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Case Report

Digitalisation and Modernisation of Hydropower Operating Facilities to Support the Colombian Energy Mix Flexibility

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Abstract: Hydropower plants cover almost 70% of the Colombian electrical demand, were built several decades ago, and present low levels of digitisation compared to other modern power-generation technologies, e.g., wind turbines, solar PV plants, and recently buil hydroelectric plants t. Renovating power plant equipment and investing in modernisation and digitisation can significantly increase the plant flexibility. Those actions will increase a plant's operational safety and contribute to the solution of environmental and social problems. This work presents the actions followed to extend the lifetime of a 1000 MW hydropower plant operating for more than 40 years. Activities included a residual life status evaluation of generators and component upgrades, among others. The rehabilitation and digitalisation of the generation units allow their integration and remote monitoring so that diagnostic actions can be carried out during a continuous and economically sustainable operation. These activities complement the plan implemented by the company during the last decade to ensure the plant's operation for another 50 years and its respective integration with nonconventional generation systems at the national level. Besides the generator's life extension, the main result of rewinding is an increase in the Minimum Breakdown Voltage by almost 140% (from 38.4 kV to 95.6 kV) with respect to the current operation state, ensuring its operation for the following years.

Keywords: hydropower digitalisation; technology development; energy transition; digital transformation; hydropower projects; sustainable energy

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1. Introduction

The increase in the world population implies a greater demand for resources and energy consumption worldwide [1]. According to the International Energy Agency (IEA) [2,3], to meet this demand, it is necessary to implement strategies that facilitate the migration of actual generation systems to use more renewable sources, avoiding increasing Greenhouse Gas Effects during electric power generation. Those initiatives are aimed in the same direction as the Sustainable Development Agenda 2030 [4] and the following Sustainable Development Goals: "Affordable and non-polluting energy" (SDG 7) and "Build resilient infrastructure, promoting sustainable industrialisation and encourage innovation" (SDG 9). Meeting the targets set in these SDGs requires, in addition to generation with renewable sources, the modernisation and adaptation of operating plants (e.g., existing hydro and thermal power plants) [5], considering the available resources, technological development, and innovation processes.

1.1. The Role of Existing Hydropower Plants in the Energy Mix

Including existing hydropower facilities included in energy transition plans toward renewable and sustainable energy demand modern equipment, components, and decision-making tools [6]. This process needs to be articulated with companies' management information systems to reduce downtime, increase safety, improve reliability margins, reduce operating costs, and increase profitability [7]. Several reports have prioritised the equipment and components of hydropower plants requiring modernisation to ensure the availability and integration of operating facilities [8]. Those reports also highlight the necessity of using, selecting, and installing new information and data acquisition systems to achieve the flexibility necessary for integrating new nonconventional renewable power systems. In this sense, Yaseen et al. [9] conducted a comprehensive study on the sustainable operation of hydroelectric projects and established guidelines for research, development, and innovation work that include modernising and monitoring assets and generation plants using state-of-the-art technologies to acquire and analyse information during the power plant's operation.

Quaranta et al. [10] proposed a large-scale estimation of the increase in the annual generation that could be achieved through the modernisation of European hydropower installations. The authors analysed several modernisation strategies applied in Europe and showed that, although digitisation would provide a 1% increase in efficiency, forecasting of the basins would increase the annual generation by 11%. It is worth mentioning that hydroelectric power plants are essential assets for the electricity sector, because they represent a crucial source of integration for generation from variable renewable resources with the electricity transmission networks, supplying almost 30% of the flexible global capacity considering hour-to-hour ramping requirements, a capability that is similar to that of thermal plants burning coal and natural gas [8]. In this sense, Rahi and Kumar [11] showed that refurbishing a 100-year-old hydropower plant can be environmentally friendly, cost-effective, and done within a short period of time. Therefore, in addition to the overall concerns that are associated with the use of fossil fuels and the shortage of available power, society and the environment should investigate many abandoned and less efficient hydropower plants.

1.2. Current State of Hydropower Projects

Most hydroelectric power plants have been in operation for several decades (see hydropower ageing profile of facilities around the world in Figure 1), making it necessary to review the technological level of the equipment and the adaptations, modifications, and possible modernisation required for their potential integration with information technologies, leading to a digital transformation of the electricity generation and transmission processes. Therefore, the sector requires verification of the technological age of equipment so that adaptations and modifications can be made and possible modernisation processes can be performed to fulfil modern requirements for integration with the Interconnected Generation System [12].

For instance, Islam et al. [13] and Guy and Sparling [14] reviewed various methods and tests for determining the lifespan and operating conditions of power transformers. Additionally, Glavan et al. [15] designed a condition monitoring system for synchronous generators of a hydropower plant. Ilseven and Göl [16] proposed an intelligent algorithm for maintenance planning and its use in hydropower plants. Hoffmann et al. [17] showed how measurement procedures could be combined with machine learning algorithms for application in the predictive maintenance of electrical equipment. Bordin et al. [18], Barbosa de Santis and Costa [19], and Zhao et al. [20] presented works related to the use of intelligent techniques for the measurement of variables and the detection of faults and anomalies, oriented to the planning of the operation and monitoring of the condition in hydroelectric plants in the digital transformation era. Huang et al. [21] presented a method for early-failure detection in hydropower plants with Gaussian regression processes.

More recently, and thanks to advances in information and communication technologies and the use of machine learning techniques, Betti et al. [22] suggested the use of a key performance indicator as a first step to establishing automatic monitoring systems in these hydropower assets, which is a necessity in energy transitions carried out within digital transformation processes. Finally, digitalisation allows an increase in the efficiency (and the produced energy) with no additional impact on the river ecosystems [10] while providing tools to improve predictive maintenance activities that are carried out in modern condition monitoring systems that allow the lifetime to be increased, the stop times to be reduced, and the cyber-security risks to be managed.

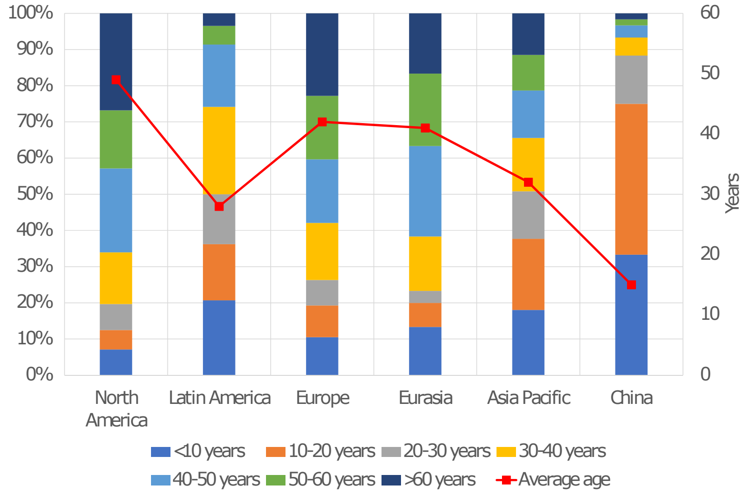


Figure 1. Worldwide hydropower age profile of installed plants. Built with data from [8].

1.3. Digitisation of the Electricity Market

The digitisation of hydropower plants implies the use of modern technologies to enhance their performance [10]. Such technologies include components that can be used at different stages: design, construction, and operation. It is possible to find distributed control systems that use modern components and condition monitoring systems that are based on Industry 4.0 technologies. Many of the existing hydropower plants that are in use nowadays were built many years ago [8]. As a result, their equipment has less digitisation than the operating and maintenance systems and components of contemporary renewable energy systems. Additionally, the digitisation of hydropower plants is complex and cross-cutting, since it includes several components and operational conditions, e.g., civil structures, turbines, generators, reservoirs, and environmental parameters. This is in contrast to photovoltaic (PV) and wind plants, where just a few components need to be digitalised. The rehabilitation and modernisation of the current fleet provides the opportunity to digitise the operation of hydroelectric equipment.

Monitoring strategies for power generation plant components and equipment have increased thanks to the availability of modern technologies [23]. Integrating them into organisational practices related to the management of automated elements and systems allows the monitoring, control, and adaptation of industrial information systems. Additionally, it has been shown that the use of systems thinking to address sustainability challenges in the energy sector is very important [24]. Welte et al. [25] developed MonitorX, a strategy used in Norway and Sweden for the monitoring and maintenance of hydroelectric plants that use Industry 4.0 technologies and digital transformation strategies. Crespo-Márquez et al. [26] developed an asset performance monitoring system using artificial intelligence and data mining to detect reliability problems in long-term industrial assets. Lu et al. [27] presented a framework for monitoring and detecting industrial asset anomalies using digital twins that can be used for operation and maintenance. In the case of hydroelectric plants, Majumder et al. [28] proposed an intelligent system to increase the reliability of the production of a hydroelectric plant and achieve a balance between the indicators desired for the operation.

Regarding software and system architecture for asset management, Asghari and Hsu [29] developed an open modular platform in Python that allows asset managers to be integrated. Furthermore, Thomson et al. [30] presented a report in which it is evident that the digital transformation of energy companies is a crucial tool in the energy transition, both for new generation plants with renewable resources and for the generation with operating hydropower plants. It is focused on cybersecurity and data quality governance. More recently, Gavrikova et al. [31] presented the design of an architecture for managing energy companies' data from assets and linking operation data with corporate strategies and expectations of the various stakeholders. According to [32], management strategies require the quantity and quality of data available for decision-making to align with advances in measurement equipment and communication technologies available today. It is possible to find recent works related to energy recovery in existing infrastructure [33], management strategies in transmission and distribution systems [34] and proposals for the development of management plans for power generation with renewable energy assets [35]. Therefore, digital transformation processes need to be monitored and promoted, because these are crucial factors for the energy sector transition [36]. In work related to the latter, the authors state that energy requirements can also be tackled from the demand point of view by reducing the cost with increases in the processes' efficiency derived from digital transformation.

1.4. Colombian Energy Market Situation

As in other countries, hydropower plants in Colombia have been in operation for several decades, as presented in Figure 2, which makes it necessary to establish preventive and proactive actions by utility companies to ensure their service and operation. In the same figure, it is shown that the AES Chivor hydropower plant (green bar) has an installed capacity of 1000 MW and has operated for nearly 45 years. The Colombian energy market is complex in its structure; electricity production is concentrated in hydropower plants that can be affected by many external factors [37]. Additionally, the Colombian electricity generation system is supported by the reliability mechanism, which has, among its essential components, firm energy obligations acquired by the generators. This is supported by generation plants that are capable of producing energy under critical water supply conditions so that long-term energy supply is guaranteed at efficient prices and that, in return, the generators receive an additional income derived from the charge for reliability. This charge consists of a payment to the generators that is proportional to the firm capacity they can offer to the system [38].

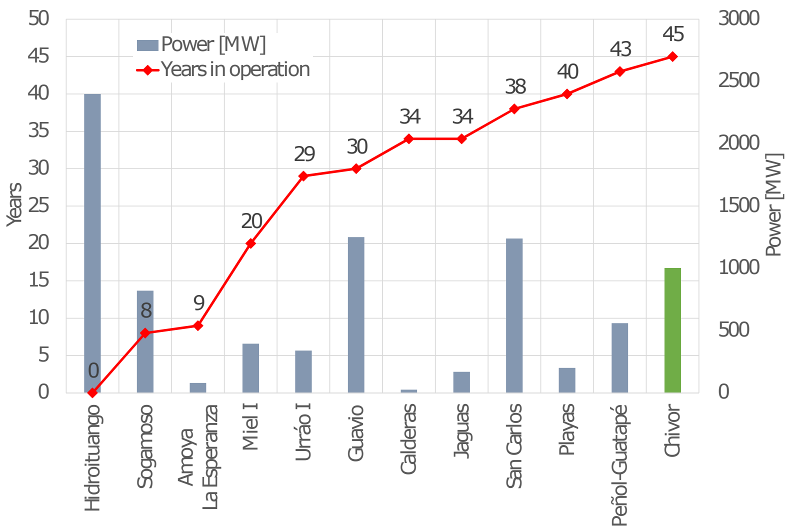


Figure 2. Age and installed capacity of Colombian hydropower plants [39].

This condition potentially hinders an adequate energy transition towards other renewable nonconventional generation sources without affecting the service's stability, quality, and availability. In energy markets, such as the Colombian one, which is dependent mainly on hydraulic energy, it is necessary to establish actions by utility companies around the modernisation and management of the operating facilities. The Colombian National Planning Department (DNP) determined the energy demand consumption by sector and analysed public policies [40]. It also determined technologies and schemes for the more efficient use of energy resources. Additionally, it recommended technical requirements for new technologies and energy transition scenarios [39]. On the other hand, the supply analysis run by the DNP [41] suggested the extention of the use of Nonconventional Renewable Energy Sources (NCRES), e.g., solar, geothermal, wind, marine, biogas, and small-scale hydroelectric. The latter refers to hydroelectric power plants with an installed capacity of below 10 MW. It also identified the barriers to NCRES implementation nationwide; analysed the energy mix's life cycle, carbon footprint, and technical requirements; described current policies; and analysed penetration scenarios with a view to 2050.

The Colombian National Energy plan, proposed by the Mining Energy Planning Unit and presented by the National Energy Plan of Colombia [42], aims to reduce the technological gap with a firm commitment to digitisation in the energy sector, economic development, adaptation to climate change, and reliable supply of the energy demand. Among the long-term objectives and actions, the National Energy Plan [43] contemplates the supply security and diversification of the energy mix and the energy efficiency and regional energy integration. Furthermore, it promotes the installation of power plants from various renewable sources, such as solar and wind, to ensure a sustainable increase in the energy supply without neglecting the need to increase the availability and reliability of the existing plants. Figure 3 portrays forthcoming power-generating projects according to the expansion plan set by the government that supports those initiatives. Furthermore, Figure 4 presents the expected capacity of those projects. It is observed that Colombia's energy mix will substantially change in the coming years, supported mainly by the NCRES.

Considering the integration and energy transition as the dominant vector of the transformation of the country's energy mix, great relevance must be given to the participation of Colombian operating hydropower plants. The Colombian electricity generation matrix is supported by hydroelectric and thermal plants with participation levels of close to 68% and 30%, respectively [41]. These hydropower plants include various technologies and generation capacities, as well as a variety of tools for management, control, and operation. Therefore, ensuring the maintenance of these plant operations over time is essential for the sector's sustainability. Within Colombian utilities, initiatives are already registered on extending the useful life of reservoirs for periods of 50 years [44], the renovation of plants with technological development in infrastructure based on sediment research [45], the monitoring of power plants for failure prediction based on data analysis [46], and digital transformation processes with modern platforms for commercial management based on specialised Industry 4.0 tools [47].

In particular, this case reports actions that AES Corporation has implemented in Colombia to give rise to digital transformation during the operation of its assets, providing process innovation in the management of the system during power generation and representing an innovative contribution to the base of knowledge around the fulfilment of SDGs 7 and 9. These actions have involved previous research and development studies performed by the company regarding the renovation of equipment and components through the adoption of new technologies, ensuring the correct interaction with existing capacities. This ongoing effort by the company seeks to ensure the operation of the company's hydroelectric plants in the coming years, providing more reliability and efficiency in the power generation process, and to facilitate the forthcoming integration of new renewable sources into the Colombian electricity generation system. The research/development efforts that led to this case report represent an example for a wide-ranging audience that includes researchers, managers, and practitioners of large-scale hydropower projects. This paper is organised is as follows: Section 2 shows the residual life assessment of the generator at different stages of its operational life, including after the overhaul maintenance performed on the stator and rotor windings. In the same sections, additional activities regarding the modernisation and digitisation of data acquisition are presented. Section 3 contains the discussion, and finally, the conclusions are presented in Section 4.

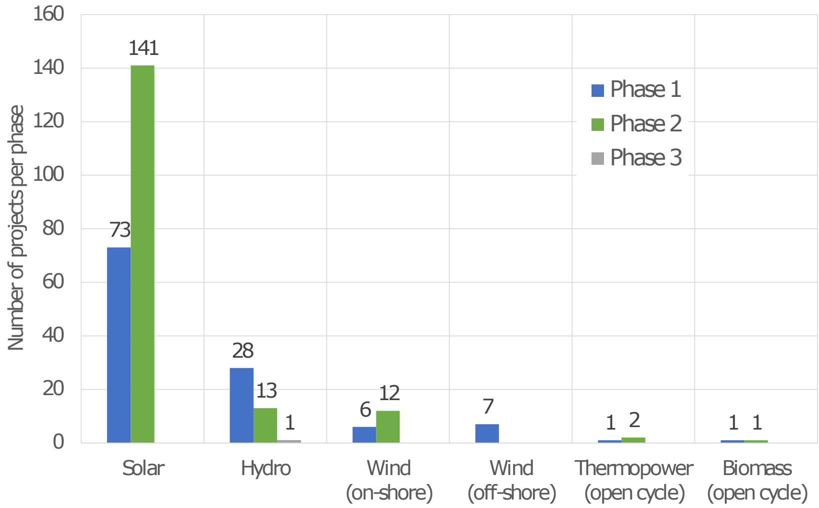


Figure 3. NCRES planned projects in stages of prefeasibility (phase 1), feasibility (phase 2), and detailed engineering (phase 3) with expected operation from 2023 in Colombia. Built with data from [39].

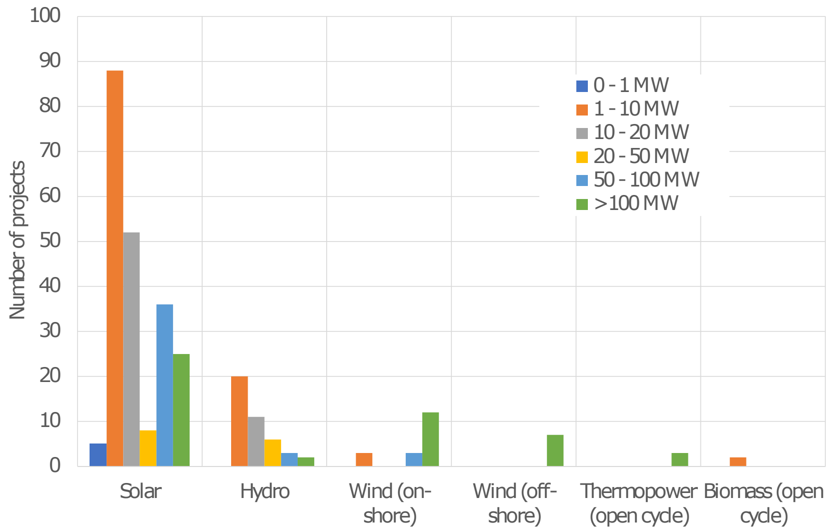


Figure 4. NCRES planned projects by capacity range with expected operation from 2023 in Colombia. Built with data from [39].

2. AES Colombia Digital Transformation and Energy Transition Process

The modernisation, transformation, and renovation project of AES Colombia hydropower generation plants is related to activities that the company has been carrying out for several years. Therefore, it allows established actions to be followed during the Digital Transformation and Energy Transition processes developed at various states within the company. In this sense, some components of the generator units at the Chivor II Hydropower Plant, such as stator and rotor windings, transformers and protections, were prioritised for intervention. Additionally, Programmable Logic Controllers (PLCs) used to control and record temperature sensors in the generation systems were close to reaching the limit of useful life or incompatible with the recently implemented information management systems. Considering the diagnosis results and the company's digital transformation strategic objective, the actions implemented and results obtained are presented in the following text.

2.1. AES Colombia Power Plant Situation

AES Colombia owns and operates two hydropower plants that serve the Colombian interconnected system. The Chivor Hydroelectric Power Project is a large-scale plant with an installed capacity of 1000 MW. Its first stage came into operation in 1977, and the second began to provide service in 1982 [44]. On the other hand, there is the Small Hydroelectric Power Plant, Tunjita, with two generating units, each of 9.8 MW, that came into operation in 2016. However, AES Colombia hydropower plants present low-efficiency technology levels compared to equipment installed in recent years by other utilities. The obsolescence has impacted informatics systems, control equipment, the power plant's data acquisition, and operation/management software.

In this sense, AES Colombia has identified, using asset detection and management strategies, power plant components with elevated levels of deterioration, including the effects of external factors that eventually compromise the current operation of their facilities [44]. Within these plants, a specific need to modernise various components of the generation system, including the generator windings of several units currently in operation, with improved and efficient devices compared to those currently in operation has been identified. In addition, the need to update the data acquisition and control systems has been contemplated, considering technologies and data acquisition instruments that interact with the management system at the Colombian subsidiary and its operation centre in Chile. Likewise, the implementation of these new components for the generation and the corresponding measurement instruments is part of the company's actualisation, in which more operation variables will be integrated and measured in real-time (e.g., state of vibrations in real-time, online characterisation of winding insulators by measuring partial discharges, among others). Together with the digital transformation actions that the company has been applying at various decision-making and management levels, the use of Machine Learning and Artificial Intelligence methods will lay the foundation to ensure the efficient and effective operation of these assets in the long term [47]. In addition, it is well known that the diversification of the electricity mix will require the status of the renewable generation plants that will come into operation in forthcoming years to be known. Moreover, it will also be essential to have online supervision of the operating plants that currently support the generation system.

In this way, operating hydropower facilities will be a backup of the generation system when large-scale wind farms and photovoltaic plants enter to ensure service quality. As mentioned, the Colombian energy mix aims to integrate more nonconventional sources within the generating park. In this regard, AES Colombia is developing a 648 MW wind power project in La Guajira, the largest in the country. The project comprises five wind farms in the Colombian Alta Guajira, that are currently in the development and licensing stage (i.e., phases 1 and 2, as portrayed in Figure 3). In addition to these projects, the company has 81 MWp of Solar PV in operation and another 26 MWp is in construction for the Colombian oil company Ecopetrol. This is part of the company's strategy to add 750 MW of NCRES projects to the AES portfolio in the country by 2025. The incorporation of these projects will not only bring the achievement of the company's expected growth plan in the Colombia market closer, it will also contribute to the Colombian goal of integrating 1500 MW of nonconventional renewable energy into the system in the coming years with the social and economic development of La Guajira. These actions will allow the company to update its operation's generation system, facilitating its online supervision and integration with generation plants from nonconventional sources and facilitating the energy transition defined by both the company and the country.

2.2. Residual Life Status of Chivor II Generators

A generator stator winding coil runs under electrical, mechanical, and thermal stresses throughout its operational life. The combination of these types of stress condition deteriorates the insulation and reduces its useful life. Figure 5 presents forced exits due to load rejection stops over the last 22 years at the Chivor power plant, causing at least

15 stoppages in generation per year due to mechanical, electrical, and instrumentation failure and outages due to external causes from the substation connection and transmission circuits, representing up to 75 days of forced outages due to equipment breakdown or malfunction [48]. It is observed that, in particular, Units 1, 5 yellow bar in Figure 5, and 8 experienced at least 50 or more load rejection stops in the period reported from 1997 to 2019. That condition has affected the company's ability to ensure the availability and reliability of the hydropower plant and has compromised the economic income of the company by affecting the charge reliability, as previously indicated.

As mentioned before, the ageing of some components is directly related to the continuous operation of power units. For instance, a fault occurred in the stator winding, causing an electrical short circuit in the lower stator head due to water leaking from the turbine enclosure (see Figure 6a). The repair required the replacement of the three lower bars affected by the short circuit, and it was necessary to replace 32 upper bars of the upper coil. Another event happened in 2013 during the stator winding wedges change: a fault was detected when the stator's upper bars 125 and 131 did not pass a high-voltage test due to deficiencies and cuts in the insulation (see Figure 6b).

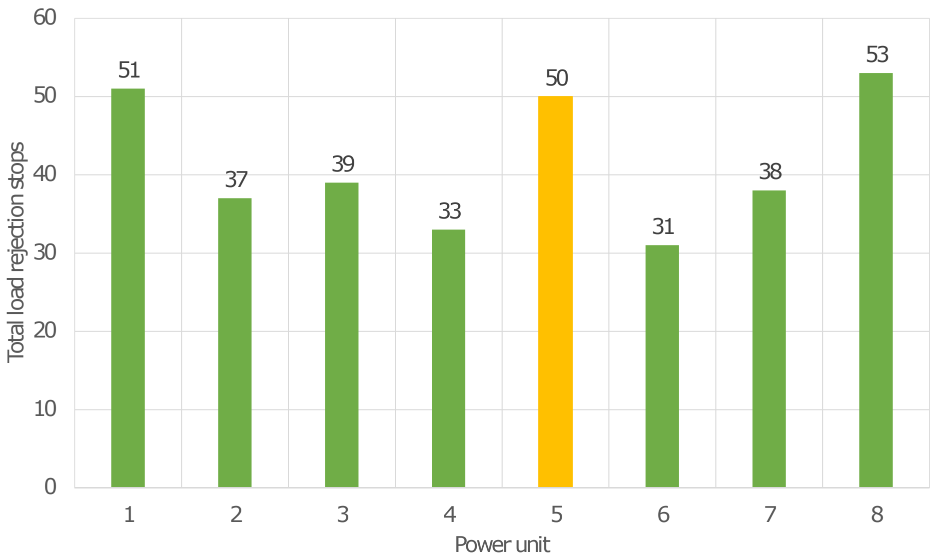
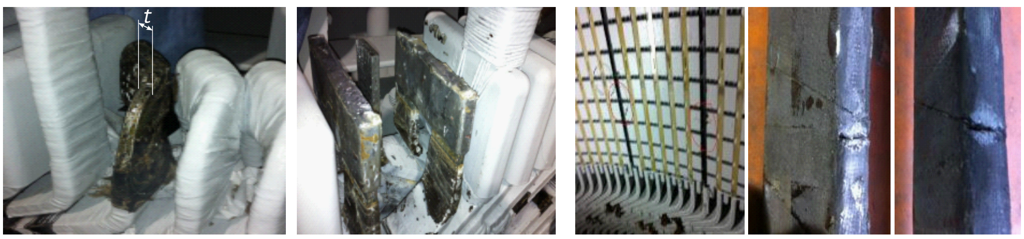


Figure 5. Historical forced exits with load rejection for the 1997–2019 period.



(**a**) Fail in stator winding (**b**) Cut insulation

Figure 6. Examples of fails that have occurred in Unit 5 in the last years. For reference, the thickness *t* of a stator bar is about 17 mm.

Figure 7 shows the Unit 5 power generator's stator and rotor state before its overhaul maintenance. A quantitative evaluation of the ageing of Unit 5 was performed following the IEEE 1043-1996 [49] and IEEE 1553-2002 standards [50] at different moments during its operational life to assess the residual life of the generator. The accelerated ageing test is a standardised practice that is often applied by specialised laboratories worldwide to estimate the residual useful life of a winding that has been in operation for several years. The first part of this study consisted of selecting a sample of coils of the winding under investigation. Then, thermal and electrical stresses were induced by changing temperatures and voltages, respectively. This was done by applying a higher load, compared to nominal values, to determine the lifetime of each specimen tested and build the average curve that indicates the residual life trend. For each test, the thermal stress was imposed through resistance plates to establish a temperature equal to or greater than that at which the machine usually operates. For this particular case, an Operation Voltage Level, E, equal to 13.8 kV was used.

(**a**) Stator (**b**) Rotor

Figure 7. State of the previously overhauled Unit 5 stator and rotor. For reference, the rotor's diameter is about 3 m.

The first test of this type was carried out in a specialised laboratory, where 12 half-coils were removed from the stator winding of Unit 5 in 2004 (i.e., after 22 years in operation). The Residual Life Analysis (RLA) results, following the IEEE 1043-1996 standard, indicated a residual life of approximately 13 years at that moment of operation. Later, in 2014, a new RLA study was carried out, where the estimated residual life was about eight years, and a safe operational level was set as twice plus one times the nominal load value E (e.g., 2E + 1 = 28.6 kV), equivalent to 28.6 kV. In this regard, Figure 8 summarises the estimated residual life of Chivor II power plant Unit 5, where the original breakdown voltage curve is plotted (black solid line). In addition, complementary tests were performed on the generator's unit, such as a partial discharge monitoring analysis, electrical test parameter trends, and historical forced outputs. The main conclusion of those tests was to define the steps of the overall maintenance of four generators, representing 125 MW each, on which a change in all windings was planned.

The upgrading project developed in 2021 re-established the operational condition of Unit 5 by using new materials and technologies, offering a more outstanding durability and reliability of the asset. For instance, unit insulation was changed from type B (maximum allowable temperature of 130 °C) to F (maximum allowable temperature of 155 °C). Additionally, state-of-the-art paints and resins were used during the process, ensuring its application through the ISO 8501 standard and various postimplementation inspection procedures to ensure the quality of the final product. For instance, the dry film thickness must be in accordance with the criteria of the standards ASTM D7091 or NBR 10443. Failures or defects in each coat of paint, during application and after exposure (e.g., bleeding, blistering, wrinkling, cracking, cratering, flaking, pitting, staining, dry spraying, and others), must be avoided, following ISO 4628 or NBR 14951. Figure 9 shows the structural configuration of the new winding installed on Chivor's Unit 5. Additionally, Figure 8 portrays the rewinding breakdown voltage curve (discontinuous black line). The final result of the maintenance process conducted in Unit 5 can be seen in Figure 10. Finally, to establish the new useful lifetime of Chivor II Unit 5, an RLA test was applied to a sample of four new coils of the manufactured batch. The accelerated ageing tests were carried out in the manufacturer's laboratory, and based on the results obtained from this test, the new coils are expected to operate for approximately 45 years.

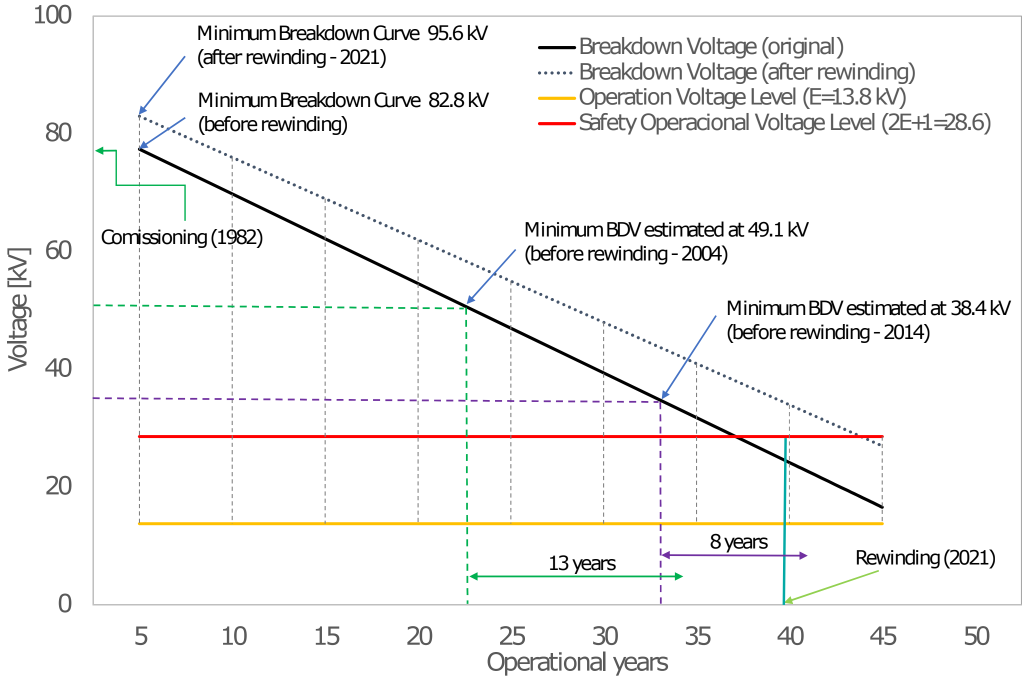


Figure 8. Residual life of Chivor II generator unit 5 before and after rewinding.

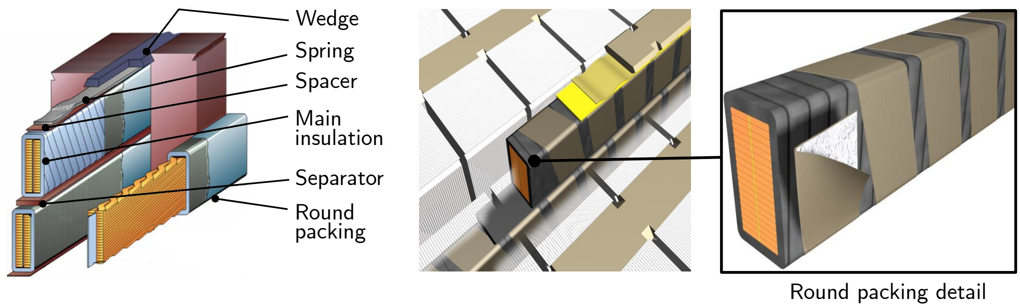
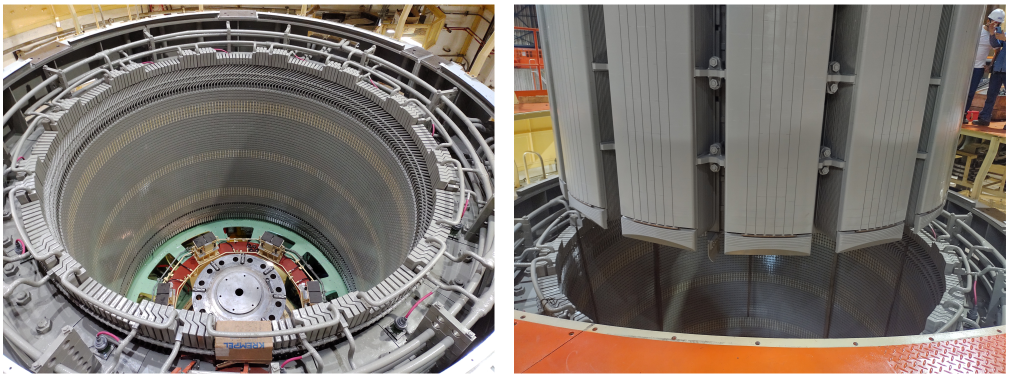


Figure 9. New winding insulation configuration. For reference, the thickness of a stator bar is about 17 mm.

As a follow-up strategy, the continuous performance monitoring of each unit was carried out during the entry into operation of the equipment updated at Chivor II. Regarding the generating units, special electrical tests were carried out after changing windings, and a dynamic balancing and vibration analysis was conducted within the condition tests for monitoring the changes implemented. The update of the control models followed the recommendations of the National Dispatch Centre, considering the behaviour of each of the machines according to the agreements defined by the National Operation Council with the required operational tests. In addition, the generator unit load curve of the Chivor hydropower plant II was updated during the tests.



(**a**) Stator (**b**) Rotor

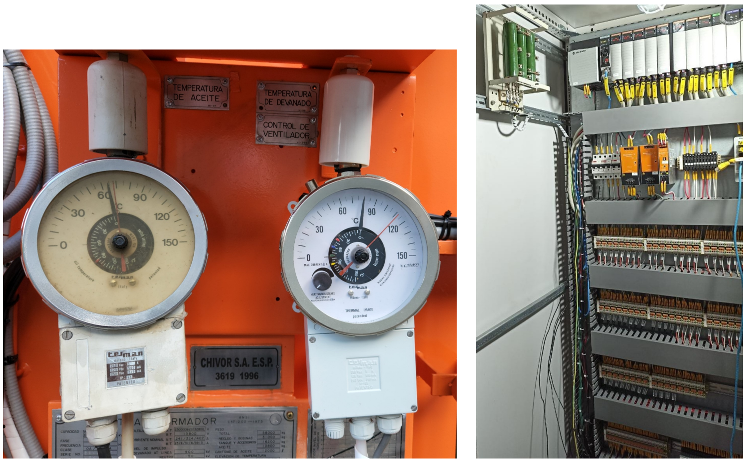
Figure 10. State of the rewinded Unit 5 stator and rotor. For reference, the rotor's diameter is about 3 m.

2.3. Selection and Adaptation of Information Systems and Data Acquisition

Modernisation projects at the Chivor hydropower plant during the last 45 years have included the implementation of new technology to allow online supervision of the behaviour of the operating variables for trend analysis and asset performance. All of those actions have been addressed to strengthen the energy sustainability and flexibility strategy that the company seeks to implement in the following years. As a result, the expectations for stable power have increased. A primary concern for the AES Colombia managing teams is the generator, transformer integrity, and power plant availability during generation.

In this regard, online temperature sensors enable the measurement of this property in real time, validating the generator's performance, the transformer's correct operation, and the system's efficiency. Figure 11a presents, on the left side, an analogous measuring instrument that has been installed at the plant since its commissioning to track the transformers and generator temperatures. The data from these devices are usually collected in operational rounds by personnel at the plant and recorded in spreadsheets to digitise the values and allow the behaviours and trends to be observed. In Figure 11a, the temperature sensors installed in the plant digitisation campaign are presented next to the analogous versions on the right side. The newly installed temperature sensors are double PT100 type stator RTD sensors with fibreglass insulation and epoxy resin (class F, calibrated at 100 Ω at 0 °C). Modern sensors/transmitters allow integration into an updated online acquisition system (see Figure 11b) for monitoring the trends of the different variables, including temperature, vibration, and electrical trends, among others. The sensors are connected to 1756 ControlLogix® modules, which include, among others, analogue, digital, diagnostic, motion control, special I/O, and computation modules to meet different application needs. In addition, data acquisition software allows anomaly detection. This includes, among others, performance assessment, early failure detection of the power unit, and predictive analytics for assertive decision-making according to the interconnected national system's requirements (see Figure 12).

Table 1 summarises the main results obtained after implementing the actual phase of the modernisation of Chivor II regarding technical and economic aspects. It was observed that the generator winding insulation failure can lead to machine shutdown for approximately three to six months to re-establish operating conditions, leading to high operating costs. Table 1 shows the estimated loss costs due to possible failure in a power generator if the total winding replacement is not carried out on time, given that these generators have been in operation for 40 years and the useful life of the windings has already been reached, according to the residual life tests carried out. Although the generators can continue to operate for an additional period of time (e.g., a couple more years), the risk of failure and its impact is very high due to the nongeneration of energy (i.e., loss of profit) plus the costs of repair and replacement with a new generator. Therefore, the profit lost in the event of an unexpected failure in the generators was calculated as follows: the company's commercial area has a water resource valuation in terms of electrical energy of 52 USD/MWh. Since each machine has a capacity of 125 MW, 6500 USD/h is generated in one hour. An operational shutdown of three months represents a projected loss of 14 million USD. For an operational shutdown of six months, this value rises to 28 million US. Those values do not consider the replacement costs of the complete winding, estimated to be approximately 1.7 million USD. It is worth mentioning that the winding replacement in plants of similar capacity lasts six months if spare parts are in stock. Finally, it is expected that, at the end of the plant overhaul, the development of an assessment allows quantification of the impact on the plant's increased security and dependability, mitigation of environmental improvements, and decreased outages and failures (due to digitisation).



(**a**) (**b**)

Figure 11. Temperature (**a**) instrumentation and (**b**) installed PLC for data acquisition.

(**a**) (**b**)

Figure 12. Temperature data acquisition software screen outputs of the generator (**a**) and its radiator unit (**b**).

Table 1. Techno-economic results after implementing the modernised hydropower Chivor II operating facility.

Parameter	Value
Extend the life expectancy	45–50 years
Minimum Breakdown Voltage (before rewinding)	38.4 kV
Minimum Breakdown Voltage (after rewinding)	95.6 kV
Estimated lost cost of a 3 or 6 month failure	14 to 28 M USD

3. Discussion

Modernisation projects for the operation of hydropower plants seek to avoid high-impact failures in the generator units, causing extra costs associated with unscheduled maintenance and avoiding fines for the non-dispatch of energy and service interruptions to the Interconnected National System (SIN), which consequently lead to profit losses for the company. Therefore, the implementation and development of modernisation projects for the operation of hydropower plants can have a significant impact on the achievement of the SDG that is conducive to "Affordable and non-polluting energy" (SDG 7) and "Build resilient infrastructure, promoting sustainable industrialisation and encourage innovation" (SDG 9). These projects aim to implement components that ensure power plant operation over time, consolidating their availability for their contribution to the electricity generation system. In addition, these components are intended to increase the efficiency in the energy transformation process of existing machines, guaranteeing access to affordable, reliable, and modern energy services. In the particular case of AES Colombia, the time plan proposed by the company through the implementation of these actions seeks, in addition to the application of more efficient components for its operation (i.e., the initial stage of the modernisation process), the application of strategies that facilitate supervision and in-line operation in the coming years. In this case, variables that were previously only measured from time to time will be tracked in real time.

To ensure the sustainable operation and digital integration of its plants, AES Colombia has been carrying out projects focused on ensuring and strengthening the stability of the service provided in the face of the energy transition of the company's and the country's power generation systems. To this end, this project developed a broad framework of operation and transformation, in which technical-operational aspects that allow the integration of the generation process to the digital management system of the company of assets with more than 40 years of operation and others with technologies not compatible with the management tools are considered. In this way, the transition of the operation of the country's generation system will be attained, in addition to achieving a digital transformation of the company that leads to an increasingly reliable operation through the implementation of a modern system for the management of information and risk.

The execution of this type of project allows management to transition from a local to a global scale, which requires, among other factors, the creation of synergies at different levels, learning experiences, the comprehension and implementation of newer decision-making methodologies, and the enhancement of soft skills such as communication and teamwork while appropriating different technological tools. Its implementation will lead to the management of the generation systems in a centralised manner through the operation of reliable generation units, in which remote monitoring can take place in the control centres of Colombia and South America in a stable manner, making it possible to carry out diagnostic actions of continuous and economically sustainable operations. In addition, the integration of new technologies in the Chivor plant will be achieved, providing greater efficiency by implementing components with lower levels of loss in the generation process, making more efficient use of the water resources and their dispatchment to the interconnected national system. These actions will provide an improved experience for end customers due to increased reliability through innovation in the real-time management process of the company's assets, guaranteeing that power generation is reliable.

In particular, the investment in modernisation and digitalisation of a hydropower plant's main components (e.g., turbines and generators) can (i) increase plant flexibility, (ii) increase safety, and (iii) help to resolve social and environmental problems depending on the country's regulations. For the AES Colombia's hydropower plants, more precisely, the Chivor generator winding insulation failure led to a machine outage for approximately three months to re-establish the operating conditions, leading to elevated OPEX costs. Therefore, following the above information, the modernisation of this generation plant that has been in operation for nearly 40 years is vital; AES Colombia has been continuously implementing projects to increase the useful life of the assets and thus provide reliability to the electrical system.

Among the activities mentioned in this work, the company is modernising the supervisory control and data acquisition (SCADA) system of PCH Tunjita. This process considers the collection of field information to identify the state-of-the-art techniques and structure associated with the PCH SCADA modernisation project. The project's second phase consists of the equipment supply, installation, parameterisation, testing, and start-up of the PCH Tunjita SCADA. Ultimately, this new SCADA will be integrated into the PCH with the Remote Operation and Supervision system SCADA of the Chivor Power Plant. This process requires the appropriate hardware and software to send and integrate the signals in the IEC104 protocol for all the field equipment in the PCH for its remote operation. In this way, both utility hydropower units in Colombia can support the integration of more nonrenewable energy sources into the country's energy mix. The main advantages yielded by the digital transformation are related to the complex nature of the Colombian market (which is mainly based on hydropower), the new changing and diverse expectations of customers, and the uncertainties that characterise decision-making processes regarding commercial matters in the energy market. The use of Industry 4.0 tools, such as those being used to extend the lifespan and digitise the Chivor Hydropower Plant, benefits the complete national electricity system, since actions executed around such modern technologies contribute to the electrical system's stability, reduce risks, and strengthen decision-making processes, hence, providing the population and productive sectors with sustainable energy.

4. Conclusions

This work addressed the actions regarding the digitalisation and modernisation processes followed to extend the lifetime of a 1000 MW hydropower plant operating for more than 40 years and support the Colombian energy mix flexibility. The rehabilitation and digitalisation of the generation units allowed their integration and remote monitoring to carry out diagnostic actions during a continuous and economically sustainable operation. For instance, rewinding the generators allowed the Minimum Breakdown Voltage to be increased by almost 140% (from 38.4 kV to 95.6 kV), which ensures its operation for the following years.

Although modernisation and digital transformation processes within a hydropower plant involve several technological challenges, as described in this work, they must be considered human-centred activities, because changes in culture are expected by different stakeholders for successful technology appropriation. Therefore, knowledge appropriation activities, such as training, workshops, and socialisation of the user experience, among others, are crucial to enhance the organisational culture regarding the use of new systems and technologies in an Industry 4.0-based scenario for the energy transition. Furthermore, these types of activities can generate various technical and economic impacts on the operation of these types of plants. In this regard, the increase in efficiency has yet to be determined, and its evaluation is planned once the adaptation of the eight units that make up the plant has been carried out. Regarding the reduction in economic losses, during the financial valuation of the project, the lost cost was estimated if a failure occurred during the stator and rotor winding with the machine being shutdown for an extended period (at least six months). This value would rise to USD 28,080,000, which compared to the cost of replacing the machine winding, would be USD 1.7 million, justifying the implementation of this process, accompanied by digital modernisation. Regarding the latter, the digital transformation process at AES Colombia has opened possibilities for improving different systems and energy production scenarios that include new variables and that allow the development of business solutions and procedures that support decision-making activities [47]. Furthermore, new trends in the energy market require the use of new technologies that next advance to the evolution of the market itself. Finally, additional advantages that could be attained by putting the techniques above into effect, such as increased security and dependability, mitigation of environmental improvements, and decreased outages and failures (due to digitisation), were not calculated. Therefore, future research should focus on these advantages, which are crucial to defending and justifying modernisation expenditure.

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Abbreviations

The following abbreviations are used in this manuscript:

DCS	Distributed Control Systems
DNP	Colombian National Planning Department
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organisation for Standardization
NCRES	Non-Conventional Renewable Energy Sources
OPEX	Operating Expenses
PCH	Pequeña Central Hidroeléctrica (Small Hydroelectric Plant)
PLC	Programmable Logic Controller
PV	Photovoltaic
RLA	Residual Life Analysis
SCADA	Supervisory Control and Data Acquisition
SDG	Sustainable Development Goal
UPB	Universidad Pontificia Bolivariana

References

1. IEA. *World Energy Outlook 2021*; Technical Report WEO-2021; International Energy Agency: Paris, France, 2021.
2. United Nations. *World Population Prospects 2022: Summary of Results*; Techreport DESA/POP/2022/NO.3; United Nations, Department of Economic and Social Affairs, Population Division: New York, NY, USA, 2022. Available online: https://www.un.org/development/desa/pd/content/World-Population-Prospects-2022 (accessed on 10 November 2022).
3. IEA; IRENA; UNSD; World Bank; WHO. *Tracking SDG 7: The Energy Progress Report*; Techreport; License: Creative Commons Attribution CC BY 3.0 IGO; World Bank: Washington, DC, USA, 2022. Available online: https://trackingsdg7.esmap.org/ (accessed on 15 December 2022).
4. United Nations. *The Sustainable Development Goals Report 2022*; Techreport; United Nations Publications: New York, NY, USA, 2022. Available online: https://unstats.un.org/sdgs/report/2022/ (accessed on 15 December 2022).
5. Hansen, K.; Breyer, C.; Lund, H. Status and perspectives on 100% renewable energy systems. *Energy* **2019**, *175*, 471–480. [CrossRef]
6. Puppala, H.; Vasanthawada, S.R.S.; Garlapati, N.; Saini, G. Hybrid multi-criteria framework to determine the hierarchy of hydropower reservoirs in India for floatovoltaic installation. *Int. J. Thermofluids* **2022**, *16*, 100229. [CrossRef]
7. Ossai, C.I. Optimal renewable energy generation—Approaches for managing ageing assets mechanisms. *Renew. Sustain. Energy Rev.* **2017**, *72*, 269–280. [CrossRef]
8. IEA. *Hydropower Special Market Report*; International Energy Agency: Paris, France, 2021; p. 126. [CrossRef]

9. Yaseen, Z.M.; Salih-Ameen, A.M.; Aldlemy, M.S.; Ali, M.; Afan, H.A.; Zhu, S.; Sami-Al-Janabi, A.M.; Al-Ansari, N.; Tiyasha, T.; Tao, H. State-of-the Art-Powerhouse, Dam Structure, and Turbine Operation and Vibrations. *Sustainability* **2020**, *12*, 1676. [CrossRef]
10. Quaranta, E.; Aggidis, G.; Boes, R.M.; Comoglio, C.; De Michele, C.; Ritesh Patro, E.; Georgievskaia, E.; Harby, A.; Kougias, I.; Muntean, S.; et al. Assessing the energy potential of modernizing the European hydropower fleet. *Energy Convers. Manag.* **2021**, *246*, 114655. [CrossRef]
11. Rahi, O.; Kumar, A. Economic analysis for refurbishment and uprating of hydro power plants. *Renew. Energy* **2016**, *86*, 1197–1204. [CrossRef]
12. Kuriqi, A.; Pinheiro, A.N.; Sordo-Ward, A.; Bejarano, M.D.; Garrote, L. Ecological impacts of run-of-river hydropower plants—Current status and future prospects on the brink of energy transition. *Renew. Sustain. Energy Rev.* **2021**, *142*, 110833. [CrossRef]
13. Islam, M.M.; Lee, G.; Hettiwatte, S.N. A review of condition monitoring techniques and diagnostic tests for lifetime estimation of power transformers. *Electr. Eng.* **2018**, *100*, 581–605. [CrossRef]
14. Guy, P.; Sparling, B. Transformer Asset Life Extension—When, Why and How to Apply Continuous Condition Monitoring Systems. In Proceedings of the 2019 IEEE PES GTD Grand International Conference and Exposition Asia (GTD Asia), Bangkok, Thailand, 19–23 March 2019; pp. 779–784. [CrossRef]
15. Glavan, B.; Haníc, Z.; Kovăcíc, M.; Vražíc, M. Condition-Monitoring System for Identification and Representation of the Capability Diagram Limits for Multiple Synchronous Generators in a Hydro Power-Plant. *Energies* **2020**, *13*, 3800. [CrossRef]
16. Ilseven, E.; Göl, M. Incorporation of generator maintenance scheduling with long-term power sector forecasting and planning studies. *IET Gener. Transm. Distrib.* **2020**, *14*, 2581–2591. [CrossRef]
17. Hoffmann, M.W.; Wildermuth, S.; Gitzel, R.; Boyaci, A.; Gebhardt, J.; Kaul, H.; Amihai, I.; Forg, B.; Suriyah, M.; Leibfried, T.; et al. Integration of Novel Sensors and Machine Learning for Predictive Maintenance in Medium Voltage Switchgear to Enable the Energy and Mobility Revolutions. *Sensors* **2020**, *20*, 2099. [CrossRef] [PubMed]
18. Bordin, C.; Skjelbred, H.I.; Kong, J.; Yang, Z. Machine Learning for Hydropower Scheduling: State of the Art and Future Research Directions. *Procedia Comput. Sci.* **2020**, *176*, 1659–1668. [CrossRef]
19. Barbosa de Santis, R.; Costa, M.A. Extended Isolation Forests for Fault Detection in Small Hydroelectric Plants. *Sustainability* **2020**, *12*, 6421. [CrossRef]
20. Zhao, W.; Egusquiza, M.; Valero, C.; Valentín, D.; Presas, A.; Egusquiza, E. On the use of artificial neural networks for condition monitoring of pump-turbines with extended operation. *Meas. J. Int. Meas. Confed.* **2020**, *163*, 107952. [CrossRef]
21. Huang, H.; Qin, A.; Mao, H.; Fu, J.; Huang, Z.; Yang, Y.; Li, X.; Huang, H. The Prediction Method on the Early Failure of Hydropower Units Based on Gaussian Process Regression Driven by Monitoring Data. *Appl. Sci.* **2021**, *11*, 153. [CrossRef]
22. Betti, A.; Crisostomi, E.; Paolinelli, G.; Piazzi, A.; Ruffini, F.; Tucci, M. Condition monitoring and predictive maintenance methodologies for hydropower plants equipment. *Renew. Energy* **2021**, *171*, 246–253. [CrossRef]
23. Kougias, I.; Aggidis, G.; Avellan, F.; Deniz, S.; Lundin, U.; Moro, A.; Muntean, S.; Novara, D.; Pérez-Díaz, J.I.; Quaranta, E.; et al. Analysis of emerging technologies in the hydropower sector. *Renew. Sustain. Energy Rev.* **2019**, *113*, 109257. [CrossRef]
24. Laimon, M.; Yusaf, T.; Mai, T.; Goh, S.; Alrefae, W. A systems thinking approach to address sustainability challenges to the energy sector. *Int. J. Thermofluids* **2022**, *15*, 100161. [CrossRef]
25. Welte, T.; Foros, J.; Nielsen, M.; Adsten, M. MonitorX—Experience from a Norwegian-Swedish research project on industry 4.0 and digitalization applied to fault detection and maintenance of hydropower plants. In Proceedings of the Hydro 2018—Progress through Partnership, Gdansk, Poland, 15–17 October 2018.
26. Crespo-Márquez, A.; de la Fuente-Carmona, A.; Antomarioni, S. A process to implement an artificial neural network and association rules techniques to improve asset performance and energy efficiency. *Energies* **2019**, *12*, 3454. [CrossRef]
27. Lu, Q.; Xie, X.; Parlikad, A.K.; Schooling, J.M. Digital twin-enabled anomaly detection for built asset monitoring in operation and maintenance. *Autom. Constr.* **2020**, *118*, 103277. [CrossRef]
28. Majumder, P.; Majumder, M.; Saha, A.K.; Nath, S. Selection of features for analysis of reliability of performance in hydropower plants: A multi-criteria decision making approach. *Environ. Dev. Sustain.* **2020**, *22*, 3239–3265. [CrossRef]
29. Asghari, V.; Hsu, S.C. An open-source and extensible platform for general infrastructure asset management system. *Autom. Constr.* **2021**, *127*, 103692. [CrossRef]
30. Thomson, J.; Wei, J.; Murrell, B.; Hardin, K.; Sanborn, S. *Digital Utility Asset Management: Building the Backbone of the Energy Transition*; Technical Report; Deloitte Research Center for Energy and Industrials: Tampa, FL, USA, 2021.
31. Gavrikova, E.; Volkova, I.; Burda, Y. Implementing asset data management in power companies. *Int. J. Qual. Reliab. Manag.* 2021, *ahead-of-print*. [CrossRef]
32. Koziel, S.; Hilber, P.; Westerlund, P.; Shayesteh, E. Investments in data quality: Evaluating impacts of faulty data on asset management in power systems. *Appl. Energy* **2021**, *281*, 116057. [CrossRef]
33. Chae, K.J.; Kim, I.S.; Ren, X.; Cheon, K.H. Reliable energy recovery in an existing municipal wastewater treatment plant with a flow-variable micro-hydropower system. *Energy Convers. Manag.* **2015**, *101*, 681–688. [CrossRef]
34. Joseph, T.; Ugalde-Loo, C.E.; Liang, J.; Coventry, P.F. Asset management strategies for power electronic converters in transmission networks: Application to Hvdc and FACTS devices. *IEEE Access* **2018**, *6*, 21084–21102. [CrossRef]

35. Pinheiro-Neto, D.; Domingues, E.G.; Coimbra, A.P.; de Almeida, A.T.; Alves, A.J.; Calixto, W.P. Portfolio optimization of renewable energy assets: Hydro, wind, and photovoltaic energy in the regulated market in Brazil. *Energy Econ.* **2017**, *64*, 238–250. [CrossRef]
36. Światowiec Szczepańska, J.; Stępień, B. Drivers of Digitalization in the Energy Sector—The Managerial Perspective from the Catching Up Economy. *Energies* **2022**, *15*, 1437. [CrossRef]
37. Arango-Aramburo, S.; Turner, S.W.D.; Daenzer, K.; Ríos-Ocampo, J.P.; Hejazi, M.I.; Kober, T.; Álvarez Espinosa, A.C.; Romero-Otalora, G.D.; van der Zwaan, B. Climate impacts on hydropower in Colombia: A multi-model assessment of power sector adaptation pathways. *Energy Policy* **2019**, *128*, 179–188. [CrossRef]
38. Botero Duque, J.P.; García, J.J.; Velásquez, H. Efectos del cargo por confiabilidad sobre el precio spot de la energía eléctrica en Colombia. *Cuad. De Econ.* **2016**, *35*, 491–519. [CrossRef]
39. UPME. *Informe de Registro de Proyectos de Generación de Electricidad*; Technical Report; Unidad de Planeación Minero Energética: Bogotá, Colombia, 2021.
40. DNP. *Energy Demand Situation in Colombia*; Technical Report; Departamento Nacional de Planeación: Bogotá, Colombia, 2017.
41. DNP. *Energy Supply Situation in Colombia*; Techreport; Departamento Nacional de Planeación: Bogotá, Colombia 2017.
42. Minenergía. *La transición Energética de Colombia: Memorias al Congreso 2019–2020*; Technical Report; Ministerio de Minas y Energía: Bogotá, Colombia, 2020.
43. Duque-Márquez, I.; Mesa-Puyo, D.; Lotero-Robledo, M.; Sandoval-Valderrama, S. *Transición Energética: Un Legado para el Presente y el Futuro de Colombia*; Technical Report; Ministerio de Minas y Energía, y Banco Interamericano de Desarrollo: Bogotá, Colombia, 2021.
44. del Río, D.A.; Moffett, H.; Nieto-Londoño, C.; Vásquez, R.E.; Escudero-Atehortúa, A. Chivor's Life Extension Project (CLEP): From Sediment Management to Development of a New Intake System. *Water* **2020**, *12*, 2743. [CrossRef]
45. del Río, D.A.; Moffett, H.; Nieto-Londoño, C.; Vásquez, R.E.; Escudero-Atehortúa, A. Extending Life Expectancy of La Esmeralda Reservoir: A Bet to Support Colombia's Future Energy Demand. In Proceedings of the ASME 2020 Power Conference, Virtual, Online, 4–5 August 2020; American Society of Mechanical Engineers: New York, NY, USA, 2020. [CrossRef]
46. González, H.A.; Piedrahita, J.D.; Castrillón, O.D. Predicción de parada de máquinas generadoras en una central hidroeléctrica por medio de minería de datos. *Inf. Tecnológica* **2020**, *31*, 215–222. [CrossRef]
47. Giraldo, S.; la Rotta, D.; Nieto-Londoño, C.; Vásquez, R.E.; Escudero-Atehortúa, A. Digital transformation of energy companies: A colombian case study. *Energies* **2021**, *14*, 2523. [CrossRef]
48. Malovic, D.; Pilger, H.E.; Arsenijevic, N.; Gassner, K.B.; Merle-Beral, E.; Monti, G.; Pooley, J.; Inouye, L.K.; Levin, J.; Kellenberg, J. *Hydroelectric Power: A Guide for Developers and Investors*; Technical Report; World Bank: Sydney, New South Wales, 2015.
49. IEEE. *IEEE Recommended Practice for Voltage-Endurance Testing of Form-Wound Bars and Coils*; IEEE: New York, NY, USA, 1997. [CrossRef]
50. IEEE. *IEEE Standard for Voltage Endurance Testing of Form-Wound Coils and Bars for Hydrogenerators*; IEEE: New York, NY, USA, 2002. [CrossRef]