Research Centre [11])

With dispatchable power generation and high potential for storage 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 for these services, which will require higher flexibility of hydropower plant (HPP) 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 is met by hydropower. Another study on the optimization of storage needs and market profitability has shown that, considering the previous scenario for 2030 and excluding gas-fired power plants from the options, the optimal additional capacity of pumped storage is 1.3 GW (and + 14.5 GW batteries), with an additional storage capacity of 62.2 GWh, of which 7% comes from hydropower.

A study conducted by the IEA [12] 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 the different time horizons, from short-term grid services to long-term storage. In the selected countries in Europe (Germany, Norway, Switzerland and Finland), the share of hydropower depends on the country, as 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 highest, such as Norway and Switzerland, even for short-term sub-hourly services.

According to these studies, it is clear 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.

3. Technological Evolution through Innovation & Digitalization

As explained above, 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 dedicated to these aspects, with the aim of raising awareness of digitalization and other innovative technologies, sharing experiences between operators, manufacturers and universities, and imagining the new generation of hydropower plants.

In the first grant period, one of the objectives of Pen@Hydropower is to identify trend technologies and the needs of the hydropower sector in terms of digitalization, flexibility and efficiency. To this end, a survey will be 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 (70% of the members are under 40 years old and 12% of the members are female), whose expertise spans a wide spectrum that includes electrical, mechanical, environmental, computer science and civil disciplines.

3.1 Methodology

Surveys are used to gather information from respondents to answer research questions. Conducting surveys is a very convenient way to gather information from a large number of people in a given period of time. Due to the locations of the respondents, an Internet survey is chosen as the survey type. A conceptual framework consisting of innovative technologies and digitalization in hydropower is constructed. Many of the questions are prepared as closed-ended. Some of the questions in the survey are asked as open-ended questions. The choices in closed-ended questions are determined based on the experience of the preparers. The questionnaire is validated through sharing the questionnaire with the experts in the COST Action 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.

The structure of the questionnaire was optimized to facilitate completion by members from different disciplines. The final form of the questionnaire is shown in Figure 4, and its explanation with the survey results is given in the following section. There are some open-ended questions as well as most of the closed-ended questions.

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

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plant or any project on variable speed operation • Yes/No	Any (realistic) plans for building new hydropower in near future, any plans to adopt digitalization approaches or any major technological innovations.

Figure 4. Questionnaire Structure

3.2 Results and Discussions

During one of the regular meetings of the Working Group, the questionnaire is explained to members of the group and the questionnaire link is shared with the members through the data sharing platform. The questionnaire is open before the submission of the manuscript. So far, ten respondents from nine different countries fill the questionnaire.

It is well known that 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 aims to analyze 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 Figure 5. 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.

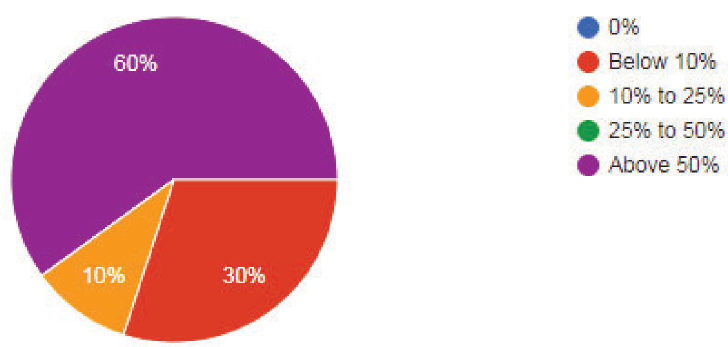

Figure 5. Distribution of Unmanned Operated Hydropower Plants

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, 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 Figure 6, which perfectly reflect the results of the first question (Figure 5): 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

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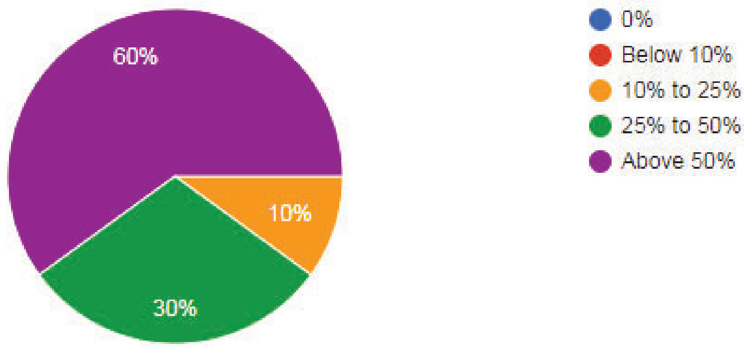

Figure 6. Presence of Modern SCADA Systems in Hydropower Plants

A pumped storage power plant is an efficient way to store electrical energy by pumping it 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 Figure 7. 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.

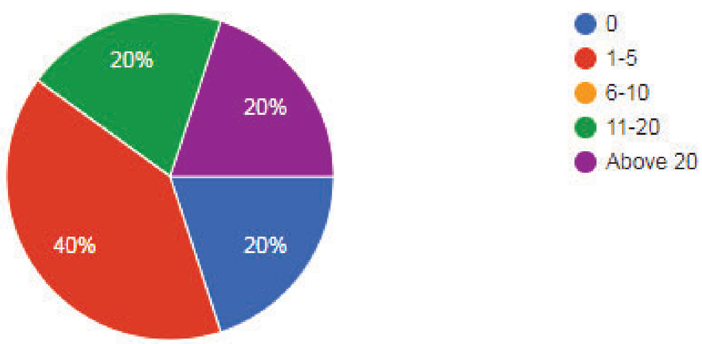

Figure 7. Number of pumped storage hydropower plants

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 [13]. 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 [14]. For example, a single eDNA study at the Spjutmo hydropower plant (Sweden) detected twice as many fish species as several electrofishing studies [15].

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.

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Regarding the presence of variable speed operation, which is 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 pressurised energy or about the existence of 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 Figure 8, the typical capacity of recovery plants ranges from 11-100 kW. This suggests that while the majority of countries have hydropower facilities in their drinking water systems, the potential of hydropower in the drinking water system needs to be explored more thoroughly.

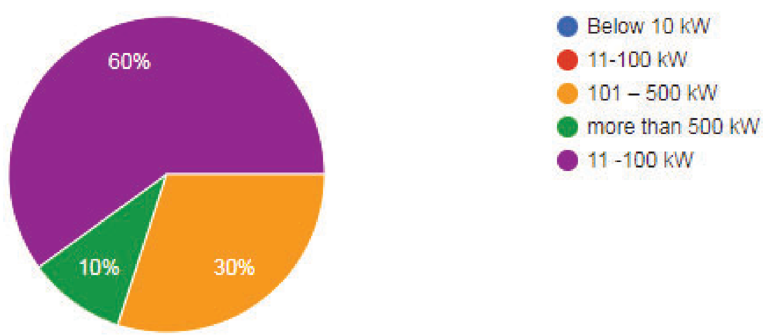

Figure 8. Typical Outputs of Recovery Units

The average age of the hydropower plant fleet can give an indication of 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 Figure 9 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.

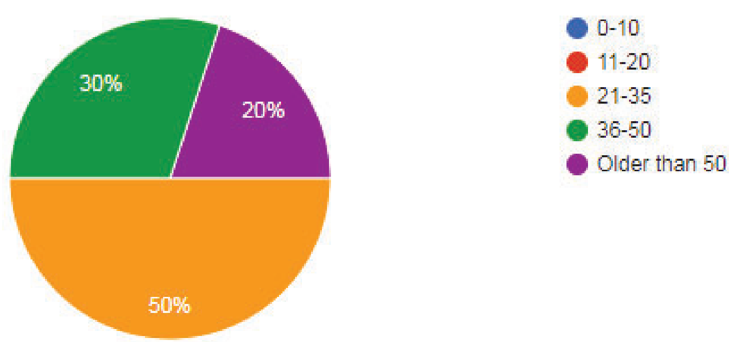

Figure 9. Average age of Hydropower plants

In the context of digitization, technical documents are stored and organised on digital media in order 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 Figure 10, 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

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industry and developers need to spend more time to digitise the technical documents for technological progress, such as the digital twin.

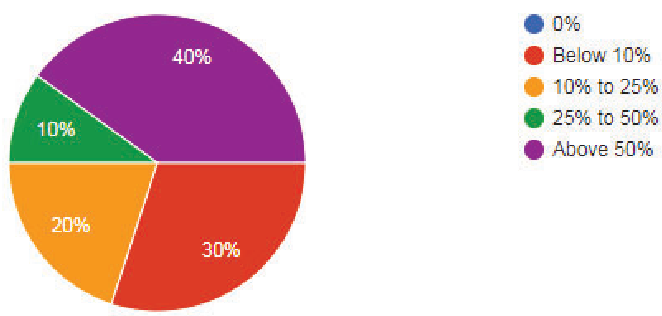

Figure 10. Technical documents in digital media

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 for variable speed control.

4. Conclusions

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.

This study summarizes the results of the first activities carried out in the framework of PEN @Hydropower. In particular, we focused on the European energy framework and on the challenges of the Clean Energy Transition. Several studies have confirmed that one of the key requirements for the successful implementation of this zero emissions scenario is flexibility in all areas of the energy system, from power generation to stronger transmission and distribution systems, storage and more flexible demand. In this context, the key role of hydropower has been highlighted by several authors, along with the technological advances that are still needed for hydropower to play this role successfully. One of the most important is certainly to increase sustainability to make these advances technically feasible and economically viable, minimize environmental impacts, and increase society's awareness of the importance of hydropower technology to the CET.

This technological development must occur through advances in digitization and innovation, the mapping of which was the second short-term goal of PEN @Hydropower. Using its multidisciplinary network (engineering, ICT, environment and climate, hydrology, social, financing, etc.), the state of hydropower technology was studied, with some interesting results. The European hydropower sector confirms a good level of digitalization, but this is not fully exploited for technological advances. 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 has to be improved in Turkiye, Crotia, Albania and Bosnia Herzegova. Another figure to improve is the number of pumped storage type hydropower plants, e.g. there is no pumped storage type hydropower plant in Turkiye and Albania. Moreover, the fleet is quite old, which offers a great opportunity for promoting innovative refurbishment strategies to increase the sustainability of hydropower worldwide.

Acknowledgments

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References

[1] IEA, The International Energy Agency Technology Collaboration Programme on Hydropower – Available at: <www.ieahydro.org>

[2] IHA, International Hydropower Association – Available at: <www.hydropower.org>

https://doi.org/10.52202/069564-0160

[3] EERA, European Energy Research Alliance, Joint Programme Hydropower – Available at: <www.eera-hydropower.eu>

[4] Pen@Hydropower, Pan-European Network for Sustainable Hydropower – Available at: <www.pen-hydropower.eu>

[5] Hoogland O, Veenstra E, Guevara Opinska L, Torres Vega PC, Rademaekers K (2019). Study on impacts of EU actions supporting the development of renewable energy technologies. PP-05441-2017. Ed. European Commission. Directorate-General for Research and Innovation. Brussels.

[6] Pen@Hydropower, Pan-European Network for Sustainable Hydropower – Available at: <www.pen-hydropower.eu/training-schools>

[7] Pen@Hydropower, Pan-European Network for Sustainable Hydropower – Available at: <www.pen-hydropower.eu/short-term-scientific-missions >

[8] AEMO, 2020, Renewable Integration Study: Stage 1 Report: Tech. Rep.

[9] CAISO, 2016, Frequency Response Phase 2: Tech Rep.

[10] International Energy Agency (IEA) (2021). Hydropower Special Market Report. Analysis and forecast to 2030

[11] Joint Research Centre, 2022, Flexibility requirements and the role of storage in the future European power system

[12] International Energy Agency (IEA) (2021). Valuing Flexibility in Evolving Electricity Markets: Current Status and Future Outlook for Hydropower.

[13] Kandimalla V, Richard M, Smith F, Quirion J, Torgo L and Whidden C (2022) Automated Detection, Classification and Counting of Fish in Fish Passages With Deep Learning. Front. Mar. Sci. 8:823173. doi: 10.3389/fmars.2021.823173

[14] Stefanni S, et.al. Framing Cutting-Edge Integrative Deep-Sea Biodiversity Monitoring via Environmental DNA and Optoacoustic Augmented Infrastructures. Front. Mar. Sci. 8:797140. doi: 10.3389/fmars.2021.797140

[15] Hellmér E. (2018) Using eDNA to improve environmental monitoring for water bodies effected by hydropower in Sweden, Dissertation, 2018.

https://doi.org/10.52202/069564-0160