# Role of Digital Solutions for Hydropower and its Importance in Energy Transition

Prajwal Shandilya M G, Michael T. Solomon, Helena M. Ramos

***Abstract*****—** As the need to move from conventional energy to renewable energy has increased, the stableness of the renewable energy systems becomes crucial to satisfy the continuous demand for power. Hydropower is a very stable renewable source of power to the grid and is critical in Energy Transition with a major share in Renewables. The digital solutions such as predictive maintenance and study with digital twin will be critical in many decision-making ability in the power plant. The paper reviews the digital solution of predictive maintenance in Hydropower, Optimization, Digital Twin and Cyber Security in Hydropower solutions. A final proposal of a model for microgrid system with data collected and forecasted from power demand is presented.

***Keywords*****—** Hydropower, Predictive maintenance, Optimization, Digital Solutions, Digital twin, Cybersecurity.

## I. Introduction

Hydropower is the Renewable source of energy with the highest percentage among all the renewables. Hydropower contribution of 1230 GW was observed at the end of 2021 with a share of 40% in comparison with all other Renewable Energies [1]. Hydropower has special advantages over other sources of Renewable power generation. Hydropower, being renewable is an abundant source of power generation. As long as the environment concerns are taken care of, the Hydropower offers a stabilized power to the grid. The reliability of Hydropower is higher in comparison with other renewable energy sources such as Solar PV and Wind Energy (Fig.1), the power can be generated whenever required as long as there is enough water in the reservoir.

The efficiency of the Hydropower is the highest with 80-90% depending on different plants. Hydropower can also be started and turned off whenever there is a demand for electricity and a shortage in supply.

Along with the major advantages brought by Hydropower, the pumped storage hydropower (PSH) acts as a huge battery bank and store a great amount of energy. The pumped storage hydropower can either be open loop or closed loop. In open loop, a runoff river is used as a lower reservoir and water is pumped to upper reservoir whereas in closed loop, both upper and lower reservoirs are storage units where the water is stored. When the water is released from the upper reservoir to the lower the lower reservoir, the turbine is turbined to produce electricity. These PSH can compete with batteries as energy storage systems.

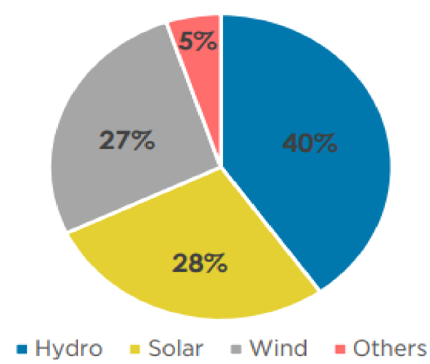


Fig 1. Energy source distribution of renewable energy [1]

Digitization and digitalization have made a lot of industrial process automatized and there have been significant increase in the efficiency of the working system. With the Internet of Things (IoT), big data analytics and other upcoming technologies many of the processes in the industry and plants are having lower errors. The general working of the IoT can be done with the help of sensors to collect data and to enable a method of communication between different processes and systems [2]. With the help of the collected data, many machine learning processes can be developed for the optimization of the systems or forecast of maintenance for industrial and plant machines. The digital twins are the virtual representation of plants in separate platforms to run simulations, these digital twins are the excellent ways for implementation and testing of new optimized methods [3].

The digitalization in Hydropower technology and plants will play an important role as there is being a shift from conventional energy sources to renewable energy sources. The paper reviews different ways in which the digitalization is being brought and can be brought in hydropower predictive maintenance. The paper with different technologies, reviews the role of digitalization in optimization of hydropower systems, predictive maintenance, cybersecurity of hydropower, importance of digital twins. The rise of off-grid systems in remote places and islands will pose a great challenge in the storage of energy. Pumped Storage Hydropower will have a big role in the storage. The predictive maintenance and failure detections become crucial in these storage plants to have a stable grid that always satisfies the demand for electricity.

## II. Predictive Maintenance In Hydropower

The Maintenance of any industry or plant is critical in its operation as any faults in the plant may lead to huge loss in costs and also a low production. Hydropower is one of the stable sources of energy with high reliability. The maintenance and continuous operation of the plant will be the key in satisfying the continuous demand for power with a Renewable energy source dominated grid. Singh et al. (2020b), Provides a sustainable framework of management considering the sustainability of the hydropower plant [4].

There can be many types of maintenance, such as reactive maintenance, preventive maintenance, Condition Based Maintenance, predictive maintenance and more. In reactive maintenance the maintenance is done after the detection of a failure. The maintenance is only done after failure, even though this saves costs, the downtime will be unexpected and might bring questions in the reliability. In preventive maintenance, the maintenance is done based on a time which is previously determined so that the maintenance can be done before failure, however, sometimes there might be an unnecessary maintenance done which will increase the cost and downtime. In the condition-based maintenance, there is a regular inspection physically or with sensors to see the need for maintenance, this will reduce the downtime. The predictive maintenance uses the new digitalized technologies such as collection of data with sensors and developing models to forecast or predict the maintenance based on many factors based on history, lifespan of equipment and so on. A reduction in downtime, cost and increase in the lifespan of the equipment can be expected with this type of maintenance. Jiang (2008b), proposes a model of predictive maintenance for hydropower plant and the model is based on the framework of Intelligent Control-Maintenance-Management System, the model is a Multi-Agent System based mix model for predictive maintenance. The paper also builds a prototype of predictive maintenance for hydropower plant [5].

Fu et al. (2004b) [6], Explains the three key elements in the predictive maintenance which are Monitoring and Forecasting, Diagnosis and Prognosis and Maintenance Decision making. In the monitoring and forecasting various data are collected and the paper says that the condition monitoring and forecasting is the basement for the predictive maintenance. Based on the forecasting and data available the different conditions of the equipment in the plant are identified, and after these results, the prediction of time of failure is done. In the last key element of Maintenance decision making, different decisions based on the first two elements are done, different questions such as when do to, where to do, how and what questions are answered in this element **[6]**. Different decision support models can be used in taking the decisions for these maintenance with the three key elements. Fu et al. (2004b), further develops an Artificial Neural Network (ANN) based model for a predictive maintenance in the electrohydraulic servomechanism of the water turbine governing system by obtaining very satisfactory results **[6]**. These AI models will be a game changing technology in maintenance which comes with several advantages both technically and economically.

Åsnes et al. (2018) [7], discusses on the machine learning method solution for three problems, one on the degradation detection technique on the servo system of the Francis Turbine, identification of the issues with the control of Pelton injectors and the Francis runner lifecycle prediction.

The first case of the paper addresses the monitoring of friction force development in the guide vanes of the Francis turbine. The purpose of this case study is to look into the possibility of automating manual inspection by continuously tracking friction forces as they occur during operation using differential pressure readings from the hydraulic system, the paper used the machine learning technique of One Class Support Vector Machine which was successful in identifying the servo forces in and define boundaries for the servo forces in the guide vanes [7]. The second case uses the data to predict the fault in the Pelton injector using machine learning and to obtain the pre indications of the defect, the model was successful with the aim it was intended in detecting the fault [7]. The last case of [7] tries to predict the lifetime of the mechanical component exposed to dynamic loading, the paper discusses that this will be helpful in the replacement of equipment and making a decision for the replacement based on the probability of the failure [7].

## III. Optimization In Hydropower

Optimization in hydropower can contribute to the Energy Transition by increasing the efficiency of hydropower plants, reducing their environmental impact, and improving their flexibility to respond to changing energy demands. Optimization can also help to reduce the cost of hydropower production, making it more competitive with other renewable energy sources. Additionally, optimization can help to reduce the amount of water used in hydropower production, which can help to reduce water scarcity and improve water security.

Then, optimizing hydropower can contribute significantly to the energy transition by making it a more efficient and sustainable energy source. Here are a few optimization options that can lead to a greener and more affordable hydropower energy such as:

1. Upgrading existing hydropower plants: Upgrading existing hydropower plants with new technology and equipment can improve efficiency and reduce downtime, resulting in increased production of energy with lower operating costs and greater profitability.

2. Dam optimization: By optimizing the design and operation of hydropower dams, their efficiency can be increased and environmental impacts minimized. For example, incorporating fish ladders, downstream migration systems, and other fish-friendly measures can ensure that fish species can continue spawning and reproducing even with the dams in place.

3. Pumped storage optimization: Pumped-storage hydropower systems store energy by pumping water uphill and generating electricity during peak demand. Optimizing these systems can increase their capacity and efficiency and make them more economically viable, increasing the system flexibility when integrated other renewable sources, such as wind and sun.

4. Smart-grid integration: Smart-grid technologies which integrate renewable energy sources can help smooth out the energy supply and demand curve, making hydropower an even more reliable source of green electricity.

5. Hydrogen production: Another way to optimize hydropower is to use it as a source of renewable energy to produce hydrogen fuel. Hydrogen produced from hydropower can be used as a zero-emission fuel for transportation, heating, and other energy industries.

These points are essential to focus the review on hydropower operation optimization by ML application (Fig. 2). For example, hybrid generation systems, being the hydropower generation operation optimized with the specific contributions and restrictions in the process of other/others generation types (photovoltaic and wind) **[8].**

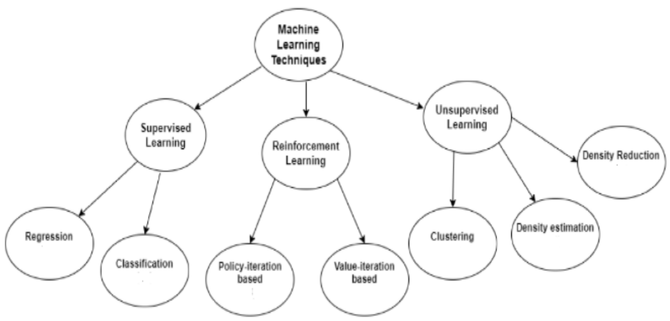


Fig 2. Machine Learning Techniques

The optimal dispatch of hydropower plants consists of the challenge of taking advantage of both available head and river flows. Despite the objective of delivering the maximum power to the grid, some variables are uncertain, dynamic, non-linear, and non-parametric. Nevertheless, some models may help hydropower generating players with computer science evolution, thus maximizing the hydropower plants' power production. Over the years, several studies have explored Machine Learning (ML) techniques to optimize hydropower plants' dispatch, being applied in the pre-operation, real-time and post-operation phases. Regarding ML technique groups considered for the analysis, supervised learning is broadly applied using regression and classification techniques. Furthermore, It was noted the extensive use of Artificial Neural networks due to its capacity to fits appropriately for most of the applications of ML on hydropower operation optimization: derivation of parameters for a forecast of river flow; optimization model for reservoir operation; multi-objective optimization model operation of multi-propose reservoirs; and derivation of operation rules; the conveyance systems and turbines (number and type) selection; Transient guidance depending on the type of turbine and the hydraulic circuit inertia [9].

Based on related data, the highest and lowest recorded of wind speed can vary more than 300%, while for Solar Irradiation was can be from 1 to 0 kW/m². The most expensive recorded energy price in hourly basis can vary from 200 €/MWh, while the cheapest was can be 10 €/MWh. And based on principle computations, the average hourly load/demand was higher than the average hourly PV and Wind Generation. Hence, the PSH scheme can be developed to ensure the hourly operation can be managed to balance the supply and demand while at the same time minimizing the cost of operation (Fig. 3).

Computations for Solar PV and Wind Turbines are described.

$$P_{PV}(t) = P_{Rated\_PV}\ x\ \frac{G_T(t)}{G_{ref}}\ x \left(1 + k_T\ x \left(T_C(t) - T_{ref}\right)\right) \quad (1)$$

$$T_C(t) = T_{amb}(t) + 0.03\ G_T(t) \quad (2)$$

$k_T$ is temperature coefficient of Solar PV modules and $T_C$ is Cell's Temperature. The dynamic data has given different temperature in hourly basis, and so the $T_C$ changes based on ambient temperature and solar irradiance. $T_{ref}$ is accustomed to reference temperature during test conditions (assumed to be 25 ˚C), while $T_{amb}$ is ambient temperature (in Kelvin).

$$P_{WT}(t) = \eta_{WT}\ x \left[\frac{1}{2}\ x\ C_P\ x\ \rho_a(t) x\ \pi\ x\ R^2 x\ U^3(t)\right]\ if\ U_{cut-In} \leq U_{(t)} \leq U_{rated} \quad (3)$$

$$P_{WT}(t) = \eta_{WT}\ x \left[\frac{1}{2}\ x\ C_P\ x\ \rho_a(t) x\ \pi\ x\ R^2 x\ U^3_{rated}(t)\right]\ if\ U_{rated} \leq U_{(t)} \leq U_{Cut-Out} \quad (4)$$

$$P_{WT}(t) = 0\ if\ U_{(t)} \leq U_{Cut-In}\ or\ U_{(t)} \geq U_{Cut-Out} \quad (5)$$

In that case, $\eta_{WT}$ is wind turbine's efficiency which usually ranges from 0.2 until 0.4, depending on wind data and wind turbine types. $C_P$ is power coefficient and its value is always less than 0.59, complying with Betz Limit's theorem. Area of wind turbine is calculated from the diameter of rotor blade, R, and its value is always constant, while on the other hand air density varies per hour, $\rho_a$ (t). $U_{(Cut-In)}$ is wind speed lower bound for the turbine to start rotating and hence producing power, while $U_{(Cut-Out)}$ is the wind speed upper bound at which the generator is decoupled from the shaft and the turbine stops producing power (No power, 0). This applicable computation is a standard practice based on wind turbine manufacturer power curve. On the other hand, rated wind speed, $U_{rated}$ is the nominal wind speed on the optimal operation of wind turbine generation. The maximum allowable power output is limited to the rated wind speed.

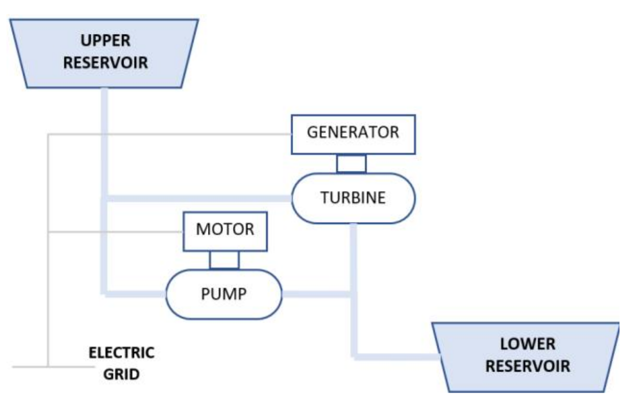


Fig 3. General Setup of Pumped Storage Hydropower (PSH) System

Overall, optimizing hydropower can significantly contribute to the energy transition by helping to lower carbon footprint and enhancing the role of renewable energy in the global energy mix. Finally, optimization can help to reduce the risk of flooding and other environmental impacts associated with hydropower production.

## IV. Digital Twin In Hydropower

As a virtual representation of the physical PSH system, DTs integrate virtual engineering models with land-scale reality models and Geographic Information System (GIS) data. DTs demonstrate accurate and reliable data that can be used to analyze different aspects of a water system. DTs and smart water grids (SWGs) foster and help digitize management systems and solve problems caused by bad design or inadequate operation. DT development requires continuous adjustments and learning techniques supported by large field data stored in big-data platform.

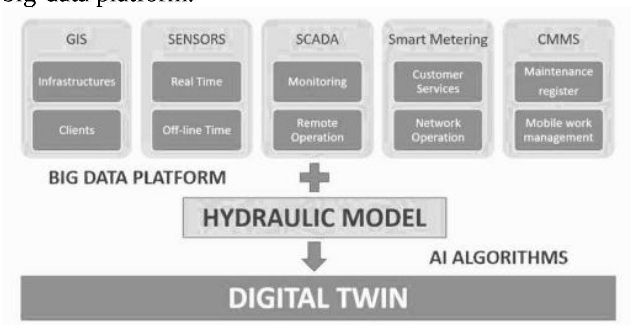


Fig 4. Structure of a typical Digital Twin model

This methodology includes: (i) GIS, which provides information regarding the location of system components; (ii) sensors, which measure hydraulic parameters of the water network; (iii) data acquisition (SCADA), which supervises, monitors, and controls the collected data; (iv) smart metering, which controls the network operation;(v) computerized maintenance management system (CMMS), which tracks and maintains stationary assets. The integration of sources in the hydraulic model, with the use of artificial intelligence (AI) algorithms and information and communications technologies (ICTs), a DT model can be developed with a huge interest to be exploited.

Hence, Machine learning (ML) and internet of things (IoT) platforms based on digital twin (DT) solutions can help reduce water-energy nexus losses by supplying advanced telemetry to control water-energy management toward a smart water-energy grids. A problem-solving holistic approach can be presented as a management technology to support a set of conditioning factors, including the following:

- Flow management: reduction in water-energy losses through a detection and communication system that intelligently supervises sensors, telemetry, and actuators to regulate valves.
- Water and energy monitoring: a monitoring system transmits the pertinent data to a data acquisition system, control, and management hub.
- Water grid control: a remote-control platform, which uses big data analytics, empowers the water–energy network manager to make the system progressively more efficient and flexible with real-time control and data-driven decisions.

Systems efficiency have become an important concern of management entities [10]. This can be viewed as an opportunity to improve the management of water systems by integrating new concepts and technologies

## V. Cybersecurity In Hydropower

Cybersecurity is essential in all industrial systems, including pumped hydro power plants, as these systems are vulnerable to cyber-attacks that can cause major damage. Pumped hydro power plants are complex interconnected systems that require constant monitoring of the different components, such as pumps, turbines, and control systems, to ensure their optimal performance and safety. However, these systems are also susceptible to cyber threats, which can be initiated either from inside or outside the system, and can lead to power outages or permanent equipment damage. Kumari et al. (2020) [11] developed a model for a parallel control framework that combines a digital model predictive controller (MPC) and an analog proportional-integral controller (PIC) is developed to safeguard hydropower plant converters from cyber-attacks. A 250 MW hydropower generating unit is chosen for the model and the results obtained from the model were reliable [11].

Here are a few ways cybersecurity is essential in pumped hydro power systems:

1. Protection of control systems: Pumped hydro power plants rely on complex control systems, including supervisory control and data acquisition (SCADA) systems to maintain efficient operation. These control systems are vulnerable to cyber threats that can disrupt operations and cause damage. Therefore, it is essential to secure these systems with strong firewalls, passwords, and user access controls to prevent unauthorized individuals from accessing critical data.

2. Ensure data confidentiality: Cybersecurity is also necessary to ensure data confidentiality in the pumped hydro power systems. The data collected by SCADA systems can provide valuable insights into operations, faults, and performance for maintenance and optimization. However, the data should be treated as sensitive and confidential, as it could be exploited by cyber attackers to compromise the system's security.

3. Cyber incident response planning: Developing a cyber incident response plan that outlines the necessary steps to take in case of a cyber-attack can help mitigate damage and minimize downtime. This plan should detail the individuals responsible for responding to the attack, including IT personnel, facility managers, and engineers.

4. Training and awareness: Finally, cybersecurity awareness and training are crucial for all personnel involved in pumped hydro power plants. Educating employees about the potential cyber threats and best practices for securing the system can help prevent human error and create a cybersecurity culture within the organization.

In summary, cybersecurity is crucial in pumped hydro power systems to prevent cyber threats that could lead to significant damage, power outages, and even fatalities. By implementing robust cybersecurity measures, pumped hydro power plants can operate efficiently, safely, and securely.

## VI. Need For Digitalization In Microgrids With PSH

Microgrid systems which are decentralized and off-grid with renewable energy sources will have the requirement of storage unit where either batteries or the other storage technologies such as Pumped Storage Hydropower (PSH) can be used. The need for digitalization is to have a smart grid that can automatically switch between different renewable sources of energy to continuously satisfy the demand for the power. The systems can be connected with Internet of Things (IoT). The pumped storage hydropower becomes crucial as it is the backup power/ storage unit that is used to supply the demand. As explained in the above sections, many different machine learning techniques can be implemented on the predictive maintenance of the hydropower and defect analysis with digitalization.

The current section explains the requirement for the digitalization in PSH of off-grid system. A model for the optimal functioning of the Microgrid with IoT is proposed in order to satisfy the continuous demand for the power. A machine learning model is also developed in forecasting the energy demand based on the data from the previous year consumption.

The energy forecast is done with the power consumption data obtained from Instituto Superior Tecnico University of Portugal. The hourly power consumption data of one of the buildings was considered to forecast the demand for power for the next year and was validated with the real data of the year. The forecast of the power consumption was done with different Machine learning models such as liner regression, random forest regression, decision tree regression, neural network, gradient boosting, extreme gradient boosting. However, the random forest regression model was closest with the forecast and was considered. The forecast for the power consumption was done by considering various data such as the weather data of incident radiation, relative humidity, wind speed, among others.

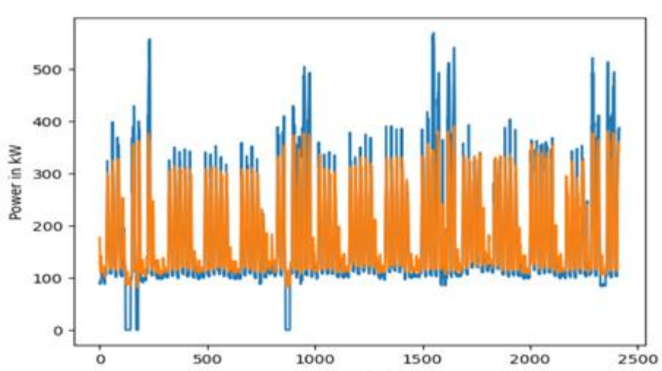


Fig 5. Demand forecast comparison with real data.

The blue curve shows the original demand for power of the forecasted year whereas the orange curve in the graph shows the predicted data from the consumption data of the previous year. The peaks that are not forecasted come from the laboratory testing which consumes a lot of power.

The **Fig 5** shows the graph of the predicted power and the real power. This shows that the demand for power can be forecasted with different machine learning models.

Just as how the forecast for the demand for power can be done, the forecast of power production can also be done with the help of weather data. Although the scope of this paper does not cover the implementation of forecasting method for power production from renewables, an extrapolation from the power demand can be done to conclude that machine learning models can be used to forecast the power production as well. With the data obtained from the forecast of demand and forecast of power production, an optimized model of microgrid can be developed as shown in **Fig 6.**

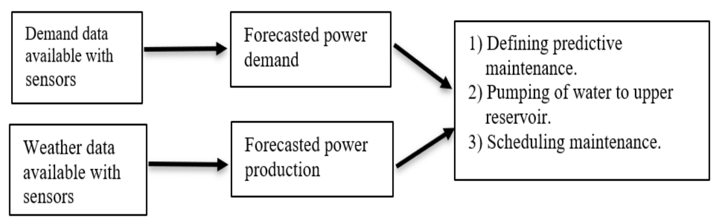


Fig 6. A simple model to depict how digitalization can be used with PSH and its maintenance.

In the **Fig 6,** the data can be collected to forecast both demand for power and power production from available renewable energy systems. These forecasted data are connected through IoT and sent to the pumped storage hydropower plant. The forecasted demand and power production data are collected and with special machine learning models, the predictive maintenance of PSH can be done. These data can also be used to pump the water from lower reservoir to upper reservoir and to produce power when there is no power is being produced from other renewable energy systems. This way, the downtime for maintenance can be scheduled at the time where the other renewable energy systems are producing the power.

Since the hydropower is a stable electricity producer, the digitalization techniques will be helpful in integration of power with other renewables and frequency regulation of the grid. With the climate change and combating global warming goals, the renewable sources of power has been inevitable for power production. Hydropower with the largest share will be the leading source of power in renewables. PSH can be a game changing technology which produces frequency variability as required and grid stability. The digitalization of hydropower with machine learning models for predictive maintenance, defect analysis and optimization is necessary in a completely off grid system.

## VII. Conclusion

With Industry 4.0 most of the industries and plants are being digitized and the processes are being digitalized for an optimized process with lower cost for maintenance and increased efficiency. Hydropower being a largest producer of renewable power will play a big role in energy transition and the digitalization processes are necessary. The predictive maintenance in the hydropower plants will reduce the downtime and costs which will provide a stable and reliable renewable power. The review and importance of optimization in Hydropower is listed and the role of Artificial intelligence to have an optimized power generation. With all the digitalization, cyber threats both internally and externally will increase and cybersecurity becomes important in plants to have a smooth running for power production. A model for using digitalization in microgrid is proposed based on which the scheduling of maintenance and pumping of water to upper reservoirs can be done. This becomes crucial in order keep satisfying the continuous demand for power. Overall, the digitalization can increase the efficiencies and reduce the costs in an optimized way for power plants and the implementation of digital solutions in Hydropower will be important in the transition towards green energy.

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