D-HYDROFLEX: An Architectural Framework for Digitalization, Flexibility and Sustainability on Hydro Power Plants

Pavlos Bouzinis*, Christos Dalamagkas*, Katerina Drivakou[†xi], Paula Hernampérez-Manso[‡], Alejandro Martín-Crespo[‡], Sergio Rodríguez-Carro[‡], Cristina Vega-Martínez[‡], Mario de-la-Rosa-Noriega[‡], Eduardo Rodríguez Fernández-Arroyo[§], Alberto Casalderrey Area[§], Eric De Oliveira[¶], Fabrice Zaoui[¶], Zuzanna Satława[‖], Przemysław Janik[‖], Artur Machalski[**], Alwyn Mathew[††], Ioannis Brilakis[††], Weiwei Chen[‡‡], Yang Su[‡‡], Eleni Tsironi[x]

***Abstract*—Hydropower plays a crucial role in renewable energy, generating more electricity than any other renewable source. It is expected to remain a significant contributor into the following decade and will continue to be vital in decarbonizing the power system and enhancing the flexibility of the grid. However, to meet the evolving demands of modern power systems, hydropower plants (HPPs) should focus on increasing flexibility and sustainability. To address this need, this paper presents the D-HYDROFLEX architectural framework, which introduces a toolkit of digital solutions for the modernization and digital renovation of HPPs. More specifically, the D-HYDROFLEX architecture outlines the components of the target system, including a suite of tools, their interconnection and their interaction with the physical infrastructure of the HPP. Finally, a link of this toolkit with a wide range of applications is provided, such as operational maximization, predictive maintenance, decision support, forecasting, hydrological modeling, HPP hybridization, biodiversity impact monitoring, and cybersecurity.**

***Index Terms*—Hydropower, Digitalization, Sustainability, Flexibility**

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* Pavlos Bouzinis and Christos Dalamagkas are with MetaMind Innovations P.C., Kila Kozani, 50100, Kozani, Greece - Email: {pbouzinis, cdalamagkas}@metamind.gr

†xi Katerina Drivakou is both with UBITECH and UBITECH ENERGY, Boulevard Edmondmachtens 79/22, Brussels 1080, Belgium - Email: kdrivakou@ubitech.eu

‡ Paula Hernampérez-Manso, Alejandro Martín-Crespo, Sergio Rodríguez-Carro, Cristina Vega-Martínez and Mario de-la-Rosa-Noriega are with the Technology Centre CARTIF, Parque Tecnológico de Boecillo, 47151 Boecillo (Valladolid), Spain - Email: {pauher, alemar, sercar, criveg, marros}@cartif.es

§ Eduardo Rodríguez Fernández-Arroyo and Alberto Casalderrey Area are with the Department of Industry and Urban Ecosystems, EnergyLab Reacher and Technological Center, R/ Fonte das Abelleiras s/n, Vigo University Campus, 36310 Vigo (Pontevedra) Spain - Email: {eduardo.rodriguez, alberto.casalderrey}@energylab.es

¶ Eric De Oliveira and Fabrice Zaoui are with the EDF R&D – LNHE (Laboratoire Nationale d'hydraulique et environnement), 6 quai Watier, 78400 Chatou, France - Email: {eric.de-oliveira, fabrice.zaoui}@edf.fr

‖ Zuzanna Satława and Przemysław Janik are with TAURON Ekoenergia sp. z o.o., ul. Obrońców Pokoju 2B, 58-500 Jelenia Góra, Poland - Email: {zuzanna.satlawa, przemyslaw.janik}@tauron.pl

** Artur Machalski is with the Department of Energy Conversion Engineering, Faculty of Mechanical and Power Engineering, Wroclaw University of Science and Technology, Wybrzeze Wyspianskiego 27, 50-370 Wroclaw, Poland - Email: artur.machalski@pwr.edu.pl

†† Alwyn Mathew and Ioannis Brilakis are with the University of Cambridge, England, United Kingdom - Email: {am3156, ib340}@cam.ac.uk

‡‡ Weiwei Chen and Yang Su are with the Bartlett School of Sustainable Construction, University College London, 1-19 Torrington Place, London WC1E 7HB - Email: {weiwei.chen, yang.su}@ucl.ac.uk

x Eleni Tsironi is with UBITECH, Mithridatou 36-38, Athens 11632, Greece - Email: etsironi@ubitech.eu

I. Introduction

The European Union's (EU) clean energy transition goals call for at least a 55% reduction in greenhouse gas emissions from 1990 levels by 2030 [1]. Achieving this target value requires electricity grids to support a system where at least 50% of electricity is generated from renewable energy sources (RES) by 2030. The rapid expansion of solar photovoltaic (PV) and wind power is transforming the energy landscape, significantly increasing the need for power system flexibility. This, in turn, demands grid modernization and digitalization to enable smarter operations as electricity consumption grows and supply dynamics shift. Power system flexibility must quadruple by 2050, driven by the rising share of variable renewables and the evolving patterns of electricity demand. This highlights the importance of dispatchable low-emission technologies such as hydropower, with capacity additions for hydropower and other dispatchable renewables expected to triple to over 125GW by 2030 [2]. Additionally, the digitalization of the energy system is a key policy priority, aligning with both the European Green Deal and the Digital Decade Policy Programme 2030, reinforcing the twin transition toward a greener and smarter energy future [3].

Hydropower is crucial for auxiliary services due to its flexibility in generating and consuming power, especially in pumped storage hydro power plants (HPP). However, its contribution to these markets is challenged by fast dynamics and the need for reliable operations. These demands force hydroelectric units to operate in off-design conditions, increasing transitions like start-ups, shutdowns, and regulatory movements. This results in higher mechanical stress, leading to more frequent maintenance, increased costs, and revenue loss due to downtime. Hybridizing hydropower, combining it with other renewable sources, can reduce resource curtailment and optimize energy use while preserving hydropower's flexibility. Digitalization further enhances plant efficiency by improving predictive maintenance and strengthening market participation. Beyond electricity generation, hydropower supports water supply, irrigation, drought mitigation, and flood control. However, sedimentation from erosion, deforestation, and agriculture threatens these services. Therefore the need for digital solutions to improve HPP's flexibility, safety, and environmental resilience, is increasingly essential.

To tackle these challenges, the D-HYDROFLEX architectural framework aims to enhance the flexibility potential of the existing hydropower fleet within the energy system while improving the overall annual efficiency of hydroelectric plants. By optimizing performance, increasing availability, and reducing outage times, D-HYDROFLEX seeks to maximize the contribution of hydropower to the clean energy transition. Moreover, D-HYDROFLEX aims to demonstrate how existing hydro plants can enhance operational efficiency and support biodiversity by integrating innovative technologies and digitalization measures. Such approach will not only strengthen market prospects but also improve the operational and environmental sustainability of hydropower, playing a key role in advancing renewable energy goals and policies.

In this direction, this paper presents the reference architecture and toolkit of D-HYDROFLEX, which serves as a key driver for advancing research excellence in sensor technologies and digital solutions while promoting hydropower digitalization to improve efficiency, flexibility, and sustainability. Specifically, the D-HYDROFLEX architecture comprises a suite of tools to upgrade existing HPPs, by leveraging sensors, digital twins (DT), artificial intelligence (AI) algorithms, hybridization modeling, cloud-edge computing, and image processing. It should be noted that D-HYDROFLEX is a Horizon Europe research programme funded by the EU which will be validated against five use cases [4].

Based on the aforementioned remarks the contribution of this paper is summarized as follows:

- Providing the reference architecture of D-HYDROFLEX, which showcases the interactions among the involved digital tools and the physical components of the HPP.
- Providing the core functionalities of the D-HYDROFLEX toolkit within the concepts of i) digital twins, ii) HPP hybridization with on-site hydrogen production, iii) intrusion detection against operation technology (OT) cyber-attacks, iv) HPP integration with local smart grids, and v) biodiversity impact monitoring.

II. Related Work

A comprehensive literature review about the state-of-art on modernizing the HPPs is presented in [5]. The authors focus on 5 basic concepts, namely: digitalization, Industry 4.0, data, KPIs, modelization, and forecast. Digitalization can speed up the energy transition by merging Information Technology (IT) and OT infrastructure, while Industry 4.0 can accelerate the evolution of conventional HPPs into smart HPPs through key technologies like Internet of Things (IoT), simulation, cloud computing, Augmented Reality (AR), big data analytics, AI and Machine Learning (ML), as well as cybersecurity and blockchain. The importance of data is highlighted as a means to conceive and implement data-driven policies, required for efficient decision making. The necessity of defining KPIs for evaluating the efficiency of energy production in HPPs is also highlighted, covering aspects of availability, revenue, return on investment, efficiency, energy output, capacity factor, and generation capacity. To address the aforementioned challenges, several EU-funded projects have been recently initiated, aiming to develop and deliver platforms for digitalizing and modernizing the HPPs.

XFLEX-HYDRO is an EU-funded project that aims to expand the flexibility of hydropower plants by integrating and testing various technologies that increase the participation and contribution of HPPs towards the energy transition [6]. XFLEX-HYDRO developed a Smart Power Plant Supervisor, which aims to optimize performance and predictive maintenance of HPPs by interacting with multiple functions of HPPs separated in 5 layers (hydroelectric unit, unit direct control, supervisory control and data acquisition (SCADA), automatic generation control (AGC), and energy management systems), similar to the 5 zones of the Purdue Model [7], achieving a flexible range of operation including the needs of the electrical power grid.

Di-Hydro is an EU-funded project that aims to improve HPPs by focusing on the areas of structural health monitoring, condition monitoring, biofouling prevention, underwater inspection, environmental and biodiversity monitoring, as well as modeling and forecasting [8]. The project aims to develop several digital solutions to improve the aforementioned areas, including innovative sensors to monitor the HPP machinery components, automatic detection of defects using unmanned vehicles, forecasting models for weather and water flow, structural health monitoring and AI-assisted prediction, monitoring of biodiversity and environmental impact of HPPs, all reinforced with advanced cybersecurity measures for secure data collection, exchange and storage. Finally, the project envisions the development of a digital twin platform that will form a cluster for collaborative operations and maintenance between multiple HPPs within a country.

Several challenges and specific needs have been identified by the iAMP-HYDRO, an EU-funded project focusing on enabling the digital transition of existing HPPs [9]. The specific needs include sensor technologies for reliable monitoring and prediction of operation as well as the assessment of the environmental impact and socio-economic sustainability, reliable weather and flow forecasting models for predicting water availability and power production, standardized and secure data collection and interoperability between hydro operations, and decision-making algorithms that aim to increase flexibility and interoperability with other energy sources. To address those challenges, iAMP-HYDRO develops an integrated information and communication technology (ICT) platform that is composed of the intelligent Data Management Layer (iDML) and the integrated Decision Optimization Layer (iDOL). The iDML is the core part of the iAMP-HYDRO platform, integrating various sub-components related to data collection, interaction with sensors and open application programming interfaces (APIs), data storage and repository for models, as well as data analytics and visualizations. A vertical data security layer provides authentication, authorization, access policies and AI security, while the platform management module provides the API gateway and orchestrates the sub-components.

Finally, V. Mladenov et al. [10] focused on the cybersecurity aspect of HPPs, by developing a set of cybersecurity scenarios and applying the SPEAR platform [11]. The SPEAR platform consists of a set of cybersecurity solutions, including AI-assisted threat detection, smart forensics, and increased EU-wide collaboration through the sharing of cybersecurity incidents, aiming to increase the situational awareness and protect the smart grid infrastructure from potential cyberattacks. V. Mladenov et al. developed four cybersecurity scenarios in HPPs, namely a) distributed denial of service (DDoS) attack against the programmable logic controller (PLC), b) buffer overflow attack against IoT sensors via Modbus, c) detection and reaction to natural hazard, and d) intelligent deployment of honeypots to lure cyberattackers and protect the production assets.

III. The D-HYDROFLEX Architecture

The primary goal of D-HYDROFLEX is to create a comprehensive toolkit of digital solutions that will renovate existing HPPs. This activity involves developing technologies that rely on smart sensors, digital twins, AI algorithms, hybridization modeling (power-to-hydrogen), cloud-edge computing, and image processing. To accomplish this, the initial step is to define the appropriate tools and establish a reference architecture that outlines their role and interactions. This architecture will ensure seamless integration and functionality, towards achieving D-HYDROFLEX's objectives.

Fig. 1 illustrates the D-HYDROFLEX architecture, which follows the convention of the interoperability layers of the Smart Grid Architectural Model (SGAM) [12]. At the lower level of the architecture lies the *component* layer, which comprises the physical components of the HPP infrastructure. These components include: SCADA systems, sensors, cameras, controllers, industrial networking equipment, and other related devices. This layer transmits essential data to the D-HYDROFLEX tools, illustrated as labeled boxes. Each tool operates across the *information*, *communication*, and *function* layers. For each tool, the information layer defines the type of data it processes. In Fig. 1, this layer specifies the data received as input, either from the *component* layer, an external source, or another D-HYDROFLEX tool. The *communication* layer outlines the supported communication protocols and serves as an interface for connectivity with other tools. It is important to note that some communication protocols may be indicative, with their selection depending on technical requirements and the designer's objectives. It is noted that the tool's output, delivered through the *communication* layer interface, also specifies the type of output data. While this output data technically falls within the scope of the *information* layer, as it represents a data type handled by the tool, it is not explicitly detailed there. Instead, the color code used in this output, subtly links it to the *information* layer, enhancing readability and minimizing visual clutter. Following that, the *function* layer defines the service that each tool provides. Finally, the *business* layer presents the business perspective of the D-HYDROFLEX, which is primarily reflected through the D-HYDROFLEX monitoring and diagnostics (HYDRO-M&D) center. This tool supports a wide range of applications, leveraging services provided by the rest of the tools. Essentially, it is a web-based dashboard for HPPs and integrator of the D-HYDROFLEX toolkit. It aims to unify the output of the D-HYDROFLEX tools and provide a central reference point for HPP operators to get real-time insights about the overall HPP operation and status. The *business* layer translates the insights and results obtained by the M&D center into tangible decisions and strategies, mainly focusing on increasing HPP's efficiency, reliability, and sustainability.

Table I lists the D-HYDROFLEX tools, accompanied by their respective brief descriptions. The following sections dive deeper into the primary functionalities of each tool. Each section represents a core concept of D-HYDROFLEX and lists the relevant functions and tools associated with it.

IV. Digital Twin Framework

Applications of digital twin (DT) in the energy production industry, including HPPs, have the potential to achieve high reliability, availability and maintainability at a lower cost. More specifically, D-HYDROFLEX utilizes DT technology to create virtual replicas of a Kaplan turbine and the dam infrastructure, employing two separate sets of tools that form the *Hydro Unit Digital Twin* and the *Dam Digital Twin* frameworks, respectively. These set of tools are described below in more detail.

A. Hydro Unit Digital Twin

The *Hydro Unit Digital Twin* encompasses the following functions, with the tools shown in Fig. 1 also highlighted.

1) Turbine DT: The HYDRO-TIN tool creates a virtual model of the turbine, continuously tracking vital parameters such as water flow, turbine blade angles, rotational speeds, and power output. This real–time data enables operators to optimize performance by making informed adjustments, such as fine–tuning turbine settings to align with efficiency curves, managing water resources effectively, and adapting to changes in demand. Moreover, computational fluid dynamics (CFD) simulations provide detailed fluid dynamics analyses, supporting design improvements and strategic operational adjustments.

2) Hydrological Modeling: It relies on the HYDRO-HMP tool, which leverages real-time and historical river flow data to forecast in water flow resulting from upstream conditions

3) Fault Prediction & Maintenance: This service is carried out by the HYDRO-PVIL tool, which is designed to monitor critical components like turbines, generators, and mechanical systems. By analyzing sensor data such as vibration patterns, HYDRO-PVIL identifies anomalies that signal potential failures. This allows maintenance teams to address problems

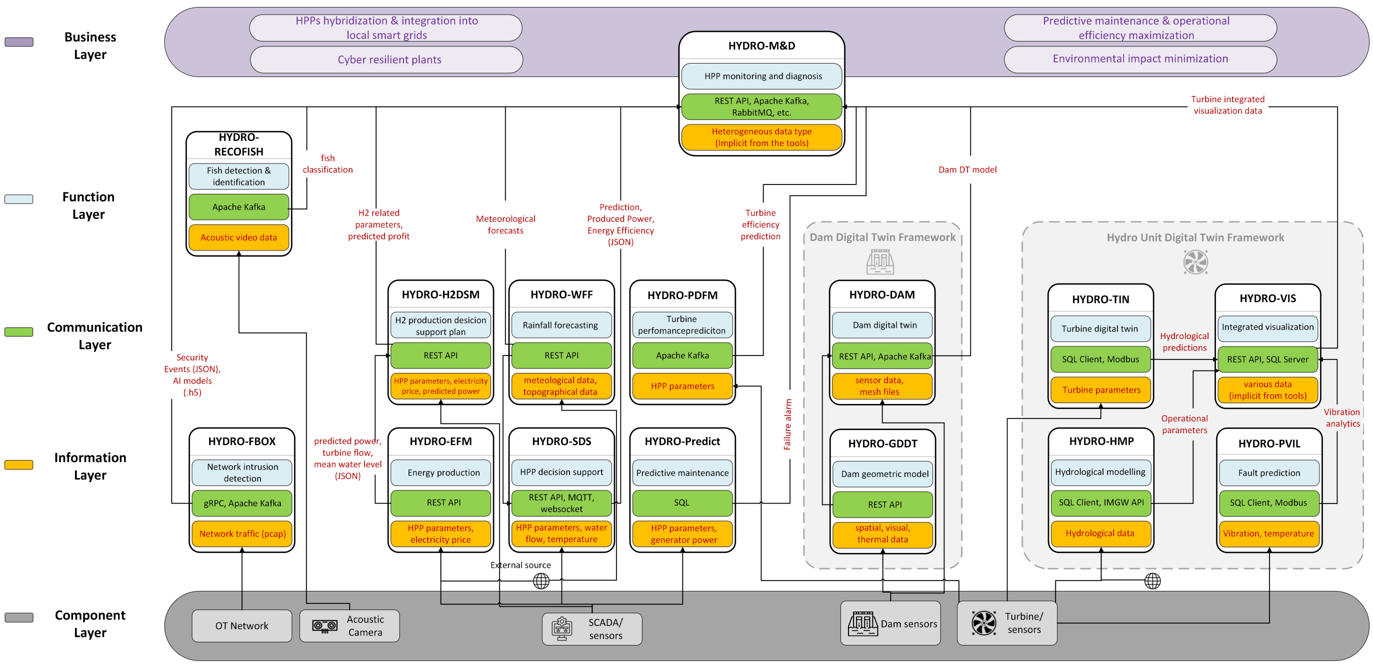

Fig. 1. Visual representation of the D-HYDROFLEX architecture.

TABLE I
D-HYDROFLEX Toolkit Description

Acronym	Description
HYDRO-TIN	Creates a virtual replica of the turbine
HYDRO-HMP	Forecasts changes in water flow
HYDRO-PVIL	Provides vibration analysis and predictive maintenance insights of the rotation unit
HYDRO-VIS	Provides integrated visualizations of operational parameters, hydrological forecasts, vibration analysis and CFD simulations
HYDRO-DAM	Generates a digital twin of the dam infrastructure
HYDRO-GDDT	Provides dam as-is geometry and spatial relationships between dam objects
HYDRO-H2DSM	Predicts the amount of hydrogen that would be possible to generate with electric power from a HPP
HYDRO-WFF	Provides weather and water flow forecasting
HYDRO-EFM	Energy forecasting model
HYDRO-PDFM	Predicts the performance degradation of Kaplan turbines
HYDRO-Predict	Predicts imminent failure of the different components monitored in the HPP
HYDRO-SDS	Predicts energy efficiency balance and optimized data for virtual power plant operation
HYDRO-FBOX	Detects cyberattacks in the networking infrastructure of the HPP
HYDRO-Recofish	Provides counting of fish passing the river and species classification
HYDRO-M&D	Monitoring and diagnostics center (web-based dashboard)

proactively, preventing costly breakdowns and minimizing operational interruptions. Real–time alerts help schedule maintenance efficiently, prioritize interventions, reduce downtime, and extend equipment lifespan. Moreover, as a complementary functionality, the HYDRO-Predict tool can predict faults in the turbine bearing based on temperature models.

4) Integrated Visualizations: The HYDRO–VIS visualization tool consolidates data from HYDRO–TIN, HYDRO–PVIL, and HYDRO-HMP into an intuitive dashboard. This platform offers a unified view of the plant's operations, including predictive maintenance alerts and efficiency metrics. The real–time data supports collaboration among operators, maintenance teams, and decision–makers, enabling coordinated efforts to optimize performance and reliability.

B. *Dam Digital Twin*

The *Dam Digital Twin* comprises the following functions and tools.

1) Dam Geometry Generation: The HYDRO-GDDT tool processes raw data, such as laser point clouds and color images, to generate a detailed geometric dam model and analyze relationships between different dam components. By leveraging advanced processing techniques, it enhances raw spatial data to create a structured and meaningful representation of the dam's structure. The tool converts the semantic point cloud into a semantic mesh, which provides a refined and enriched dataset for further analysis. This semantic mesh then serves as the primary input for the HYDRO-DAM tool, that act as the foundation of the tool.

2) Predictive Maintenance & Operational Maximization via Dam DT: This service is carried out by using the HYDRO-DAM tool, which generates a digital twin of the dam infrastructure that enhances operational management and safety through predictive maintenance. Specifically, HYDRO-DAM utilizes the dam geometry provided by HYDRO-GDDT, along with hydrological, environmental, vibrational, and pressure data, as well as building information modeling and geographical information system (GIS) data, to create a comprehensive digital twin of the dam, offering valuable insights and opportunities for operational optimization.

V. Hydro Power Plant Hybridization with on-site Hydrogen Production

Hydrogen generated using electricity from renewable energy sources is particularly valuable because its production is free of CO_2 emissions. To speed up the adoption of green hydrogen technologies, the electricity costs for producing green hydrogen using the power-to-gas system should be optimized. Electricity produced by the HPP cannot be freely utilized for hydrogen generation due to several constraints. These include the requirement to adhere to the production schedule set by the system operator, the need to provide system services, and the necessity to maintain the water level above the minimum allowable threshold, as water is also used in electrolysis. To this end, the subsequent list of functions aims to develop a physical and economic model for run-of-river hybrid H_2 power plant.

1) Decision Support for Hybrid HPPs: This service's objective is to a create decision-making framework to determine the optimal conditions for generating electricity or hydrogen. It is mainly reflected through the HYDRO-H2DSM tool. More specifically, HYDRO-H2DSM receives as input the predicted turbine flow, predicted power generation, mean water level, and data relevant for hydrogen and other fuels (e.g., water consumption in electrolysis, hydrogen production per electrolyzer, green hydrogen price, diesel emission factors, etc.). Afterwards, HYDRO-H2DSM estimates the potential hydrogen production using electric power from a HPP and formulates a future decision strategy for balancing hydrogen and electricity generation based on specific hydrogen plant characteristics. Additionally, the model assesses: i) the environmental impact of utilizing hydrogen for mobility compared to other fuels, ii) water consumption, and iii) the economic advantages of hydrogen production versus electricity generation. In a similar spirit, the HYDRO-SDS tool forecasts the ideal timing for water turbination, hydrogen storage, and green hydrogen electricity generation.

2) Energy Production & Turbine Performance Prediction: The HYDRO-EFM cool can estimate the electrical energy output under specified boundary conditions, making it a crucial component of HPP energy planning. This tool plays a vital role in forecasting future energy production for HPPs and will serve as the foundation for feeding HYDRO-H2DSM. Specifically, it receives data from SCADA systems and can predict i) turbine flow, ii) generated power, and iii) mean water level. Additionally, HYDRO-PDFM provides prediction of the performance degradation of Kaplan Turbines.

VI. Intrusion Detection against OT networks

The increasing digitalization and the continuous technology development have supported the deployment of advanced industrial control systems (ICS), which are used to monitor, control and automate industrial processes. However, the ICS infrastructure increases the attack surface, since it introduces new threat vectors as well as new vulnerabilities and weak points that can be exploited by adversaries to disrupt the HPP operations. AI-based intrusion detection systems (IDS) show great potential in effectively defending against those threats. Below we describe some key functions that address cybersecurity threats within HPPs, which are supported by HYDRO-FBOX tool, as illustrated in Fig. 1.

1) Federated Learning-based IDS: This function offers an IDS trained using a federated learning approach [13], ensuring that no raw data leave the premises of the HPP, thereby preserving privacy. Once trained, the IDS can be deployed in real time to detect cyberattacks and malicious activities within the HPP's networking infrastructure, such as PLC controllers utilizing communication protocols like Modbus, DNP3, and others.

2) Security Event Generation: The IDS generates security events in real time by analyzing network traffic and system activities for potential cyber threats. These security events provide valuable insights into detected anomalies, unauthorized access attempts, or malicious activities targeting the HPP's networking infrastructure. The IDS can classify and prioritize security events, enabling timely responses to mitigate risks. Additionally, these events can be logged, correlated, and shared with security operations teams.

3) IDS Explainability: To enhance transparency and trust in the IDS decision-making process, eXplainable AI (XAI) techniques are integrated into the IDS models. These techniques provide insights into how and why specific alerts or security events are generated, helping cybersecurity analysts interpret the model's decisions. Methods such as SHAP (Shapley Additive Explanations) [14] are employed to highlight the most influential features in detecting malicious activities. By incorporating XAI, the IDS not only improves threat detection but also enables human operators to validate and fine-tune the model's responses.

VII. Hydro Power Plant Integration with Local Smart Grids

With the further inclusion of variable renewable energy sources into the energy mix (e.g., wind power, solar power, and green hydrogen), there is an increased need to employ flexibility and ancillary services, to ensure constant supply and demand balance as well as high power quality. HPPs are a useful asset for grid operators to achieve that goal, since they can provide flexibility in terms of adjusting power output based on grid demands. While some types of HPPs can provide stable and predictable power output (e.g., impoundment HPPs), RoR HPPs are characterized by increased dependency from weather conditions (e.g., drought, rainfall), challenging their integration with local smart grids. To address the challenge of integrating RoR HPPs with local smart grid, D-HYDROFLEX introduces a weather and water flow forecasting function integrated in a smart decision support system, both analyzed bellow.

1) Weather and Water Flow Forecasting: This service is provided by the HYDRO-WFF tool, and is responsible for predicting the amount of water flow in the HPP river. Given the critical role of weather conditions on the water flow, and hence for predicting the potential power generation of RoR HPPs, HYDRO-WFF predicts the water flow in three steps. First, climate predictions are generated at climate station level by applying weather down-scaling techniques on open source weather data, followed by spatial-temporal down-scaling to infer the climate at any location and at a smaller temporal scale. Finally, a rainfall-runoff model is applied to forecast how rainfall is converted into runoff water, thus providing the expected water flow.

2) Smart Decision Support System: Considering the predicted water flow from HYDRO-WFF as well as the availability of electric power from solar and hydrogen, the HYDRO-SDS tool undertakes to generate a power production plan for RoR HPPs. Given a specific market frame, the HPP administrator can request a power production plan from HYDRO-SDS. To produce this plan, HYDRO-SDS requests from HYDRO-WFF relevant water flow predictions, which are applied on a hydroelectric model in order to predict the power generation. Moreover, the availability of solar power and electrolyzers is also considered for estimating the potential power generation capacity. Finally, by combining the potential power generation capacity with the local grid requirements provided by the local grid operator, HYDRO-SDS generates an operation plan, which is presented to the administrators.

VIII. Biodiversity Impact Monitoring

Despite their benefits, the HPP infrastructure imposes a considerable threat to the environment due to the substantial changes introduced to the surrounding landscape and water flow. One of the most common ecological impacts reported include fish injuries and the obstruction of fish species migration. Migratory species such as salmon and eel are particularly vulnerable [15].

To assess the biodiversity impact of HPPs, D-HYDROFLEX provides the biodiversity impact monitoring service through the HYDRO-Recofish component, with the goal to identify and count fish species' populations, particularly focusing on salmon and eel species. To accomplish this, HYDRO-Recofish obtains acoustic video streams from a set of acoustic cameras, which is a non-intrusive method that allows to continuously monitor fish passage, at higher efficiency compared to optical cameras and with low dependence on environmental conditions (e.g., water turbidity). Then, HYDRO-Recofish processes the acoustic video streams for feature extraction, obtaining morphological features of fishes (e.g., length estimation, shape characterization) as well as fish locomotion characterization through a 2D deformation model. Finally, a ML-based classification model automatically identifies the fish species, based on the extracted features, in real-time.

IX. Conclusions

This paper presents the D-HYDROFLEX architecture, which introduces and integrates a set of tools that aim to digitalize and renovate HPPs. The components of the D-HYDROFLEX toolkit cover 4 main use cases, namely: i) Predictive maintenance and operational efficiency maximization, ii) HPP hybridization and integration into local smart grids, iii) intrusion detection against OT networks, iv) environmental impact minimization. Moreover, D-HYDROFLEX introduces a comprehensive DT framework that comprises the simulation and prediction of faults, covering not only the mechanical components of an HPP but also the structural health of the dam infrastructure. Finally, a central monitoring and diagnostics control center integrates the D-HYDROFLEX tools and provides visualisation and user interaction capabilities, providing to the HPP operator a central point of reference and assisting in the decision-making processes.

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