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Review

Digitalization, Industry 4.0, Data, KPIs, Modelization and Forecast for Energy Production in Hydroelectric Power Plants: A Review

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Abstract: Intelligent water usage is required in order to target the challenging goals for 2030 and 2050. Hydroelectric power plants represent processes wherein water is exploited as a renewable resource and a source for energy production. Hydroelectric power plants usually include reservoirs, valves, gates, and energy production devices, e.g., turbines. In this context, monitoring and maintenance policies together with control and optimization strategies, at the different levels of the automation hierarchy, may represent strategic tools and drivers for energy efficiency improvement. Nowadays, these strategies rely on different basic concepts and elements, which must be assessed and investigated in order to provide a reliable background. This paper focuses on a review of the state of the art associated with these basic concepts and elements, i.e., digitalization, Industry 4.0, data, KPIs, modelization, and forecast.

Keywords: hydroelectric power plant; digitalization; Industry 4.0; data; KPIs; modelization; forecast

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Citation: Pepe, C.; Zanoli, S.M. Digitalization, Industry 4.0, Data, KPIs, Modelization and Forecast for Energy Production in Hydroelectric Power Plants: A Review. *Energies* **2024**, *17*, 941. https://doi.org/10.3390/en17040941

Academic Editors: Chiara Martini and Claudia Toro

Received: 8 December 2023
Revised: 10 February 2024
Accepted: 13 February 2024
Published: 17 February 2024

1. Introduction

The efficiency of large production facilities, in terms of energy and more generally in terms of the use of the resources exploited, is of primary importance in a world that aims to respect nature and that desires to limit air pollution and the waste of environmental resources. Increasing alarm over current climate change and the future of the planet is leading to a shift away from nonrenewable resources (e.g., fossil fuels). Renewable energy source (RES) exploitation is encouraged, and this encouragement contributes to decarbonization. Projects on energy sustainability are shifting political–economic focus from fossil fuel consumption to the use of alternative and less polluting energies, such as wind, hydropower or solar energy [1–3].

Water represents a key RES, and its rational usage represents a crucial milestone when targeting the challenging goals for 2030 and 2050 [4,5]. Water resource systems require advanced and innovative solutions to guarantee the needed performance required to focus on, assess and approach these objectives. Water is exploited in many sectors, e.g., water distribution networks (WDNs) [6,7] and renewable energy production. Among the various types of renewable energy that exploit water, hydroelectricity is certainly of fundamental importance. Hydropower is a type of renewable energy generation based on the production of electricity via exploitation of the movement of large masses of water. Electricity is generated thanks to the action and to the force of these masses, moved by gravity within penstocks. In fact, moving or falling water generates kinetic energy and this kinetic energy is converted into electricity by plants equipped with turbines, generators and transformers. It is indeed essential to make full use of available resources, e.g., water from river courses, in order to avoid waste and maximize plants' efficiency [8].

Hydroelectric power plants are experiencing strong growth in global energy production, partly due to the exploitation of innovative technologies that have a focus on electricity production monitoring and the proper use of water resources [9,10]. Hydropower plants can take the form of a reservoir (water is managed through one or more reservoirs) or run-of-river (placed directly on the course of rivers). Within reservoir hydropower plants, a particular subcategory is that represented by pumped storage stations. In this type of plant, reservoirs are located at significantly different vertical levels and water is brought back to the upper reservoirs through pumps. The output of a plant, on the other hand, depends basically on two factors, i.e., flow rate and head. The mass of water flowing through a point in the unit of time is named as flow rate and the head is the difference in height that exists between the elevation at which the water resource is available and the level at which it is returned, after passing through the turbine. Hydroelectric power plants are characterized by electrical, hydraulic and mechanical coupling effects and their management can also involve market conditions and incentives [11–13]. Different components can be included in hydroelectric power plants, including rivers, intakes, regulation gates, water collection reservoirs, sand traps, turbines, floodgates, and dams. Figure 1 depicts some typical elements of a hydroelectric power plant. Figure 2 depicts a general scheme of a hydroelectric power plant.

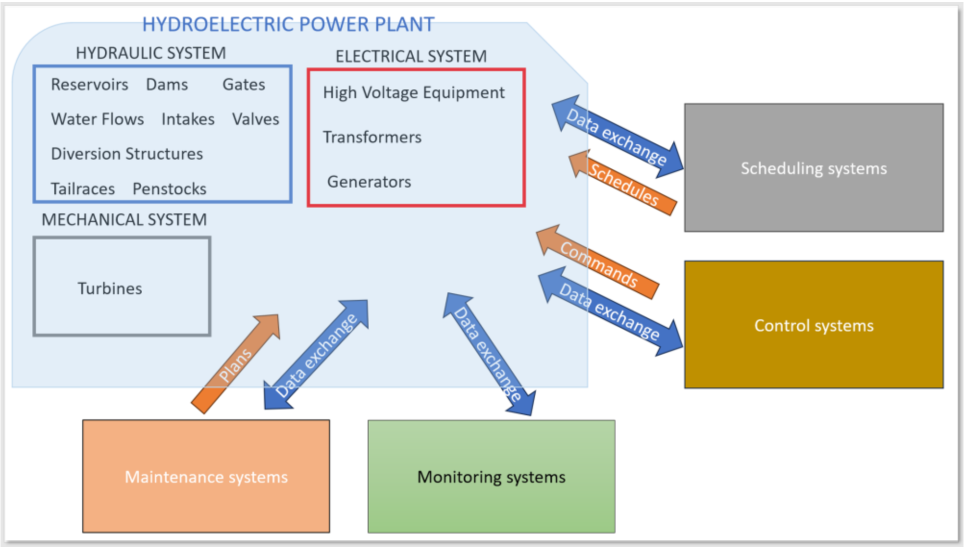

Figure 1. Overview of the general features of a hydroelectric power plant and of the different systems that can be installed on a hydropower plant.

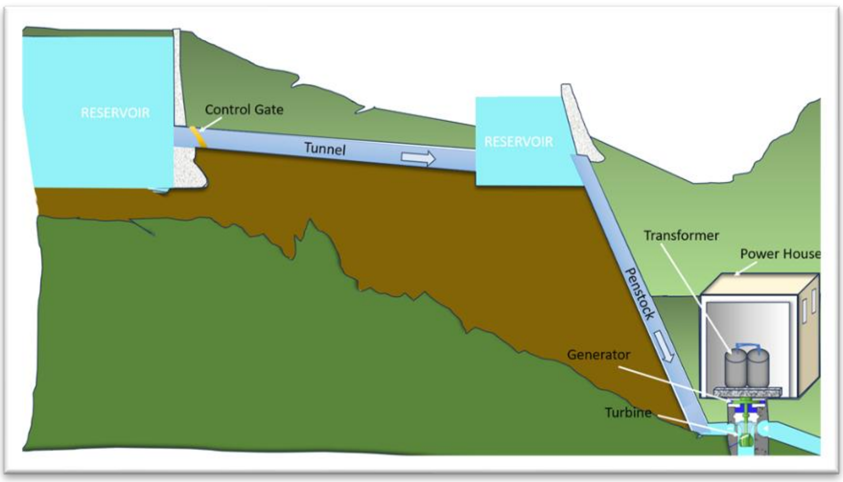

Figure 2. Example of a hydroelectric power plant.

In the last decades, equipment in hydropower plants has been enhanced in order to target high levels of availability, performance, and flexibility, and these results have been contributing to the energy transition. The efficiency of hydroelectric power plants has been improved thanks to the key role of Industry 4.0 and digitalization in monitoring, maintenance, control, and optimization applications [14–18]. Tailored cross-fertilization procedures can be applied in order to exploit the available knowledge on these topics in other fields, thus customizing them for the hydropower sector. Monitoring, maintenance, control and optimization systems are included in Figure 1, together with some typical information exchanged with the hydroelectric power plant.

The design, manufacture and installation of hydropower plants require a large initial investment. Moreover, in many cases, the revenue that can be obtained depends on the weather; periods of water scarcity, resulting in low inflows from rivers, could limit the production of this type of plant. In this sense, and similar to other types of renewable energy production, effective production is not always guaranteed for hydropower and, as a consequence, management of the plants is not a trivial task [19]. Energy efficiency is a crucial need in the management of hydropower plants. Energy efficiency can be associated with the single components of the plants and/or subparts of the plants; tailored key performance indicators (KPIs) must be defined and exploited for efficiency certification. In order to optimize the plants' management with regard to different aspects, tailored monitoring, maintenance, control, and optimization procedures must be applied.

Different review papers are present in the current literature of hydroelectric power plants. Some of the proposed topics are:

- Assessment of innovative technological aspects for hydropower plants, focusing on research and development (R&D) [9];
- Climate change mitigation and adaptation for the hydropower sector [20,21];
- Energy revolution for the hydropower sector [22];
- Analysis of the greenhouse gas (GHG) emissions in the hydropower sector [23];
- Operation strategies for hydropower plants [24–29];
- Methods for the solution of scheduling problems in hydroelectric power plants [30–35];
- Modelization and control in hydroelectric power plants [26,27,36–38];
- Hydropower case study collection [39].

Table 1 reports the topic and the main findings of the previously mentioned review papers.

Table 1. Main features of some review papers for the hydropower sector.

Topic	Main Findings	Ref.
Analysis of emerging technologies in the hydropower sector.	Review of R&D aspects in the hydroelectric power sector, including digitalization and operation.	[9]
Climate change mitigation and adaptation.	Significant role of hydropower technology in the mitigation of climate change and its crucial role in the adaptation of the availability of water resources to climate change.	[20]
Climate change mitigation and adaptation.	Assessment of the relationship between climate change and the hydropower sector. Identification of methods for improvement on the analysis of the net pros of hydropower technology subject to climate change.	[21]
Energy revolution.	Revealing the as-yet untapped potential of the hydropower sector in most areas of Europe and of its contribution to future energy needs.	[22]

Table 1. *Cont.*

Topic	Main Findings	Ref.
GHG emissions.	Discussion on GHG emissions from hydroelectric reservoirs, mitigation techniques, methodological know-how, and relationship between the parameters affecting GHG emissions. Review of crucial approaches and methods for the prediction of GHG emissions associated with reservoirs, investigating also life cycle assessment, uncertainty sources, and knowledge gaps.	[23]
Operation strategies.	Review of the optimization of operation in hydropower plants with a focus on minimizing the costs, minimizing the environmental impact, and maximizing energy generation.	[24]
Operation strategies.	Evaluation of revenue maximization focused on head impact and price values. Comparison between mean yearly energy generation and mean yearly revenue. Identification of benefits provided exploiting various operation methodologies.	[25]
Operation strategies, modelization and control.	Investigation of applications, control, operation, modeling and environmental impacts of hydroelectric power with a focus on power systems.	[26]
Operation strategies, modelization and control.	Focus on the priorities of the European Union (EU) with regard to applications, case studies, challenges, limitations, benefits, technology readiness level (TRL), and transversal pros associated with predictive operation and maintenance (O&M) and energy generation	[27]
Operation strategies.	Review of impact and role of distributed flexible AC transmission system (D-FACTS) devices in the function of microgrids.	[28]
Operation strategies.	Review of retrofit and upgrade of hydro power plants through the analysis of research papers, reports, guidelines and standards.	[29]
Scheduling problem.	Survey on optimal scheduling generation methodologies with a focus on meta-heuristic optimization methods.	[30]
Scheduling problem.	Review of machine learning (ML) for short-term hydropower scheduling, considering the cyber–physical systems (CPSs) paradigm.	[31]
Scheduling problem.	Review of mathematical programming methods for the solution of the short-term scheduling problem on single hydropower units. Classification of different techniques for the modelling of constraints and objectives.	[32]
Scheduling problem.	Review of the hydropower scheduling problem with focus on ML and artificial intelligence (AI) applications for optimization, prediction, and scheduling.	[33]
Scheduling problem.	Review of ML techniques for hydropower operation optimization, with a focus on optimal dispatch of hydropower plants in the context of energy production enhancement.	[34]
Scheduling problem.	Review of hydropower optimization R&D activities using a metaheuristic approach, also considering scheduling problems.	[35]
Modelization and control.	Review of modelling and control systems development of the hydro turbine.	[36]
Modelization and control.	Review of models, stability analysis and control methods for hydro turbine governing systems.	[37]
Modelization and control.	Review of data-driven methods for modeling plant operations.	[38]
Hydropower case study collection.	Discussion of significant case studies on hydropower installations of different companies, highlighting decarbonization and ecosystem protection aspects.	[39]

The present paper aims to supply a comprehensive review of the existing literature on the basic concepts and elements needed for the design of monitoring, maintenance, control and optimization strategies with a focus on energy production. Some basic concepts and elements, if in-depth approached, may provide the ingredients for the construction and implementation of these strategies. Based on the authors' knowledge and based on the literature analysis of review papers reported in Table 1, a thorough overview on the proposed topics is not present on the literature. Figure 3 reports a word cloud containing the most important words of the paper.

Figure 3. Word cloud containing the most important words of the review paper.

The organization of the paper is as follows: Section 1.1 details the methodology used for the conduction of the literature analysis. Section 2 focuses on digitalization and Industry 4.0 for the hydropower sector. Section 3 analyzes data and KPIs while modelization and forecast are detailed in Section 4. Section 5 reports some discussion while conclusions and future research directions are reported in Section 6.

1.1. Methodology for the Conduction of the Literature Analysis

For the identification of the documents to be analyzed in the proposed review, different databases have been explored, i.e., IEEE Xplore, Scopus, Web of Science, Google Scholar, Springer Link, and MDPI. In addition, Google search has been exploited.

Different search strings were used to identify significant documents. An example of one of these search strings is "hydropower" AND "word". "word" was replaced based on the effective topic to be investigated, e.g., "Industry 4.0". Starting from the available documents, a selection based on the impact and on the relevance to the considered topics was performed. A total of 159 references was considered.

Figure 4 reports the number of reviewed and investigated documents associated with previous review works in the hydropower sector (see Table 1), based on the year of publication. The total number of documents is 21. Among the 159 references, 115 documents on hydropower plants were exploited for the technical core of the paper (Sections 2–4). Figure 5 reports the number of reviewed and investigated documents on hydropower plants that were exploited for the technical core of the paper (Sections 2–4), based on the year of publication. Figure 6 reports the number of reviewed and investigated documents on hydropower plants that were exploited for the technical core of the paper (Sections 2–4), based on the topic. Some documents were considered for more than one topic, so these documents are considered more than once in Figure 6. In addition, all of the references considered for each topic are summarized in Table 2.

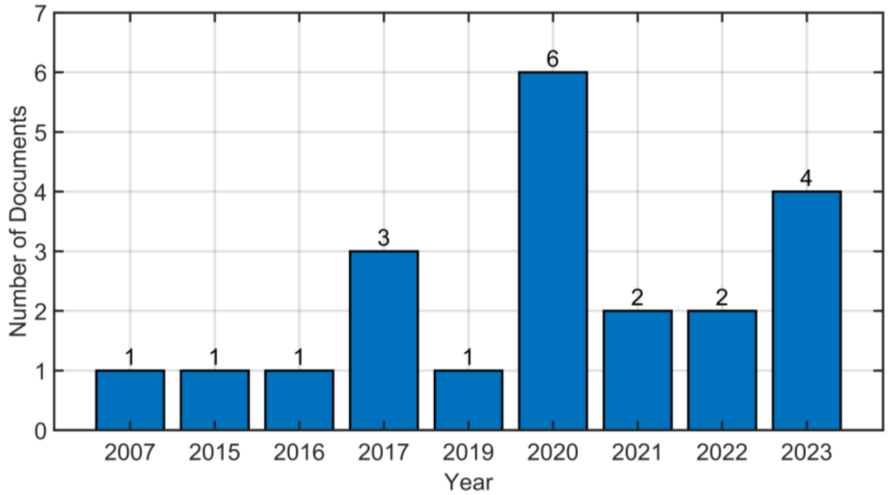

Figure 4. Bar graph showing the number of reviewed and investigated documents (previous review works) based on the year of publication.

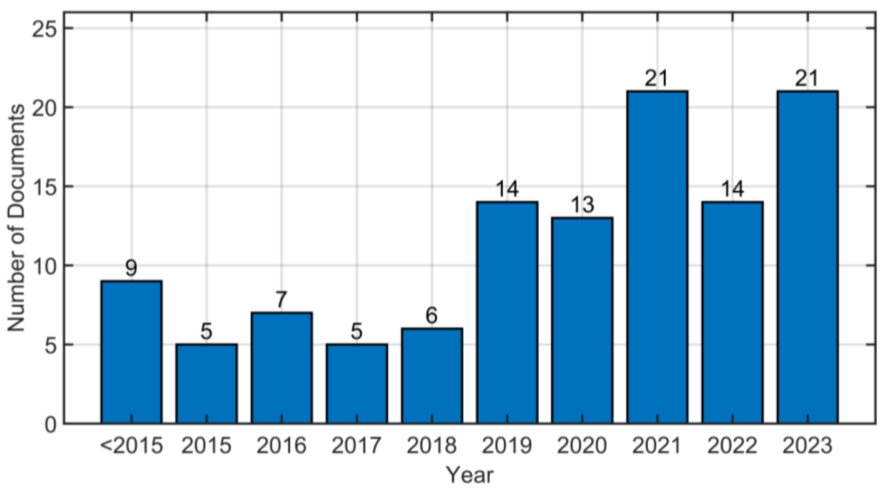

Figure 5. Bar graph showing the number of reviewed and investigated documents (hydropower plants) based on the year of publication.

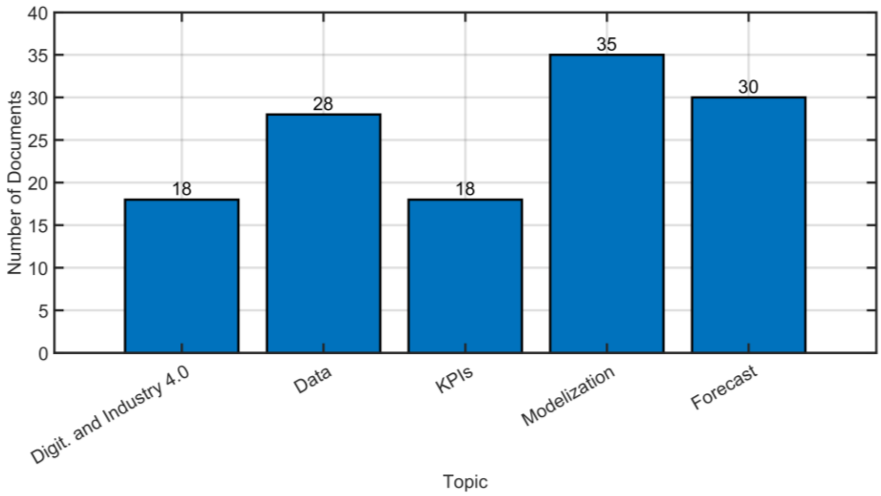

Figure 6. Bar graph showing the number of reviewed and investigated documents (hydropower plants) based on the topic.

Table 2. References associated with each topic.

Topic	Associated References
Digitalization and Industry 4.0	[9,15,16,27,39–55]
Data	[9,31,41,47,53,56–80]
KPIs	[6,7,75,81–101]
Modelization	[57,75,94–96,102–136]
Forecast	[75,94–96,117,127,130–132,137–157]

2. Role of Digitalization and Industry 4.0 in the Hydropower Sector

In this section, the role of digitalization and Industry 4.0 in the hydropower sector is analyzed. In particular, some research works about these themes are reported, with a focus on the main topic, on the scope and on the main findings.

The concept of Industry 4.0 was created as part of the fourth industrial revolution. Industry 4.0 represents the way to digitalization and it is focused on the encapsulation of the “digital industry” concept in different industrial areas. Applying cross-fertilization procedures to the sectors that exploit RESs, the Industry 4.0 paradigm can allow conventional plants to evolve into smart plants. In particular, Industry 4.0 technologies, e.g., the internet of things (IoT), simulation, cloud computing, augmented reality (AR), big data analytics, CPSs, cybersecurity, blockchain, AI and ML, can contribute to the improvement of the energy processes [15]. In the hydropower sector, digitalization can allow remote monitoring that is oriented to diagnostic actions to be executed for sustainable operation. This digital transformation can be coupled to modernization actions in order to support energy flexibility [16]. This potential could be effectively verified if the field implementation of digitalization takes place in the hydropower sector. In this context, a revolution is occurring because a large number of hydropower plants were designed a long time ago and their design working conditions consequently differ from current scenarios [9]. Practical projects can be implemented in order to exploit Industry 4.0 and digitalization to maintain and monitor hydropower plants. Some examples of applications are condition monitoring, fault detection, and operations’ optimization aimed at efficiency improvement [39,40]. These projects could lead to the implementation of Industry 4.0 platforms, which can then contribute to risk reduction and to a sustainable energy supply through the facilitation of data consultation and analysis [41]. In addition, digital technology platforms may represent a key tool in the proposal of pioneering business models [42].

Digitalization in the hydropower sector includes digital technologies, e.g., systems, infrastructures, networks, sensors, and connected devices [43–45]. The digital technologies aim to improve efficiency and/or to increase the competitiveness of the business models. Digitalization provides access to new sources of data and communications, while exploiting decision support systems (DSSs), automation, and control. Digitalization tools, aimed at the convergence between information technology (IT) and operation technology (OT), can be exploited for design, construction, investment decisions, O&M, rehabilitation, and modernization. Some fields of interest are safety, sustainability, and commerce [46]. In [47], five key themes are claimed as drivers of the digital transition of hydropower plants: production management and optimization, asset analytics, process improvement and automation, connected workers, and cybersecurity. Digitalization activates an improved reliability of forecasting associated with internal factors (e.g., reservoir level), external factors (e.g., water inflow and weather), and market conditions (e.g., price and demand). Predictions that are more reliable can play a key role in the automation, control, optimization, and maintenance fields [48]. Power production, spillage minimization and energy sources integration represent some of the benefits that could be obtained. In addition, the selection, acquisition, storage, analysis and visualization of data on O&M of assets represent drivers for the transition from periodic maintenance to predictive maintenance. Furthermore, IoT can contribute to process improvement and automation, enabling remote operations which can in turn improve safety and reduce costs [49]. In this context, the connected worker is a fundamental requirement. As a main drawback, data protection can be subjected to threats and cybersecurity approaches are needed [47]. In [50], digitalization is defined as a modernization technology for hydropower plants' upgrade. In particular, a hydropower gain can be obtained with regard to the provided power and to the optimization of storage. In [51], the digitalization process in hydropower plants is defined as a driver for asset performance management, equipment condition monitoring, outage management, supervisory control and data acquisition (SCADA) systems, IoT, AI, and ML. In addition, the concept of "Hydropower 4.0" is mentioned. All of these features allow one to obtain an enhanced flexibility of operations in hydropower stations and an enhancement of the digital tools in order to fully exploit the resources and to provide upgraded digital security levels [52]. Industry 4.0-enabling technologies, e.g., IoT, ML and big data analytics, can be successfully combined with tools provided by other areas, e.g., photogrammetry [53]. Connecting and contaminating different research areas, it can be observed that the digital and the green transitions are interconnected challenges. In this context, digitalization plays a key role in the path toward these transitions. Environmental and energy benefits can be obtained through this process in the hydropower sector, e.g., hydropeaking mitigation, and water management improvement [27]. Tailored methodologies can be used to evaluate the potential economic benefits provided by digitalization in hydropower generation and operation. Increase of efficiency, improvement of the reservoir operation and damage prevention can be taken into account together with the fact that the hydropower sector can be associated with other sectors in a water–energy–food ecosystem [54]. Optimal trade-offs between empowering renewable energy and the reduction of the costs in hydropower plants must be ensured;, hydropower trading and predictive maintenance on hydro plants are methodologies that can be accelerated by digital transformation [55].

Table 3 reports some research work about digitalization and Industry 4.0 in the hydropower sector, with a focus on the main topic, on the scope and on the main findings.

Table 3. Main features of the selected papers regarding digitalization and Industry 4.0 in the hydropower sector.

Main Topic	Scope	Main Findings	Ref.
Optimization opportunities in the digital revolution for renewable energy sector.	Evaluation of the impact of the Industry 4.0 paradigm within RESs energy generation sectors.	Industry 4.0 can enhance the existing plants and offer some opportunities to increase efficiency, e.g., sustainable circular economy aimed at waste management.	[15]
Digitalization and modernization of hydropower operating facilities.	Define the actions for the extension of the lifetime of a hydropower plant.	Evaluation of the residual life of generators and retrofit of components can help in the modernization of hydropower plants. Digitalization can allow remote monitoring oriented to diagnostic actions to be executed during sustainable operation.	[16]
Analysis of emerging technologies in the hydropower sector.	Collection of information on the challenges, innovation trends and emerging hydropower technologies.	There is an emerging need to digitalize hydropower design and operation. In this sense, a revolution in hydropower plants is expected.	[9]
Hydropower case study collection.	Discussion regarding a number of representative examples of hydropower installations from different companies, highlighting decarbonization and ecosystem protection aspects.	Digitalization can improve efficiency in hydropower plants through different ways, e.g., preventing failures and optimizing their operation.	[39]

Table 3. *Cont.*

Main Topic	Scope	Main Findings	Ref.
Report on an Industry 4.0 and digitalization research project applied to maintenance and fault detection of hydropower plants.	Provision of a set of methods for the implementation of Industry 4.0 and digitalization on hydropower plants	Proof of the potential of Industry 4.0 and digitalization methods for the optimization of maintenance through condition monitoring and fault detection.	[40]
Case report on a developed commercial digital transformation process for a hydropower plant.	Implementation of a modern platform based on Industry 4.0 tools in order to facilitate consultation and analysis of data for the management of applications of hydrological, operational, and market information, and commercial information systems and platforms.	The developed activities contribute to risk reduction and to a sustainable energy supply.	[41]
Report on the exploitation of digital technology platforms in an RES context.	Investigation of the impact of digital technology platforms on the implementation of innovative business models in the RES sector.	Digital technology platforms play a key role in the development of innovative business models.	[42]
Report on the digital revolution of hydropower in Latin American countries.	Investigation of the digitalization status in hydropower plants of Latin American countries.	Assessment of the level of digitalization in hydropower sector in Latin American countries through the detection of barriers and challenges of incorporating digitalization.	[46]
Report on the opportunity to transform the future of hydropower sector through digital generation.	Investigation of challenges of digitalization and its risks.	Assessment of the current challenges toward a digitally enabled and data-driven operation of hydropower plants. Assessment of the risks to be taken into account and to be mitigated within the digital transition.	[47]
Report on the technical route, maturity evaluation and content planning associated with the digital transformation of hydropower plants	Study and analysis of the technical route, the maturity evaluation and construction planning of hydropower digital transformation.	Assessment of the problems encountered within the digital transformation process. Definition of a digital maturity evaluation model for hydropower systems. Assessment of digital transformation planning, including top-level design, information and communication standards, and intelligent application.	[48]
Report on digital technologies for hydropower plant operation.	Study on the impact of digitalization, contemporary technologies and optimization on hydropower plants operations.	Enhanced flexibility, better safety, larger energy production and lower costs of maintenance can be targeted through the implementation of digital technologies.	[49]
Report on the energy potential of modernizing the European hydropower fleet.	Evaluation of different options for upgrading existing facilities, excluding measures that are expected to increase hydromorphological pressure on water bodies.	Indicative estimation of the additional annual generation and power that could be obtained compared with the current condition if modernization techniques are implemented.	[50]

Table 3. *Cont.*

Main Topic	Scope	Main Findings	Ref.
Report on state-of-the-art hydropower technologies.	Provision of an overview of the state of the art of hydropower technologies and techniques, in order to set a baseline reference to identify and prioritize future R&D actions.	Process analysis and assessment of recent technologies for hydropower plants aimed at enhancing flexibility, improving efficiency and resilience, and optimizing O&M. Discussion of current techniques and technologies by which to mitigate the environmental impact of hydropower projects.	[51]
Report on the most recent advances in hydropower technology.	Presentation of a set of research activities for hydropower plants.	Focus on technological projects. Focus on studies aimed at the improvement of the simulations of the hydrological cycle and climate change associated with hydropower operation.	[52]
Case study for the design of a small hydropower plant.	Exploitation of IoT, photogrammetry, ML and big data analytics as support tools toward the digital transition.	Evaluation and application of the proposed design method based on data analysis, cost estimation, and revenues.	[53]
Digitalization and real-time control of rivers for the mitigation of environmental impacts.	Discussion on the development of different technologies for the hydropower sector.	Focus on the priorities of the EU with regard to challenges, case studies, applications, limitations, benefits, and TRL.	[27]
Digitalization of the European water sector to nudge the digital and green transitions.	Investigation of advantages provided by digital solutions in the hydropower sector in terms of economic benefits for operation and generation.	Computation of the benefits for EU states and for UK (excluding environmental and social benefits).	[54]
Digital transformation in renewable energy.	Provision of significant use cases and experiences with regard to a Nordic power producer.	The digital transformation can act for the empowering the value of renewable energy and to the reduction of the costs. Examples of significant use cases are hydropower trading and predictive maintenance on hydro plants.	[55]

3. Role of Data and KPIs in the Hydropower Sector

In this section, the role of data and KPIs in the hydropower sector is analyzed. In particular, some research works about these themes are reported, with focuses on the main topic, on the scope and on the main findings.

Thanks to Industry 4.0 and digitalization, data selection, acquisition, and storage is acquiring high relevance in the hydropower sector. The overall hydropower fleet can benefit from data gathering and from data analysis [9]. The development of information technology in the hydropower sector has resulted in abundant data resources, thus introducing the hydropower big data era [56]. In this context, big data analytics can play a crucial role at all O&M and business levels through the harnessing of data for proactive decision-making [9]. Cross-fertilization procedures can be applied from industrial sectors in order to define efficient data analysis methodologies [57]. The collection and analysis of data associated with the overall equipment of hydropower plants represents a challenging objective. These steps can provide huge advantages thanks to the information contained in the data [31]. Consultation and analysis of data through specific platforms is a real added value for hydropower plants [41]. Decision-making could benefit from these platforms thanks to the integration of big data collection, storage, and analysis for monitoring purposes [58]. Data-driven O&M and business management may represent a nudge for energy efficiency improvement and O&M cost reduction [47]. In order to acquire a large amount of data, different technologies can be used, e.g., IoT, photogrammetry, and satellite [53,59,60]. Big data can be exploited for different types of analysis, e.g., the investigation of potentially untapped hydropower exploitation based on the exploration of the energy markets [61]. A strategic combination of cloud computing, big data and IoT can support an intelligent hydropower enterprise construction process. Efficient and scalable unified data management and analysis platforms can guarantee intelligent, safe, efficient and economic operation and can support command and decision-making [62]. In order to exploit all of the needed data for a defined scope, extensive databases may be needed. In these databases, data associated with the crucial general information and process variables in terms of plant operation are stored. For example, spatial distribution and georeferenced data may represent important sources of information for preliminary analysis [63,64], while rainfall data can support the decisions [65]. On the other hand, extensive datasets may represent a driver for hydropower system modelling purposes [66]. Data on full operating ranges may represent an added value because they may be able to cover a large number of working conditions [67]. In this context, data mining can play a significant role. It would introduce big data characteristics, connotation and origin, allowing in-depth analysis to be performed and providing a basis for the principles of large data associated with hydropower science [68]. Data mining techniques can be integrated in a SCADA system in order to speed up the data processing and allow an acceleration of the decision processes to the decision makers [69]. In fact, decision makers are not usually able to work with large databases or to extract information in a short time horizon. The extracted information can be used for different purposes, e.g., scheduling [70]. An issue to be tackled with big data is the analysis of the data quality. Data quality can be subjected to different issues, e.g., failures of sensors, actuators and data transmission systems, and defects of data storage systems. Data reliability is a fundamental requirement when extracting the needed information from the available data. In this context, data cleaning represents a strategy by which to detect abnormal conditions within data and to correct them [71]. In order to fully exploit data potential, data classification and classification management aspects are important steps. These phases can be based on databases and aim to provide support for data analysis [72]. In addition, in the exploration of massive data, data island and data heterogeneity issues can arise, and customized platforms are thus required [73].

The added value provided by data can also be appreciated in terms of the long-term analysis associated with market and business development for hydropower plants. For example, a recent contaminated combination between the data of different research areas, e.g., market and policy, showed an expected slowdown of the growth of the hydropower sector in the decade 2021–2030 [74].

Data analysis, selection, storage, and acquisition can also assume a crucial role for the feasibility study of an advanced process control (APC) project in order to perform an in-depth plant inspection with the help of information related to that plant's devices [75]. Another field of application of data analysis in hydropower plants can be the evaluation of silt erosion in order to intelligently plan maintenance scheduling activities. In this context, clustering and ML can be exploited [76]. Massive data information can also be used for the development of digital twins aimed at fault diagnosis in hydropower plants [77]. For the creation of advanced systems like an APC system and digital twins in a hydropower CPS, networks of connected subsystems are needed. For example, digital twins need to simulate the real world in cyber space. Real-time connections between physical and digital systems are required and cybersecurity represents a challenging objective [78]. Cyber-attacks and cyber threats must be managed through multilevel protection architectures, which must be characterized by encryption, access control, and secure virtual private networks [79]. Suitable standards, e.g., the IEC 62443 standard, can be exploited for the development of cyber security systems in hydropower plants with different generation units [80].

Table 4 reports some research works about data in the hydropower sector, with focuses on the main topic, on the scope and on the main findings.

Table 4. Main features of the selected papers focused on data for the hydropower sector.

Main Topic	Scope	Main Findings	Ref.
Analysis of emerging technologies in the hydropower sector.	Collection of information on the challenges, innovation trends and emerging hydropower technologies.	The overall hydropower fleet can benefit from data gathering and from data analysis. In this context, big data analytics can play a crucial role at all O&M and business levels through harnessing data for proactive decision-making.	[9]
Big data assessment for the hydropower sector.	Exploration for promoting the exploitation of big data and the associated resources.	The exploration, analysis and application of big data will retain an important role in hydropower facilities, thus providing new opportunities and challenges.	[56]
Review of ML techniques for hydropower scheduling.	In-depth assessment of the state-of-the-art of ML for scheduling in hydropower plants.	The collection and analysis of data associated with the overall equipment of hydropower plants represents a challenging objective. These steps can provide huge advantages thanks to the information contained in the data.	[31]
Report on a developed commercial digital transformation process for a hydropower plant.	Implementation of a modern Industry 4.0 platform in order to facilitate consultation and analysis of data for the management of applications of hydrological, operational, and market information, and commercial information systems and platforms.	The developed activities contribute to risks' reduction and to a sustainable energy supply.	[41]
Design of university hydropower intelligent decision service platform.	Implementation of a big data-driven platform for decision-making support based on data collection, storage, and analysis.	Design of a platform architecture with explicit references to technologies and tools.	[58]
Report on the opportunity to transform the future of hydropower sector through digital generation.	Investigation of challenges of digitalization and its risks.	Assessment of the current challenges toward a digitally enabled and data-driven operation of hydropower plants. Assessment of the risks to be taken into account and to be mitigated within the digital transition.	[47]
Case study for the design of a small hydropower plant.	Exploitation of IoT, photogrammetry, ML and big data Analytics as support tools toward the digital transition.	Evaluation and put into practice of the proposed design method based on data analysis, cost estimation, and revenues.	[53]
Assessment of the reliability of the hydropower sector in Malawi.	Design and validation of an energy-climate-water system associating remotely sensed data from multiple satellite missions and instruments and field observations.	A framework for modelling exploiting open-access data from satellites and based on ML algorithms and regression analysis can provide data and enhance vulnerabilities explanation.	[60]
Big data analysis for the hydropower sector.	Investigation of the hydropower development potential within ASEAN-8.	Existence of an untapped potential for hydropower development. The potential development must assume an international power exchange.	[61]
Research on intelligent construction of hydropower enterprises.	Provision of a strategic framework and scheme of intelligent construction of hydropower enterprises.	Cloud computing, big data and IoT can reinforce operation, command and decision-making in hydropower enterprises.	[62]

Table 4. *Cont.*

Main Topic	Scope	Main Findings	Ref.
Spatial distribution and key parameters of hydropower plants.	Investigation of spatial distribution and key parameters of bio- and river hydro powerplants in Germany.	Provision of a dataset that includes the spatial configuration, capacity, and year of commissioning of river- and bio hydropower plants in Germany.	[63]
Enhance the consideration of data for decision support tools.	Investigation of hydropower plants in Africa.	Georeferenced database on existing and proposed plants in Africa.	[64]
Quantitative precipitation estimates.	Investigation of quantitative precipitation estimates and the needed checks for ensure good data quality.	Provision of a dataset that contains precipitation statistics calculated by German Weather Service and their combination with rainfall statistics through rain gauge data.	[65]
Enhance the consideration of data for power system modelling purposes.	Creation of a dataset for European hydropower plants modelling.	Provision of a dataset that collects some information on the European hydro-power plants.	[66]
Digitalization in hydropower generation.	Development of a model-based Smart Power Plant Supervisor.	Digital tools can play a crucial role with regard to the optimization of O&M to enhance the supply of auxiliary services to the electric system.	[67]
Big data and data mining in the hydropower sector.	Investigation of the hydropower big data science and technology based on data mining.	Provision of a value analysis application prospect of hydropower science large data.	[68]
Enhance operation of hydropower plants through data mining.	Empowering of a SCADA system through the inclusion of data mining algorithms.	Implementation of a SCADA system with the integration of data mining techniques to support decision makers.	[69]
Enhance the scheduling operations in the hydropower sector through data mining.	Investigation of the application of data mining and clustering techniques for scheduling pattern identification.	Implementation of a rule-based procedure aimed at daily generation scheduling enhancement.	[70]
Research on data cleaning method for hydropower plants.	Investigation of data quality enhancement through data cleaning on dispatch and operation datasets.	Design and implementation of a data cleaning framework.	[71]
Big data management for hydropower enterprises.	Investigation of classification issues for big data.	Development of a data classification and classification management framework for hydropower enterprises big data.	[72]
Massive data value exploitation in hydropower stations.	Investigation of the construction of a platform for the development of a smart hydropower station.	Assessment of the origin, definition, and development of data middle platform for smart hydropower station. Test of the designed system on practical application scenarios.	[73]
Exploration of the data related to market for hydropower plants.	Data-driven investigation of past, present and future of hydropower sector, with outlook to 2030.	Based on today's policy settings, the growth of hydropower globally is set to slow in the decade 2021–2030.	[74]
Reservoir advanced process control (APC) for hydroelectric power production	Design and implementation of an APC system for water management in a hydroelectric power plant.	Definition of data-driven methods for in-depth plant study before the design of an APC system. The selection, acquisition, storage, and analysis of data cover a crucial role in the plant study, together with an in-depth analysis of the devices.	[75]
Application of ML for silt data analysis in hydropower plants.	Exploitation of ML for the reduction of the risk caused by the silt erosion.	Based on silt data analysis, maintenance planning of hydropower plants can be obtained.	[76]

Table 4. *Cont.*

Main Topic	Scope	Main Findings	Ref.
Digital twin for hydropower plants.	Construction and application of a data-driven model for different purposes.	The model is investigated with a hydropower fault diagnosis application.	[77]
Digital twins for energy systems and smart cities.	Review of literature and practices of digital twin in energy systems and smart cities.	Assessment of cybersecurity, efficiency, sustainability and reliability through digital twin.	[78]
Security in automated control systems of hydropower engineering facilities.	Assessment of the concept of CPS to manage computer security of automated process control systems at hydropower engineering facilities.	Security systems can be integrated in an efficient manner with automated process control systems of hydropower engineering facilities.	[79]
Cybersecurity in hydropower plants.	Assessment of cybersecurity in hydropower plants.	Exploitation of the standard IEC 62443-2-1 for the implementation of a cybersecurity management system on a hydropower plant with two generation units.	[80]

In the context of Industry 4.0 and digitalization, thanks to the added value provided by massive data, KPIs represent a fundamental tool in the hydropower sector. Tailored KPIs must be defined based on the studied context. KPIs can be associated with different objectives, e.g., business, optimization, control, and maintenance. Generally, KPIs can be exploited to evaluate whether a project really provides benefits in terms of efficiency and optimal performance. As mentioned above, a project can be referred to different areas. KPIs represent a metric by which to evaluate performance. Examples of general project KPIs in hydroelectric power plants are availability, revenue, return on investment, efficiency, energy output, capacity factor, and generation capacity. KPIs can support a wide variety of economic, ecological, cultural, and social objectives [81].

In order to enhance a system's availability, i.e., the percentage of current uptime considering the total service hours, tailored plant models can be obtained using the reliability block Diagram and of the stochastic block diagram. This approach can support decision makers in the optimization of maintenance management [82]. In addition, intelligent mitigation measures can be adopted in order to manage the trade-off between economic constraints, climatic variability, and increased demand. These measures can be associated with tailored indicators that explain the production reliability of hydropower plants [83]. Plant modelization can be used also to obtain tailored sustainability KPIs in order to assess the sustainability of hydropower plants [84]. Generally, KPIs can be formulated based on tailored process models in order to achieve a global evaluation of the performance of hydropower plants [85]. For example, transfer function modelling can be exploited and models can be obtained based on input/output data and the statistic features of the computed indicators can be analyzed in order to compare different production periods [86].

KPIs can also be exploited for companies' sustainability analyses based on key environmental, technical and social aspects [87]. For example, relationships between water supply, biodiversity and ecosystem service losses can be investigated [88]. Furthermore, electricity consumption of hydropower plants, economic growth and a power system's losses can be related in order to support decision-making regarding electric energy policies [89]. In addition, KPIs can be used as proof of the feasibility of hydropower projects thanks to their capability to take into account financial and non-financial aspects [90].

Tailored KPIs can also be exploited for the design of condition monitoring, early diagnostics and predictive maintenance systems aimed at supporting and enhancing the O&M of hydropower plants [91]. In-depth analysis is required in order to formulate peculiar indicators [92]. Poor maintenance can cause process failures that can represent threats to revenue, operation feasibility and people's health. For this reason, the performance of maintenance must be monitored and analyzed through specific indicators based on tailored regulations [93].

In order to formulate the mathematical optimization problems and to verify the performance of APC systems in hydropower plants, tailored KPIs can be formulated, monitored and analyzed [75,94]. An example of a KPI to be verified is the service factor, i.e., the time percentage associated with full service of the APC system [6,7]. The service factor can also represent a significant performance metric for the achievement of plant operators' feedback when they are required to use APC systems based on different methodologies and techniques, e.g., model predictive control (MPC) [95–99]. The formulation of mathematical optimization problems associated with control and optimization systems may depend on tailored KPIs, represented by the cost functions to be minimized/maximized. These cost functions can be formulated taking into account different objectives, e.g., the maximization of hydropower production, water supply reliability, spill prevention, and revenue income [100,101].

Table 5 reports some research works about KPIs in the hydropower sector, with focuses on the main topic, on the scope and on the main findings.

Table 5. Main features of the selected papers focused on KPIs for the hydropower sector.

Main Topic	Scope	Main Findings	Ref.
System availability improvement.	Maintenance management optimization aimed at system availability improvement.	Design of a method based on a stochastic block diagram adopting a hydropower plant as case study.	[82]
Reliability of performance in hydropower plants.	Selection of features able to provide a reliability analysis associated with the performance of hydropower plants.	Adoption of multi-criteria decision-making methods for the identification of the indicators.	[83]
Assessment of the sustainability in the hydropower sector	Development of a sustainability framework.	Design of a sustainability index based on plant mathematical modelization.	[84]
Evaluation of the performance of Brazilian hydropower plants.	Investigation of the performance of the largest Brazilian hydropower plants based on O&M indicators and quality of service.	Design of an approach for the construction of composite indicators based on modelization.	[85]
Hydropower generation system performance evaluation.	Development of a method for the evaluation of the hydropower generation facilities for performance improvement.	Exploitation of transfer function modelling to obtain performance indicators.	[86]
Environmental reporting associated with some Italian hydropower companies.	Analysis on the evaluation of sustainability data by the companies.	Reporting on the key environmental, technical, and social aspects (significance, indicators, and improvement objectives).	[87]
Integrated energy and economic evaluation for hydropower plants.	Assessment of the impact of the donor-side and the user-side on ecosystem services.	Design of an integrated evaluation framework able to evaluate impacts on water supply, biodiversity and ecosystem service losses.	[88]
Losses (power), consumption, performance (economic) of hydroelectricity in Indonesia.	Investigation of causality relationship between electricity consumption of hydropower plants, losses of the power system and economic growth.	Proposal of a statistical method for the evaluation of the considered causality relationships and exploitation of the results for the decision of electric energy policy.	[89]
Small-scale hydropower project attractiveness analysis.	Design of tools for the assessment of small-scale hydropower plants performance in the pre-implementation phase.	Exploitation of balanced scorecard as evaluation tool in the feasibility studies on plant implementation.	[90]

Table 5. *Cont.*

Main Topic	Scope	Main Findings	Ref.
Condition monitoring and predictive maintenance methodologies for hydropower equipment.	Development of a system able to support O&M through condition monitoring, early diagnostics, and predictive maintenance.	Formulation of a KPI for operating hydropower plants in order to identify faults and to support O&M tasks.	[91]
Performance analysis of hydropower units.	Condition monitoring of hydropower generation units.	Formulation a correlation transmissibility indicator to analyze degradation performance.	[92]
Maintenance monitoring and analysis in hydropower plants.	Determination of maintenance performance indicators for asset management.	Formulation of tailored indicators associated with different evaluation levels and test of the proposed methodology on a Brazilian hydroelectric power plant.	[93]
Reservoir advanced process control (APC) for hydroelectric power production.	Design and implementation of an APC system for water management in a hydroelectric power plant.	Use of tailored KPIs for the mathematical formulation of the control problem. The satisfactory performance of the developed APC system was proven by the high service factor achieved.	[75]
APC for water resources systems.	Presentation and analysis of two case studies where APC systems were successfully applied.	Use of tailored KPIs for the mathematical formulation of the control problem. Use of the service factor as support KPI for APC system's performance evaluation.	[94]
Production plan satisfaction for hydropower production.	Design and implementation of an MPC strategy for the satisfaction of the production plan in a hydroelectric power plant.	Use of tailored KPIs for the mathematical formulation of the control problem. The satisfactory performance of the developed MPC strategy was proven by the high service factor achieved.	[95]
Reservoir water management for hydropower production.	Design and implementation of an MPC strategy for reservoir water management.	Use of tailored KPIs for the mathematical formulation of the control problem. The satisfactory performance of the developed MPC strategy was proven by the high service factor achieved.	[96]
Performance appraisal of agricultural–water systems.	Assessment of the performance of agricultural–water systems based on comparative performance indicators.	Formulation of a high-level optimization problem to maximize monthly irrigation and hydropower releases.	[100]
Performance evaluation for multipurpose multi-reservoir system operation.	Development of a performance evaluation model.	Formulation of a performance index that takes into account spill prevention, reliability of water supply, revenue income, and energy production.	[101]

4. Role of Modelization and Forecast in the Hydropower Sector

In this section, the role of modelization and forecast in the hydropower sector is analyzed. In particular, some research works about these themes are reported, with focuses on the main topic, on the scope and on the main findings.

Modelization can play a crucial role in the hydropower sector. Modelization practices represent an important aspect in both design and in the O&M phases of the hydropower plants. Data support the modelization phase, especially in the O&M phase. Reliable data allows one to obtain robust models, which are crucial for different applications [57]. Design could also benefit from reliable data. For example, data from already commissioned hydropower plants could be exploited to improve the design of future plants.

Another area that can significantly affect the design and O&M of hydropower plants is associated with the capability to forecast. Forecasts can be exploited for different purposes and in different contexts.

4.1. Modelization for Design

Effective design procedures require reliability assessment. In [102], a mixed integer non-linear program (MINLP) is proposed as an optimization problem by which to guarantee the maximization of the hydropower production while considering the reliability level. The model-based optimal design is applied to a real plant. Reliability assessment can represent a crucial aspect in large-scale hydropower plants, e.g., hydropower plants characterized by multiple interconnected reservoirs. In order to guarantee an optimal design for the energy generation, cellular–automata-based approaches can be exploited for the modelization of reliability, taking into account the interdependency between O&M and design [103]. Reliability could also be referred to the energy yield in multi-reservoir systems. For this purpose, a reliability-based simulation model is needed in order to formulate objective functions, taking into account reservoir releases and/or reservoir storages [104].

Accurate modelization procedures could also be exploited for design changes on already installed plants. For example, multi-objective optimization models can be used to analyze economic–ecological tradeoffs in order to support decision making regarding dam removal [105]. Additionally, ex-post assessments can be performed in order to discover trade-offs, dependencies and robustness in hydropower plants, e.g., in dam design and operation. For this purpose, design problems associated with operation and dam sizing must be formulated and solved [106]. In addition, sensitivity analysis could support plants' modifications; an example is represented by a dam that supplies drinking water, where, thanks to sensitivity analysis, some margins for the installation of a hydropower unit can be detected [107]. Furthermore, different tools can be used for the computation of the potential associated with a design change. For example, geographic information system (GIS) tools can be exploited for the evaluation of the benefits that can be achieved through the transformation of conventional hydropower schemes into pumped hydropower schemes [108].

O&M and design challenges may result in a highly non-convex optimization problem, so tailored methods for the achievement of a feasible solution must be applied, e.g., honey bee mating optimization (HBMO) [109]. In this context, multi-objective evolutionary algorithms can reduce the computational cost [110]. Specific software and routines are needed to solve the obtained optimization problems. An example of such software is Water Evaluation and Planning (WEAP), which can be exploited as simulation software for water resources planning. The invasive weed optimization (IWO) algorithm represents another specific tool [111].

Effective design procedures require reliable simulation frameworks. In this way, some crucial features of the hydropower plants to be constructed can be simulated, e.g., the capacity of installation (design discharge) [112]. In order to provide holistic simulation frameworks, environmental impact evaluation must be incorporated into optimization and decision making, wherein different scenarios are needed for the optimization of the design of the facilities [113]. Various factors must be included in the simulation frameworks, e.g., market price. These factors could support the assessment of the economic feasibility of a hydropower project. In this context, design parameters associated with plant sizing cover a crucial role and the computation of their optimal values can be performed through effective simulation frameworks based on reliable models and efficient optimizers [114]. Hydropower projects can affect the ecosystem and a proper planning of hydropower projects must include an efficient cost–benefit analysis framework. In this way, decision-making can also take into account ecosystem services [115]. For the mitigation of the huge budget required for projects of the hydropower field, the design phase must optimize both the design and the future operation. An example is represented by reservoir plants equipped with pump stations, because these systems are energy producers characterized by cost effectiveness; an optimization model can be formulated in order to maximize the net benefit [116].

The potential of AI can be exploited for planning and design in dam engineering [117]. In addition, the visualization of a construction process could represent an added value for the design of hydropower plants. This involves a modelization approach that is able to provide real-time and interactive 3D scenes through virtual reality (VR) [118]. In this context, realistic terrain simulation could also aid in the design through dynamic visual simulation based on VR [119].

Table 6 reports some research works about modelization for design in the hydropower sector, with focuses on the main topic, on the scope and on the main findings.

Table 6. Main features of the selected papers focused on modelization (design) for the hydropower sector.

Main Topic	Scope	Main Findings	Ref.
Optimization of the design and of the operation of hydropower plants.	Formulate an optimization problem aimed at the maximization of the produced energy and at controlling the reliability level.	The developed system is exploited for the capacity optimization of the plants to be designed.	[102]
Hydropower plants design.	Incorporate reliability models in the design procedures.	Cellular automata are exploited for reliability model formulation.	[103]
Analysis of the integrated operation of multi-reservoir hydropower systems.	Reliability assessment as a support for the design.	The developed model allows one to exploit tailored objective functions able to take into account both reservoir release and storage.	[104]
Proof-of-concept demonstration on the effects of dam's removal on a plant.	Exploit modelization for decision-making support.	The developed optimization problem allows one to take into account both economic and ecological objectives.	[105]
Ex-post assessment of the design of hydropower plants.	Solve design problems that include operation and sizing of dams.	The proposed method allows one to reduce capital costs.	[106]
Sensitivity analysis.	Detect potential margins for the installation of a hydropower plant on an already existing dam.	The proposed method revealed that a small-scale hydropower plant can be installed on the already existing plant.	[107]
Calculation of the potential that can be achieved from hydropower plants' design change.	Development of a GIS-based model.	The developed model was tested on some case studies and revealed its applicability.	[108]
Design-operation of multi-hydropower reservoirs.	Illustrate and test the option to use the HBMO algorithm in a highly non-convex optimization problem.	The HBMO algorithm outperforms other existing algorithms.	[109]
Design of cascade hydropower reservoir systems.	Formulation of a multi-objective optimization model for the determination of the design parameters.	Multi-objective differential evolution can be exploited to solve hydropower design optimization problems.	[110]
Optimal design and operation of hydropower plants.	Formulate an optimization problem aimed at generated energy maximization and at flood damage minimization.	WEAP software and IWO algorithm can be exploited for the optimal design and operation of a hydropower plant.	[111]
Simulation of hydropower plants aimed at design optimization.	Formulation of a simulation model.	The developed model allows for the simulation of hydropower plants' main features, e.g., capacity of installation.	[112]
Sustainable planning of multipurpose hydropower reservoirs.	Provide a simulation–optimization framework for design optimization based on different scenarios.	Environmental economics can significantly affect the project results.	[113]
Optimal design of hydropower projects.	Provide a simulation-optimization model for multi-reservoir systems design.	The proposed framework exploits WEAP software and adds a hydropower computation module; the optimization problem is solved through PSO and takes into account different economic factors.	[114]

Table 6. *Cont.*

Main Topic	Scope	Main Findings	Ref.
Optimal development of hydropower projects.	Inclusion of ecosystem services within the optimal development of hydropower projects.	The formulated cost–benefit analysis framework allows incorporation of the services of the ecosystem into decision-making and into models for the optimization of the projects.	[115]
Plan a design phase equipped with simultaneous design-operation optimization for pumping systems in reservoir power plants.	Maximization of the net benefit of installations in reservoir systems.	Pumped-storage systems have better outcomes than individual hydropower systems, taking into account benefits and efficiency.	[116]
AI and digital technologies in dam engineering.	Review of AI and digital technologies application in dam engineering.	Assessment of the role of AI and digital technologies in dam engineering with regard to design and planning.	[117]
Exploitation of VR for the construction process of dams in hydropower plants.	Development of a system able to achieve a realistic, 3D real-time and interactive virtual scene.	The developed system can represent a support analytical tool to optimize the construction management of hydropower plants.	[118]
Dynamic visual simulation of hydropower construction project.	Development of a system that uses VR.	The developed system could provide a design and management environment for hydropower projects.	[119]

4.2. Modelization for O&M

O&M activities can be supported by modelization and simulation tools. For example, deep learning, support vector regression and artificial neural network (ANN) techniques can be exploited for reservoir operation modeling and simulation in order to support decision making [120]. In addition, data-driven AI can also be exploited for reservoir operation policy computation; in this context, pattern recognition and metaheuristic optimization are useful concepts [121]. Dam operation can also benefit from deep learning in order to build models able to provide key insights through the simulation of different scenarios [122]. In the field of dam engineering, AI and digital technologies could provide predictive modeling [117]. Dam–reservoir system modelization can be exploited for the computation of a balance between environmental management and hydropower generation [123]. Cascade hydropower systems can be considered as complex systems and cellular automata methodologies can be exploited for modelization and optimization in order to maximize energy production [124]. In order to solve reservoir operation optimization problems, animal-inspired evolutionary algorithms can be applied, e.g., particle swarm optimization (PSO), ant colony optimization (ACO), artificial bee colony (ABC), shuffled frog leaping algorithm (SFLA), firefly algorithm (FA), HBMO, bat algorithm (BA), and cuckoo search (CS) [125]. In addition, surrogate modeling could contribute to release decisions at the desired timescale [126].

Different variables and indexes can be modelized for O&M activities. A significant index that can be modelized is the reliability level of hydro-energy production. The inclusion of this index in the optimization problem associated with optimal design and operation strategies can represent an overall enhancement of the considered plant [102]. Among the variables that can be taken into account are design and operation variables. These variables can be affected by different factors and they can retain different impacts on the overall system performance [111]. A crucial process operation variable that can be taken into account is the dammed water level. In order to modelize it, different approaches can be exploited, e.g., neural networks, support vector regression, and Gaussian processes [127].

Techno-ecological synergy frameworks may be needed in order to evaluate the sustainability of hydropower plant operation at local and regional levels. Life-cycle assessment can be exploited for this purpose [128]. In addition, externality theory models can be used for the evaluation of the impact of a hydropower project [129].

O&M of hydropower plants could benefit from modeling and simulation combined with forecasting. Hydropower allocation can be guided by forecast-informed reservoir operations. Hydroclimatic predictions can be converted into actionable information for the enhancement of the management of hydropower plants [130]. Another context of application of the combination between modeling, simulation and forecasting is short-term hydropower operations planning. In this context, a short-term model is required in order to dispatch the available water to the turbines on a daily basis. The model can be characterized by a stochastic nature in order to include uncertainties, e.g., inflow uncertainty [131]. The scheduling task can also be performed through multi-objective models that are particularly recommended for large-scale systems [132].

An additional field of application of the combination between modeling, simulation, and forecasting is reservoir level control. Different APC techniques can be applied to solve this problem, e.g., MPC [133–136]. Among the features needed to apply MPC, model and forecasts reliability cover a crucial role. A reliable model of the plant allows the provision of a tool with which to simulate and predict the effect of the manipulated and unmanipulated inputs on the outputs; on the other hand, forecast reliability can be referred to the availability of predictions associated with the unmanipulated inputs in order to include them in the control law computation [75]. Unmanipulated inputs can be represented by the water discharged toward the turbines, which is connected to the energy that has to be generated. The relationship between the hydroelectric energy and the water that has to be provided to the turbines can be obtained by exploiting linear regression models [94]. The reliability of these models can impact the reliability of the models of the upstream devices, e.g., reservoirs. The modelization of reservoirs' levels can be performed using different types of model, e.g., first-principles models [95]. In order to mitigate model uncertainties, suitable model mismatch compensation strategies must be used [96]. Table 7 reports some research works about modelization for O&M in the hydropower sector, with focuses on the main topic, on the scope and on the main findings.

Table 7. Main features of the selected papers focused on modelization (O&M) for the hydropower sector.

Main Topic	Scope	Main Findings	Ref.
Modeling and simulation of reservoir operation.	Development of models for decision-making support.	ANN, support vector regression and deep learning techniques are exploited to build models for simulation of reservoir operation.	[120]
Hydropower reservoir operation policy computation.	Exploitation of AI for modelization.	The developed models are included in a metaheuristic optimizer and satisfactory operation results are provided.	[121]
Modeling and simulation of dam operation.	Development of deep learning models for decision-making support.	Assessment of the explainability of the developed deep learning model on dam operation.	[122]
Exploration of digital technologies and AI for dams.	Review of digital technologies and AI application in dam engineering.	Assessment of the role of AI and digital technologies with regard to predictive modeling.	[117]
Dam–reservoir system management.	Mathematical modelling and computation of a balance between hydropower generation and environmental management.	The balanced operation policy is obtained through the solution of a stochastic control problem.	[123]

Table 7. *Cont.*

Main Topic	Scope	Main Findings	Ref.
Energy production maximization in complex plants.	Development of a modelization and optimization method for energy production maximization.	Cellular automata can be used for modelization, simulation and optimization of complex hydropower plants.	[124]
Modelization of the operation of reservoirs.	Review of applications of animal-inspired evolutionary algorithms in reservoir operation modelling.	PSO, ACO, ABC, SFLA, HBMO, CS, FA and BA algorithms can be exploited for reservoir operation modelling.	[125]
Hydropower optimization.	Exploitation of ANNs surrogate models and water quality models.	The proposed approach provides high-fidelity modelization and allows one to support decisions at the desired timescale.	[126]
Optimal operation and design of hydropower plants.	Formulate an optimization problem aimed at produced energy maximization and at controlling the reliability level.	The developed system is exploited for the capacity optimization of the plants to be designed.	[102]
Optimal design and operation of hydropower plants.	Formulate an optimization problem aimed at generated energy maximization and at flood damage minimization.	The optimization of design variables can affect the system performance in a different manner with respect to the optimization of operation variables.	[111]
Dammed water level analysis and prediction in a hydropower reservoir.	Short- and long-term analyses.	Machine learning could represent a significant driver.	[127]
GHG mitigation in hydropower plants.	Investigation of techno-ecological synergies of hydropower plants.	The developed techno-ecological framework, based on life cycle assessment, can be exploited for the evaluation of the supply and of the demand of hydropower plants in order to evaluate their sustainability level.	[128]
Evaluation of hydropower projects.	Investigation of externality evaluation models for hydropower projects.	Externality theory can be exploited for hydropower projects evaluation.	[129]
Guide hydropower allocation.	Provision of forecast-informed reservoir operations.	The developed model allows one to convert hydroclimatic predictions into actionable information for the enhancement of plants' management.	[130]
Short-term hydropower operations planning.	Exploitation of modeling, simulation and forecasting for the optimal dispatch of the water to the turbines.	Stochastic short-term models can be exploited due to their ability to deal with uncertainty.	[131]
Short-term hydropower scheduling.	Development of a multi-objective model for peak shaving.	The proposed approach is applicable, tractable and robust enough to obtain near optimal results efficiently.	[132]
Reservoir advanced process control (APC) for hydroelectric power production.	Design and implementation of an APC system for water management in a hydroelectric power plant.	The achievement of a robust plant model and of reliable forecasts on the production plan represent fundamental requirements for the application of MPC technique.	[75]
APC for water resources systems.	Presentation and analysis of two case studies where APC systems were successfully applied.	The relationship between the hydroelectric energy and the water that has to be provided to the turbines can be obtained by exploiting linear regression models.	[94]

Table 7. *Cont.*

Main Topic	Scope	Main Findings	Ref.
Production plan satisfaction for hydropower production.	Design and implementation of an MPC strategy for the satisfaction of a production plan.	Different types of models may be formulated and integrated in an MPC strategy for production plan satisfaction.	[95]
Reservoir water management for hydropower production.	Design and implementation of an MPC strategy for reservoir water management.	The design of ad hoc model mismatch compensation strategies can mitigate the model uncertainties.	[96]

4.3. Forecast

Dam engineering could benefit from predictive modeling for the forecasts needed in order to make the due decisions at the right times [117]. Crucial process variables need to be predicted in order to support the management of areas with hydrology stress; in this context, machine learning could represent a significant driver [127]. In addition, hydroclimatic predictions can support the decision-making process in order to optimally allocate hydropower energy [130]. The hydropower generation represents a crucial process variable and its prediction is a very challenging task. Tailored algorithms can be used for this purpose, e.g., the developed wildebeest herd optimization (DWHO) algorithm; the convergence speed and the required time to provide a solution represent significant factors to be considered in the selection of an algorithm [137]. Combinations of different techniques can be exploited for hydropower generation prediction, e.g., grey wolf optimization (GWO), and the adaptive neuro-fuzzy inference system (ANFIS) [138]. Additionally, ANNs can be exploited for the prediction of power production. Good performance can be obtained if large amounts of significant data are available [139]. The water inflow into reservoirs represents another crucial process variable to be predicted. For this purpose, historical data can be exploited together with dynamic non-linear auto-regressive (NAR) and non-linear auto-regressive with eXogenous input (NARX) models [140]. Additionally, ensemble forecasts can be used for the verification of the inflow into hydropower reservoirs, taking into account different meteorological models. These forecasts can provide enhancement in different aspects, e.g., benefits and flood control [141].

With regard to streamflow, the quality and the value of the forecast are crucial aspects to be taken into account. The quality refers to the accuracy of predictions while the value refers to the impact of the decisions' predictions on the results of the operations [142]. Machine learning could be very useful in the modelization of complex, non-stationary, and non-linear time series aimed at streamflow forecasting. In particular, data preprocessing can be combined with modelization and an optimizer can be selected for the achievement of a feasible parameter configuration [143]. Middle and long-term streamflow forecasts can also be exploited for hydropower maximization; in order to deal with the stochastic nature of streamflow, the combination of AI, adaptation and parameter optimization could be needed [144]. Another paradigm that can be used for streamflow forecasts is that of the ensemble forecasts used in order to deal with uncertainties [145]. Biases on the ensemble streamflow predictions could impact the electricity production in the hydropower reservoir management. Methods for streamflow prediction with a poor robustness to uncertainties could cause a high risk for the level of reservoirs in the pursuit of maximized short-time profit; the introduction of suitable constraints can mitigate this aspect [146]. With regard to short-term streamflow prediction, the combination of stochastic weather generation and ensemble weather forecasts can help in the extension of the forecasting horizon [147].

The optimal dispatch of the available water to the turbines in a hydroelectric power plant can benefit from reliable predictions. In particular, stochastic short-term models can be exploited in order to provide reliable one day ahead forecasts [131]. In addition, multi-objective short term scheduling models can be exploited for this purpose. The main challenges are represented by large scale systems, numerous power-receiving grids, complex constraints, and cascaded systems [132]. In this context, the impact of hydrological forecasts on the revenue and on the management of reservoirs can be obtained through sensitivity analysis. In addition, the forecast quality affects the stock evolution, the spillage, the production rates, and the production hours [148]. Different performances can be provided by probabilistic and deterministic forecasts in the optimization (short-term) of the reservoirs. Ensemble forecasts (probabilistic) and multi-stage optimization (stochastic) techniques could provide a higher level of flood protection while guaranteeing an acceptable energy production [149]. Another problem that can benefit from reliable forecasts is the monthly runoff prediction in hydropower plants. For this purpose, for the enhancement of the accuracy of the predictions, hybrid prediction models can be formulated through the combination of empirical mode decomposition (EMD), time varying filtering (TVF), extreme learning machines (ELM), and salp swarm algorithm (SSA) [150]. ELM algorithms can be integrated with the Monte Carlo method in order to provide reliable predictions of hydropower production and energy saving [151].

The outputs of the optimal dispatch problems are usually represented by the hydroelectric energy production plan. This plan is connected with the water that has to be sent to the turbines by the upstream devices. A reliable model between the hydropower generation and the provided water can provide reliable forecasts of the water that has to be discharged from the upstream devices [75]. Reliable forecasts of the water that has to be discharged from the upstream devices can be obtained through the application of different algorithms, e.g., ANFIS and the cooperative search algorithm (CSA) [152]. Reliable forecasts of the water that has to be discharged from the upstream devices allows one to obtain reliable predictions of the process variables associated with these devices, e.g., the reservoir level [94]. These predictions also depend on the inflows to the upstream devices; reliability on these forecasts is required in order to accurately predict the needed process variables, e.g., the reservoir level [95,96]. Inflow prediction is significantly influenced by precipitation forecasts. Uncertainties and probabilities of the precipitation must be taken into account [153]. Inflows can be characterized by different lead times. For this purpose, short-, long-, and medium-term forecasts on inflow can be computed [154]. As mentioned above, a strategy that can be implemented based on predictions is MPC. In this regard, the prediction horizon must be selected based on the effective reliability window of the computed forecasts [155].

Reliable forecasting methods could also be useful in the evaluation of the impact of hydropower facilities on sustainable development. For example, the long-term prediction of GHG risk is needed in order to assess life cycle emissions [156]. GHG risk could be detected through CO_2 and CH_4 fluxes prediction. Specific tools can be exploited for the evaluation of GHG emissions vulnerability; in-depth analysis must be conducted in order to evaluate the reliability of the predictions [157].

Table 8 reports some research works about forecast in the hydropower sector, with focuses on the main topic, on the scope and on the main findings.

Table 8. Main features of the selected papers focused on forecast for the hydropower sector.

Main Topic	Scope	Main Findings	Ref.
AI and digital technologies in dam engineering.	Review of AI and digital technologies application in dam engineering.	Assessment of the role of AI and digital technologies in dam engineering with regard to predictive modeling.	[117]
Analysis and prediction of dammed water level in a hydropower reservoir.	Long- and short-term predictions of dammed water level in a hydropower reservoir.	Machine learning could represent a significant tool.	[127]
Guide hydropower allocation.	Provision of forecast-informed reservoir operations.	Hydroclimatic predictions can be converted into actionable information in order to actively support the decision-making process.	[130]

Table 8. *Cont.*

Main Topic	Scope	Main Findings	Ref.
Prediction of hydropower generation.	Investigation of the algorithms that can be used.	DWHO algorithm represents a suitable solution due to its convergence speed and to the required time to provide the solution.	[137]
Prediction of hydropower generation.	Investigation of the algorithms that can be used.	GWO and ANFIS algorithms can be combined in order to provide accurate predictions.	[138]
Prediction of hydropower generation.	Investigation of the algorithms that can be used.	ANNs algorithms can represent a suitable solution.	[139]
Water inflow prediction for dam reservoirs.	Development of a prediction method.	NAR and NARX models can be exploited for the prediction.	[140]
Verification of inflow into hydropower reservoirs.	Exploitation of ensemble forecasts and TIGGE database.	The obtained forecasts can provide enhancement in terms of benefit and flood control.	[141]
Subseasonal hydrometeorological forecasts for hydropower operations.	Assessment of the quality and of value of subseasonal hydrometeorological forecasts for hydropower operations.	The improvement of forecast quality and value is strictly related to the used preprocessing techniques. The forecast value–quality relationship is complex and it is related to many factors.	[142]
Streamflow time series forecasting of hydropower reservoir.	Improvement of the conventional hydrological forecasting models.	Machine learning and tailored optimizers could represent significant tools.	[143]
Middle and long-term streamflow forecasts.	Deal with the stochastic nature of streamflow in order to maximize the hydropower generation.	The combination of AI, adaptation and parameters' optimization could represent a significant tool.	[144]
Streamflow predictions on short and long ranges.	Deal with the uncertainties that characterize the streamflows.	Ensemble forecasts can successfully predict the streamflow.	[145]
Ensemble prediction on streamflow.	Evaluation of the impact of prediction bias on electric energy production.	Exploiting algorithms with a poor robustness to uncertainty, the reservoir levels can be calibrated to configurations characterized by high risk in order to maximize short-term profit. Constraints can mitigate this aspect.	[146]
Short-term streamflow prediction.	Development of a method that combines stochastic weather generation and ensemble weather forecasts.	The proposed strategy could help in the extension of the forecasting horizon.	[147]
Short-term hydropower operations planning.	Exploitation of modeling, simulation and forecasting for the optimal dispatch of water to the turbines.	Stochastic short-term models can be exploited due to their ability to deal with uncertainty.	[131]
Short term hydropower scheduling.	Development of a multi-objective model for peak shaving.	The proposed approach is applicable, tractable and robust enough to obtain near optimal results efficiently.	[132]
Evaluation of the impact of the hydrological forecast quality on operation of reservoirs.	Development of a conceptual approach for the evaluation of the hydrological forecast quality impact on management and revenue.	The developed approach allows one to evaluate the impact of the revenue and forecasts, stock evolution, spillage, production rates, and production hours.	[148]
Short-term optimization of hydropower reservoirs.	Evaluation of the performance of deterministic and probabilistic forecasts.	The exploitation of probabilistic forecasts is more convenient due to its major robustness with respect to flood control while guaranteeing an acceptable level of energy production.	[149]

Table 8. *Cont.*

Main Topic	Scope	Main Findings	Ref.
Monthly runoff prediction in hydropower plants.	Formulated an enhanced prediction formulation.	The combination of different techniques, i.e., TVF, EMD, SSA and ELM, can provide significant enhancements.	[150]
Production capacity prediction of hydropower industries for energy optimization.	Investigation of a method for the prediction of hydropower production and energy saving.	ELM algorithms can be successfully integrated with the Monte Carlo method.	[151]
Reservoir advanced process control (APC) for hydroelectric power production.	Design and implementation of an APC system for water management in a hydroelectric power plant.	The availability of reliable forecasts on the hydroelectric power production plan and the formulation of a reliable model between hydropower generation and discharged water represent fundamental ingredients of an MPC strategy.	[75]
Prediction of discharge time series under hydropower reservoir operation.	Investigation of the algorithms that can be used.	ANFIS and CSA algorithms can be combined in order to achieve better performance with respect ANFIS algorithm.	[152]
APC for water resources systems.	Presentation and analysis of two case studies where APC systems were successfully applied.	Reliable predictions of the water discharged toward the turbines allow one to obtain reliable predictions of crucial process variables, e.g., reservoir levels.	[94]
Production plan satisfaction for hydropower production.	Design and implementation of an MPC strategy for the satisfaction of the production plan in a hydroelectric power plant.	Reliable predictions of the water supplied to the reservoirs contribute to the computation of reliable predictions on some reservoirs' crucial process variables, e.g., reservoir level.	[95]
Reservoir water management for hydropower production.	Design and implementation of an MPC strategy for reservoir water management.	Reliable predictions of the water supplied to the reservoirs contribute to the computation of reliable predictions on some reservoirs' crucial process variables, e.g., reservoir level.	[96]
Real-time decision-making in hydropower operations.	Development of a decision-making strategy that includes precipitation forecasts.	Uncertainty of precipitation, operation policies and a risk evaluation model are integrated into the strategy.	[153]
Optimal operation model of hydropower stations.	Development of a model that includes inflow forecasts with different lead-times.	The developed reservoir model can exploit the short-, long- and medium-term forecasts on inflow.	[154]
Optimization of the generated hydroelectric energy.	Evaluation of forecast and decision horizons assuming medium-range precipitation forecasts.	The efficiency and reliability are improved with a shortened effective decision horizon.	[155]
Long-term prediction of greenhouse gas risk in hydropower reservoirs.	Evaluation of the impact on the sustainable development of electricity production by hydropower reservoirs.	The proposed method predicts long-term GHG risk and the associated life cycle emissions.	[156]
Assessment of risk of GHG emissions in hydropower reservoirs.	Development of a tool for the prediction of CO_2 and CH_4 fluxes.	The developed tool allows one to evaluate the selected fluxes taking into account potential prediction errors.	[157]

5. Discussion

Decarbonization represents a primary objective and the use of RESs can act as a driver in this context. Water is an RES and its rational exploitation is a fundamental requirement. Renewable energy production can exploit water, such as in hydroelectric power plants. Hydropower production is a very complex sector due to process, environmental and economic reasons. With regard to the process, hydraulic, mechanical and electrical aspects interact and the optimal management of these interactions may have to take into account conditions and incentives associated with the market. The economic area is also involved in hydropower plants management for this reason.

Customization of monitoring, maintenance, control and optimization strategies for the hydropower sector is not a trivial task. This task can be tackled by highlighting the basic elements and concepts that can represent the basis for the construction of these strategies. These strategies, if effectively approached, could represent strategic items for the mitigation of the huge costs that characterize the setup and the management of a hydropower plant. The design of proficient approaches for the development and implementation of monitoring, maintenance, control and optimization strategies strictly depends on the level of robustness associated with some basic elements and concepts, i.e., digitalization, Industry 4.0, data, KPIs, modelization and forecast.

Digitalization and Industry 4.0 play key roles and will retain these roles in the hydropower sector. Industry 4.0 is a driver for digitalization and suitable cross-fertilization procedures are being applied for its adaptation to non-industrial sectors like hydropower. Digitalization, through its capability to merge IT and OT and through the connection and contamination between different research areas, can speed up the green and digital transitions.

Energy production and efficiency can benefit from the tools provided by Industry 4.0. Industry 4.0 technologies, e.g., the internet of things (IoT), simulation, cloud computing, augmented reality (AR), big data analytics, CPSs, cybersecurity, blockchain, AI and ML, can speed up the evolution of conventional plants into smart plants. This evolution can massively support the digital and energy transition.

Digitalization and Industry 4.0 highlight the importance of data from different points of view: selection, acquisition, storage, analysis and visualization. Hydropower 4.0 and hydropower CPSs provide hydropower big data. Design, O&M and business levels can benefit from an effective exploitation of the information provided by data. In this context, DSSs can be designed and implemented in order to enhance command and decision making at all levels. In this way, data-driven policies can be conceived and implemented thanks to the shrinking of the time horizon required for making decisions. Databases, data classification, data mining, data quality and data reliability represent strategic features to be implemented in order to totally exploit data potential.

To compute, evaluate, assess, analyze and process information about the efficiency of energy production in hydropower plants, tailored KPIs are needed. These KPIS could be associated with availability, revenue, return on investment, efficiency, energy output, capacity factor, and generation capacity. The automatic evaluation of these parameters represent an additional powerful tool with which to optimize the time horizon for making decisions, as well as the optimality of those decisions.

Figure 7 reports a summary of the key results that digitalization, Industry 4.0, data and KPIs can obtain on hydropower plants.

All of the previously cited elements and concepts, together with the knowledge provided by different research areas, can be exploited for modelization and forecast. Design, O&M and business can benefit from reliable modelization and forecast. Data, process knowledge and methodology represent the two main elements needed for the development of robust modelization and forecast frameworks. Modelization could be referred to design and O&M. Robust models, together with different Industry 4.0 tools, e.g., AR and VR, are innovating the design field. Meanwhile, effective and optimized O&M solutions can massively benefit from the information provided by robust models. In this context, robust models implemented on the field and run with reliable data have become the digital twins of their physical counterparts. Figure 8 reports a summary of the role of modelization and forecast in hydropower plants.

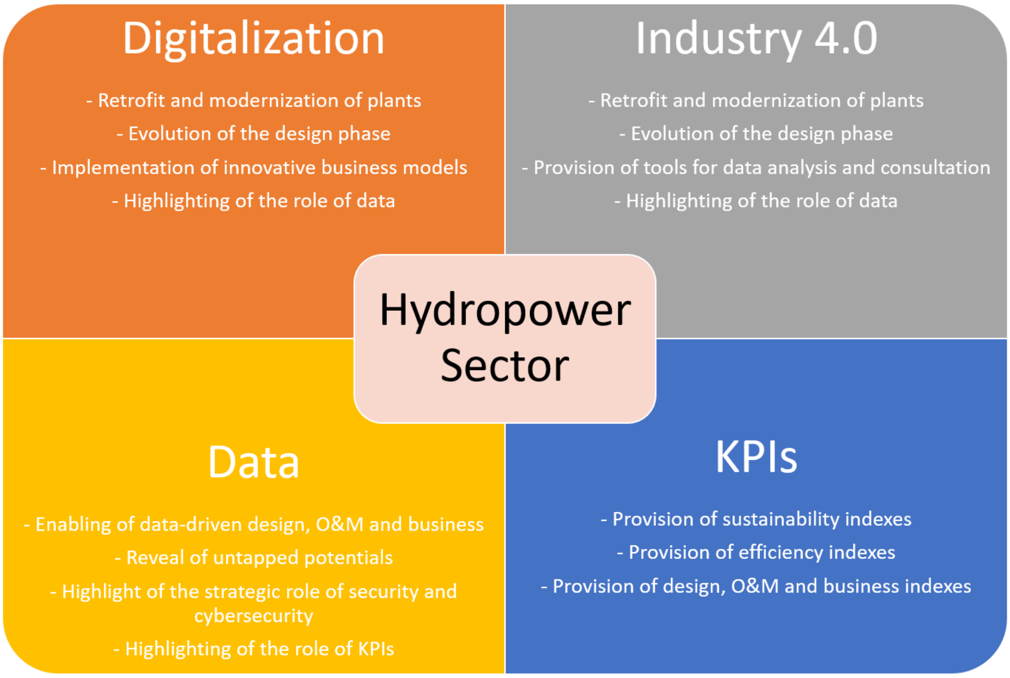

Figure 7. Summary of the key results that digitalization, Industry 4.0, data and KPIs can obtain on hydropower plants.

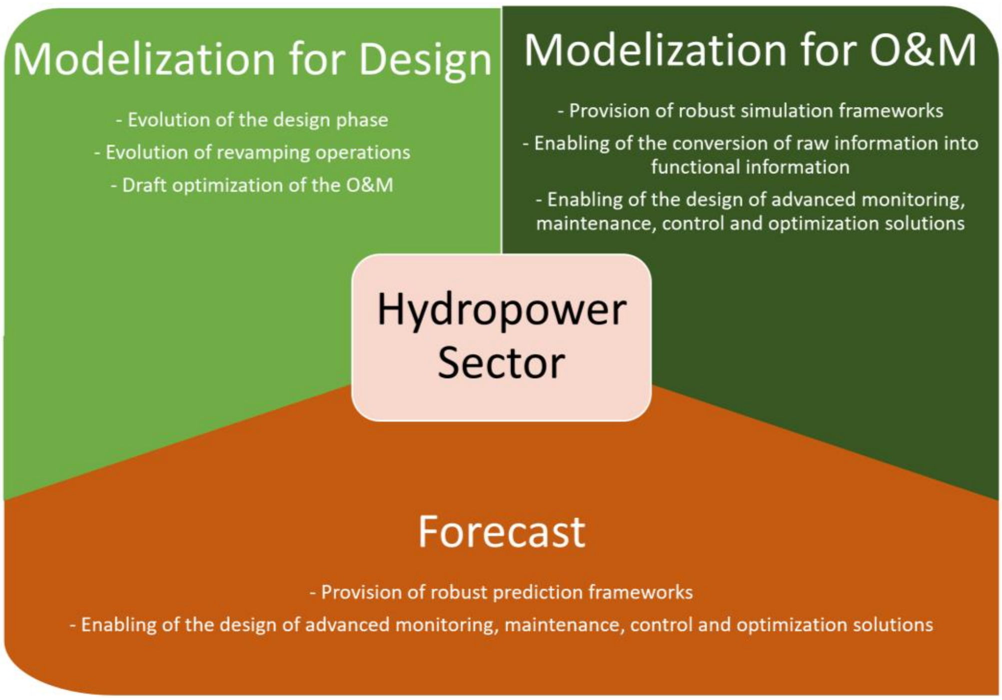

Figure 8. Summary of the role of modelization and forecast in hydropower plants.

The presented discussion highlights the potential of each basic element and concept addressed in the present review paper but at the same time highlights the interactions that can occur between them.

The described concepts represent a solid background for many applications associated with monitoring, maintenance, control and optimization strategies. In the authors' opinion, in order to further assess and enhance the potential of digitalization, Industry 4.0, data, KPIs, modelization and forecast in hydropower plants, the following principles must be applied:

- Continue to create multidisciplinary teams for the development of specific projects: due to the extreme complexity of the hydropower CPSs, many competences must contaminate each other and a fusion of knowledge is required.
- Reduce the gap between university and facilities, the theoretical and scientific approach provided by university can represent a win-win solution only and only if it is accompanied by the field experience and knowledge provided by facilities. The reduction of the gap between university and facilities can speed up the digital and energy transition in the hydropower sector. In fact, the combination between the innovative methodologies proposed by the university research groups and the field experience and knowledge retained by plant managers, engineers, practitioners and operators represents a strategy with huge potential.
- Increase the small-scale laboratories: small-scale laboratories can support the design and the O&M of real hydropower plants through the small-scale implementation of subparts of the real plants. Small-scale implementation can support the design and the O&M thanks to the fact that it is more convenient and practical to perform modifications and tests in laboratories instead of on the real plants. These modifications and tests can enhance both the methodological and practical aspects associated with design and O&M.
- Increase the open access datasets: data represent the main source of information and the availability of open access datasets reporting, for example, issues and problems, can significantly promote the cross-fertilization of already existing algorithms to hydropower sector and the conceiving of new strategies tailored for this sector. This cross-fertilization can represent a powerful method by which to import into the hydropower sector effective solutions for the speed-up of the energy and digital transition.
- Exploit the analyzed basic elements and concepts, i.e., digitalization, Industry 4.0, data, KPIs, modelization and forecast, for the development of advanced monitoring, maintenance, control and optimization solutions. Based on the provided analysis, a clear and straight connection was created between the basic elements/concepts and these strategies.
- Exploit the analyzed basic elements and concepts for the enhancement of the control and monitoring rooms (onsite and remote) of the hydropower plants.
- Exploit the analyzed basic elements and concepts for the search of the best decision in terms of design, retrofit and O&M on hydropower plants.

6. Conclusions and Future Research Directions

A comprehensive literature review of hydropower plant technology with a focus on the basic elements and concepts needed for monitoring, maintenance, control and optimization tasks has been proposed in the present paper. The authors agree that digitalization, Industry 4.0, data, KPIs, modelization and forecast represent milestones for the design of complex tools; for this reason, an assessment and an outline of the existing state of the art associated with these basic concepts and elements has been proposed in this paper. In addition, some insights associated with methods and concepts that can also be applied for their further assessment and enhancement in hydropower research area have been proposed.

Future research directions should be associated with the following:

- Assessment of Industry 5.0 for the hydropower sector: the "technology-driven" concept promoted by Industry 4.0 (born in 2011) has to be adapted to a new "value-driven" concept (born in 2017). In this context, a hydropower sector investigation of the co-existence between Industry 4.0 and Industry 5.0 and on the benefits each can derive from the other must be conducted [158]. Human-centricity, resiliency and sustainability concepts must be assessed for the hydropower sector. Based on the authors' knowledge, an assessment of resiliency and sustainability concepts was begun from a methodological point of view, but it still needs massive field implementation. For example, resiliency can be referred to the idea of implementing flexibility into hydropower plants with respect to market conditions in order to maximize the desired KPIs. On the other hand, sustainability can be considered a rational usage of the water RES. With regard to human-centricity, for example, advanced control and monitoring rooms (onsite and remote) can represent a driver. Operators can be placed out of the lower-level loops in order to gain a crucial supervisory role.

- Assessment of Industry 6.0 for the hydropower sector: the AR/VR and digital twin concepts must acquire major importance within the hydropower sector; in addition, accurate analysis on the possible utilization of quantum computing can be performed [159]. Based on the authors' knowledge, AR/VR and digital twin concepts are gaining the attention of researchers, practitioners, engineers and managers in the hydropower field. For example, the design of new hydropower plants and the proof of their features can be massively supported by AR/VR. In addition, digital twins can support the road to sustainability. With regard to quantum computing, this can support the computation at different automation and business levels, especially with very complex CPSs.
- Reduce the gap between simulation and field implementation: projects that examine hydropower sectors characterized by lasting field implementation are not widespread. The real implementation of a system in the field requires additional robustness and reliability assessment with respect to the requirements of a system tested through virtual environment simulations.
- Further assessment of KPIs aimed at further emphasizing the potential impact of innovative technologies in the hydropower sector.

Author Contributions: Conceptualization, C.P. and S.M.Z.; formal analysis, C.P. and S.M.Z.; investigation, C.P. and S.M.Z.; methodology, C.P. and S.M.Z.; validation, C.P. and S.M.Z.; visualization, C.P. and S.M.Z.; writing—original draft, C.P. and S.M.Z.; writing—review and editing, C.P. and S.M.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Green Hope s.r.l.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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