frontiers | Frontiers in Water

TYPE Mini Review
PUBLISHED 30 September 2025
DOI 10.3389/frwa.2025.1681345

OPEN ACCESS

EDITED BY
Jiangjiang Zhang,
Hohai University, China

REVIEWED BY
MohammadHossein Homaei,
Universidad de Extremadura, Spain

*CORRESPONDENCE
Tingxiang Cao
✉ 2216094841@qq.com

RECEIVED 07 August 2025
ACCEPTED 15 September 2025
PUBLISHED 30 September 2025

CITATION
Cao T, Gao S, Shi X, Mo L, Zhang B and Zhu J (2025) Core technologies for hydropower digitalization within the Energy Internet framework: a mini-review.
Front. Water 7:1681345.
doi: 10.3389/frwa.2025.1681345

Core technologies for hydropower digitalization within the Energy Internet framework: a mini-review

Tingxiang Cao[1]*, Song Gao[1], Xiangjian Shi[2], Li Mo[1], Bing Zhang[2] and Jingan Zhu[2]

[1]Western Maintenance and Testing Branch, Southern Power Grid Energy Storage Co., Ltd., Xingyi, Guizhou, China, [2]Nanjing NARI Relay Protection Engineering Technology Co., Ltd., Nanjing, Jiangsu, China

Hydropower, a cornerstone renewable energy source globally, is undergoing a transformative evolution through digitalization technologies within the emerging Energy Internet paradigm. This review examines the critical role, applications, enabling architectures, security considerations, and future directions of hydropower digitalization. Digitalization optimizes resource allocation and accessibility, enabling enhanced operational oversight and integration. Key applications include smart monitoring via Internet of Things (IoT) sensors and big data analytics for predictive maintenance, digital twin implementation for equipment prognostics and optimized real-time dispatch, sophisticated water resource scheduling leveraging diverse datasets (meteorological, hydrological, grid demand) for maximized utilization efficiency, and ecological impact mitigation via intelligent flow control and habitat design simulation. Deployment necessitates robust security measures adhering to industrial control standards (e.g., IEC 62443) and often employs redundant network architectures (dual-active or independent operation) to ensure safety and continuity. Future advancement depends critically on progress in interoperability, next-generation predictive digital twins, edge computing, advanced communication infrastructure, and cybersecurity resilience. Collectively, the ongoing evolution of hydropower digitalization technologies represents a vital pathway toward realizing the goals of efficiency, stability, and sustainability within the global Energy Internet.

KEYWORDS

hydropower digitalization, Energy Internet, digital twin, smart monitoring, resource scheduling

1 Introduction

Hydropower stands as a cornerstone renewable energy source globally, playing a vital role in contemporary power systems. Consequently, leveraging digital technologies like digitalization to enhance hydropower plant operations and integration represents a critical research and development objective for the future energy landscape. Digitalization promises integrated, intelligent transformations for hydropower systems, contributing significantly to the stability and flexibility of future energy supplies worldwide (Siddik et al., 2024; Zhang et al., 2020). This drive aligns with the broader evolution toward the Energy Internet, a transformative paradigm integrating diverse energy systems through electronics, information, and smart technologies to create interconnected networks enabling bidirectional energy flows and comprehensive lifecycle management (Zhang et al., 2020). This concept emerged fundamentally in response to global shifts in energy demand, security imperatives, and the need for enhanced sustainability. International initiatives have accelerated its development, aiming to combine renewable energy sources with advanced internet and digital technologies to enhance the intelligence and integration of energy collection, transmission, utilization, and management, thereby driving sustainable energy development globally. Renewable energy is universally central to the Energy Internet. As global requirements for efficient, resilient, and clean energy systems intensify, traditional technologies prove increasingly inadequate. Advanced digital solutions, including the Internet of Things (IoT), Artificial Intelligence (AI), Big Data, and critically, Digitalization, are therefore being deployed to construct smarter, more stable, and adaptive energy networks (Niu et al., 2024). These innovations are revolutionizing energy management, trading, and service models, with digitalization specifically enabling significant upgrades to global energy infrastructure.

The Energy Internet (Mishra and Singh, 2023) can be defined as a next-generation energy system that integrates advanced information and communication technologies with traditional energy infrastructure. Similar to how the Internet transformed information exchange, the Energy Internet aims to enable smart, flexible, and decentralized energy generation, distribution, and consumption. The Energy Internet architecture fundamentally comprises five interconnected functional modules: Production integrates distributed renewable sources like wind, hydro, solar, and biomass via IoT for optimized resource allocation. Transmission utilizes smart electrical grids alongside networks for other energy carriers (e.g., natural gas, hydrogen) for efficient long-distance transfer. Storage employs diverse technologies to balance supply and demand dynamics and improve utilization efficiency. Consumption leverages smart terminals enabling bidirectional flow and autonomous response to user demand, with distributed generation feeding surplus back into the grid. Management relies on integrated intelligent control systems and leverages AI and Big Data analytics for holistic oversight and enhanced system adaptability. The digitalization of hydropower thus represents a crucial technological pathway within the global pursuit of the Energy Internet, offering substantial potential gains in efficiency, stability, and sustainability across the energy value chain.

This review examines the critical role, applications, enabling architectures, security considerations, and future directions of hydropower digitalization. The analysis focuses primarily on literature from 2019 to 2025, sourced from databases including Web of Science, Scopus, and IEEE Xplore. The selection criteria prioritized research articulating the integration of core digital technologies—such as IoT, AI, and digital twins—into hydropower systems for enhancing operational efficiency, advanced scheduling, ecological management, and security within the Energy Internet paradigm.

2 Role of hydropower digitalization in the Energy Internet

Building upon its foundational role, hydropower digitalization significantly enhances the functionality of the Energy Internet. By creating sophisticated virtual models (digital twins) of hydropower plants, it enables enhanced visual management and operational oversight, directly improving overall energy efficiency (Tan et al., 2025). This digitalization critically boosts system responsiveness and flexibility, facilitating real-time monitoring and enabling rapid adaptation to emergencies or demand fluctuations. Furthermore, the integration of AI and Virtual Reality (VR) technologies with these virtual models allows for optimized energy dispatch, contributing substantially to stable system operations within the interconnected network (Vagnoni et al., 2024). Beyond operational efficiency, digitalization serves as a key enabler for the seamless integration of distributed renewable energy sources—including wind, hydro, solar—into broader energy networks, fostering their effective participation and supporting the development of diversified, sustainable energy systems globally. This capability simultaneously stimulates innovative applications of digital and virtual technologies across the entire energy supply chain. Given the Energy Internet's paramount priority on system security and stability, hydropower digitalization contributes directly by enhancing supply quality through automated improvements in power delivery processes and advanced fault diagnosis capabilities (Dao et al., 2024; Li et al., 2024). Crucially, by facilitating the effective combination and management of diverse energy sources within the virtual framework, it strengthens overall risk resilience, reduces critical dependencies on single energy channels, and thereby ensures more secure and stable energy utilization across the integrated system, providing a robust foundation for the Energy Internet's objectives.

3 Key technologies in hydropower digitalization

3.1 Smart monitoring and data analytics

Hydropower digitalization enables comprehensive smart monitoring through the strategic deployment of IoT sensors and advanced data acquisition systems. These technologies continuously gather real-time operational data across the hydropower facility. Subsequent big data analytics transform this raw data into actionable insights, facilitating predictive maintenance algorithms and significantly enhancing the efficiency and reliability of equipment management, thereby reducing downtime and operational costs. Vagnoni et al. (2024) assessed the current and future role of sustainable hydropower in providing critical flexibility services to European power systems facing high penetrations of variable renewable energy, leveraging a comprehensive database collected from stakeholders across 34 European countries within the COST Action Pen@ Hydropower network. They figured that innovative monitoring and optimization technologies include AI-assisted tools such as convolutional neural networks (CNNs) for automated, image-based fish species detection and classification at passages, eDNA analysis for biodiversity assessment, computational fluid dynamics (CFD)-driven geometry optimization for turbine design flexibility, and the digitalization of technical documentation as a foundation for future digital twins and lifecycle management. In the Energy Internet field, Shui et al. (2024) proposed a Stackelberg game-based distributed optimization framework for multi-entity virtual power plants (VPPs) integrating electric vehicles (EVs) and carbon capture systems. The framework employs a master–slave architecture where the VPP operator (leader) sets energy prices and four aggregators—energy supply, residential demand response, EV, and carbon treatment (followers)—optimize their operations, with equilibrium uniqueness rigorously proven. Case studies using real-world Shanghai community data demonstrate a 10.80% increase in VPP profit, 15.59% reduction in carbon emissions, and 99.29% acceleration in solution speed via the hybrid NOA-QP algorithm, validating its efficacy in balancing economic and environmental objectives while preserving participant privacy.

3.2 Digital twin technology implementation

A cornerstone application involves the development and utilization of digital twin models (Xie et al., 2019). These sophisticated virtual replicas of physical hydropower plants integrate real-time sensor data with historical performance metrics, as shown in Figure 1. This integration allows for accurate simulation of operational scenarios, enabling critical functions such as predictive equipment health assessment, optimized remote maintenance planning, and dynamic, real-time energy dispatch optimization, ultimately maximizing plant performance and lifespan. Zhao et al. (2021) presented a digital twin model for hydropower plants that leverages massive data from modern power systems to digitally represent physical entities, events, and their interrelationships, thereby enabling large-scale data fusion and mining. To address the complexity and nonlinearity of power systems, a data-driven framework for model construction and application is proposed. The effectiveness of the approach is demonstrated through a case study on fault diagnosis in hydropower systems. Similarly, in the domain of dam safety, Ding et al. (2025) proposed a practical digital twin framework for smart safety management of earth/rockfill dams, enabling dynamic evaluation of performance indicators like deformation. The framework integrates physics-based models with monitoring data through Bayesian updating to create a continuously learning "living" model. Implemented in the Danjiangkou Digital Twin Project for a core-wall rockfill dam, it achieves three novel capabilities: real-time simulation, future forecasting, and scenario projection of dam behavior. Hydropower systems indeed face complex challenges in load control and fault detection. In response, Guo et al. (2024) proposed a predictive model for hydro turbine failures by leveraging a digital twin to simulate rare fault scenarios that are difficult to capture in real-world data. By generating synthetic data under varied and extreme conditions, the digital twin enhances the robustness and generalization of deep learning-based fault prediction beyond traditional historically dependent methods. The approach improves maintenance planning, operational reliability, and cost-effectiveness, demonstrating significant potential for application in the hydropower industry. Further advancing this line of research, Tan et al. (2025) introduced a hybrid Digital Twin and Deep Learning framework that significantly enhances fault detection accuracy by 7%, reduces detection time by 12.14%, and improves system efficiency by 8.97%. The proposed approach demonstrates substantial gains in operational resilience and cost-effectiveness, offering a data-driven strategy for advanced hydropower management.

3.3 Optimized water resource scheduling

Digitalization facilitates highly sophisticated water resource management (Sun et al., 2024). By integrating diverse datasets including high-resolution meteorological forecasts, detailed basin-wide hydrological information, and real-time grid electricity demand signals digitalization platforms empower operators to execute stochastic optimization models. This capability allows for dynamic, multi-objective reservoir scheduling decisions, significantly improving the overall utilization efficiency of water resources for power generation, flood control, and supply security across diverse global contexts. Mousavi and Ponnambalam (2025) introduced analytical derivations of hydropower equations to enhance the recently extended Fletcher–Ponnambalam method. The developed method is applied to optimize the long-term operations of a three-reservoir system in Iran,

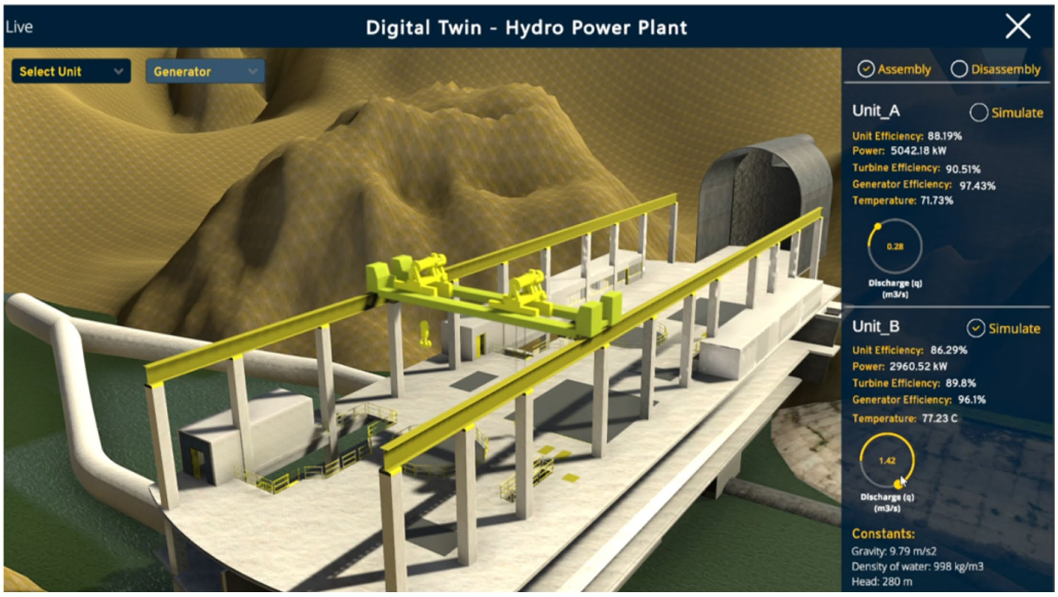

FIGURE 1
Simulated view of the entire hydropower plant with real-time IoT data. Source: Reproduced from Chalamalasetty (2024), licensed under CC BY NC ND 4.0 license.

specifically targeting the maximization of expected annual energy production—a complex multiplicative nonlinear function of both reservoir releases and storage levels. Guo et al. (2024) proposed a forecast-informed framework for reservoir flood control under uncertainty, applied to China's Lishimen Reservoir. It develops the Stochastic Errors-based Cloud (SE-Cloud) method, merging AI-based individual forecasts into ensemble forecasts using Cloud modeling and error-based copulas. Results show SE-Cloud significantly improves uncertainty characterization and peak flow capture, increasing hypervolume by 13–40% over basic Cloud modeling. While higher deterministic forecast quality did not consistently improve operational outcomes, SE-Cloud ensembles enhanced solution robustness.

3.4 Ecological impact mitigation

Digitalization technologies actively contribute to minimizing the ecological footprint of hydropower operations (Ao et al., 2023). Intelligent systems enable precise, adaptive control of ecological water releases, ensuring downstream ecosystem requirements are reliably met. Furthermore, simulation capabilities inherent in virtual models support the optimized design and virtual testing of fish passage facilities and habitat restoration strategies (Yu et al., 2024). These applications collectively reduce adverse impacts on riverine biodiversity and promote sustainable hydropower development aligned with broader environmental stewardship goals. Fleming et al. (2024) evaluated spatially and temporally complete MODSCAG fractional snow-covered area (fSCA) as input for operational water supply forecasting in four western U.S. watersheds. Compared to traditional data, fSCA consistently improved accuracy for challenging short-lead late-season forecasts by 10–25%. AI-based hydrologic models generally outperformed statistical models and better utilized satellite data.

4 Application of digitalization technology in hydropower plant monitoring systems

Digitalization technology fundamentally optimizes resource allocation and accessibility by partitioning or aggregating physical computer resources (CPU, memory, storage) into logical environments, transforming them into manageable units and breaking down structural barriers (Xie et al., 2019; Kumari and Chelliah, 2024). Its proven success in sectors like finance, telecommunications, and IT demonstrates its capability to maximize resource utilization and simplify system scalability. Within the power industry globally, leading utilities and power generation enterprises are increasingly deploying digitalization and hyper-converged technologies to enhance resource allocation, although applications often remain concentrated within administrative domains rather than critical production control areas (Zhou et al., 2024; Xiang et al., 2024).

Security is paramount for digitalization deployment in hydropower control systems, which are a critical class of Industrial Automation and Control Systems (IACS) (Yang et al., 2023). The security architecture must therefore be designed according to internationally recognized IACS-specific standards, not generic IT guidelines. The IEC 62443 series of standards provides the primary framework for securing such systems (International Electrotechnical Commission, "IEC 62443-3-3:2013 Security for industrial automation and control systems—System security requirements and security levels," 2013). This framework mandates a risk-based approach centered on the concepts of zones and conduits, where assets are grouped into security zones based on functional and criticality requirements, with strict security policies governing all communications between them (conduits) (Stouffer et al., 2015). The integration of digitalization technologies fundamentally alters the security landscape and imposes new requirements within this framework.

To guarantee operational safety and continuity within the demanding context of hydropower monitoring systems, digitalization deployments necessitate redundant network architectures capable of maintaining functionality during hardware or software failures. Two primary architectural solutions are employed (Kumar and Saini, 2022), each presenting distinct trade-offs between cost, complexity, and recovery efficacy. The first, a Dual-Active Architecture, as shown in Figure 2a, utilizes two interconnected virtualized platforms (Clusters A and B) where virtual machines (VMs) run on one platform while their states (memory, storage, configuration) are continuously and synchronously mirrored to the other. A dedicated dual-active management software component monitors the heartbeat and health of all nodes. Upon failure detection in the primary platform (e.g., a server or switch failure), this management software automatically triggers a rapid switchover, promoting the mirrored VMs on the standby platform to an active state with minimal service interruption. The primary advantage of this model is its high availability and automated failover capability, which minimizes recovery time objectives (RTO). Based on this architecture, Liu et al. (2004) designed an automated safety monitoring system for the operational phase of the shiplock slope at Wuqiangxi Hydropower Station. The system incorporates several key features, including integrated monitoring of critical slope sections, thunderproof protection for instruments, all-weather displacement monitoring, advanced data management, and visual analysis capabilities. It effectively supports safety evaluation and decision-making, enhancing both flood-storage capacity and the safe operation of the shiplock. Bishwakarma and Støle (2008) developed a real-time sediment monitoring system for hydropower plants to address operational challenges caused by sediment accumulation in Run-of-River facilities built on sediment-laden rivers. The authors conducted sediment measurements in two Nepalese and one Indian hydropower plant using a real-time monitoring system developed at NTNU, supplemented by manual water sampling. However, it introduces significant complexity, requires expensive dedicated software, and can incur performance overhead due to constant synchronous data replication, potentially impacting the performance of latency-sensitive monitoring applications (Han et al., 2022). The alternative, an Independent Operation Architecture, as shown in Figure 2b, features two parallel, self-contained virtualized platforms running concurrently without direct, synchronous interconnection. Critical upper-level monitoring nodes (e.g., SCADA servers, historian servers) are distributed evenly across both platforms based on functional groups. The networks are typically routed to allow application-level communication between platforms for data coherence, but no direct VM state mirroring exists. If one platform fails entirely, the monitoring nodes on the other platform continue

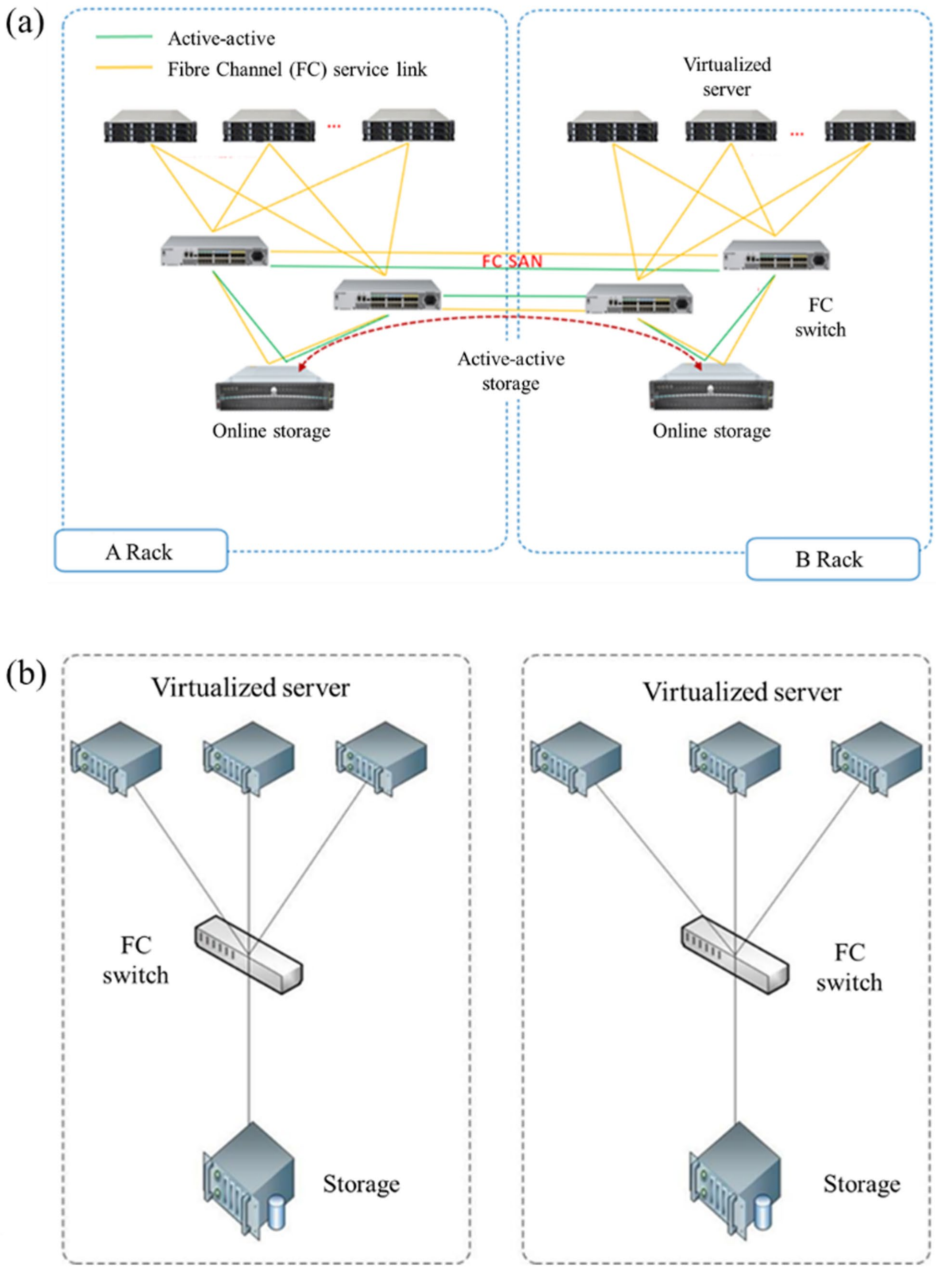

FIGURE 2
Redundant network architecture: **(a)** Dual-Active Architecture with a direct link for state mirroring and the dual-active manager facilitating automatic failover; **(b)** Independent Operation Architecture, showing two separate virtualization clusters with distributed monitoring nodes and routed network connectivity between them.

operating independently. The main advantage of this model is its simplicity, lower cost (no need for specialized mirroring software), and isolation of faults, preventing a single failure from cascading across both platforms. Based on this architecture, Zhang and Tongji (2011) developed an integrated hydro-data collection and analysis system to achieve multi-channel data acquisition and multifunctional analysis for hydropower applications. Utilizing advanced sensor, computer, and communication technologies, the system was successfully implemented at the TianQiao Hydropower Station. It collects critical turbine data—such as bearing throws and rack vibration—via a data acquisition module, which is then calibrated and stored in a database. Processed results are displayed through a human-machine interface, enabling effective monitoring and analysis. Its chief disadvantage is the lack of automatic VM recovery; any VMs on the failed platform require manual intervention to be restarted on the surviving platform, leading to a longer recovery time for those specific services. A comparative summary of the two architectures is provided in Table 1.

Finally, adapting digitalization to monitoring systems requires careful consideration of compatibility. The digitalization platform software must provide full support for the specific operating system (OS) chosen for the monitoring system's upper-level nodes to ensure seamless integration and prevent OS runtime anomalies. Additionally,

TABLE 1 Comparison of redundant architecture designs.

Feature	Dual-Active Architecture	Independent Operation Architecture
State synchronization	Synchronous, continuous mirroring	None; applications manage data
Failover mode	Automatic and rapid	Manual for VMs; services on surviving platform remain online
Recovery time objective (RTO)	Very low (seconds–minutes)	Higher (minutes–hours for manual VM recovery)
Complexity and cost	High (requires specialized software)	Lower (uses native virtualization features)
Performance impact	Potential overhead from replication	None from replication
Fault isolation	Lower (software defect could affect both)	High (platforms are independent)
Best suited for	Mission-critical control functions	Less critical services, distributed applications

given the extensive data synchronization requirements between upper-level nodes in monitoring systems, rigorous testing is essential to verify the timeliness and accuracy of inter-node communication within the virtualized environment.

5 Future perspectives on key hydropower digitalization technologies

Building upon the established applications and architectures, the future advancement of hydropower digitalization hinges on overcoming key technological challenges and harnessing emerging innovations. Enhanced interoperability between diverse digitalization platforms, edge computing capabilities, and heterogeneous data sources (IoT, SCADA, meteorological, hydrological, market) is crucial to fully realize the integrated potential demonstrated in optimized scheduling and ecological management. Significant progress is anticipated in the sophistication of digital twin models, moving beyond current descriptive and diagnostic capabilities toward truly predictive and prescriptive analytics. This evolution will leverage deeper integration of multi-physics simulations, hybrid AI models combining knowledge-based systems with machine learning, and near real-time data assimilation, substantially improving the accuracy of equipment health prognostics, failure prediction, and optimized maintenance strategies. Furthermore, the convergence of digitalization with next-generation communication technologies (e.g., 5G/6G, quantum-secure networks) promises to overcome current limitations in data latency and bandwidth, enabling truly responsive real-time control and remote operation capabilities essential for complex, geographically dispersed hydropower systems. Concurrently, developing robust, lightweight digitalization frameworks capable of deployment on resource-constrained edge devices near turbines, generators, and ecological monitoring points will be vital for enhancing local decision-making speed and resilience, particularly in remote locations. Finally, addressing the inherent cybersecurity challenges within increasingly interconnected virtualized environments requires continuous innovation in intrusion-tolerant digitalization architectures, zero-trust security models tailored for operational technology, and advanced cryptographic techniques for securing data integrity and access control across the entire digitalization lifecycle. Successfully advancing these core technologies will be paramount for unlocking the full potential of hydropower digitalization within the evolving global Energy Internet, driving unprecedented levels of efficiency, resilience, and environmental sustainability.

6 Conclusion

Hydropower digitalization stands as a pivotal technological enabler within the global Energy Internet framework, fundamentally transforming the operation, management, and integration of hydropower resources. By leveraging core principles such as resource abstraction, logical environment creation, and integrated data intelligence, digitalization significantly enhances operational efficiency, system flexibility, and grid stability. Beyond basic optimization, key applications include IoT-driven smart monitoring coupled with big data analytics for predictive maintenance, sophisticated digital twins for real-time equipment prognostics and dispatch optimization, advanced water resource scheduling that synergizes meteorological, hydrological, and grid signals, and ecological impact mitigation through intelligent environmental flow management and habitat simulation. While existing deployments—often implemented via dual-active or independent redundant architectures alongside stringent security protocols such as IEC 62443—demonstrate considerable value, future progress depends on overcoming several critical challenges. These include achieving seamless interoperability across heterogeneous systems, developing predictive and prescriptive digital twin capabilities, deploying high-bandwidth and low-latency communication infrastructures (e.g., 5G/6G), advancing edge computing for localized processing and resilience, and reinforcing OT-specific cybersecurity frameworks. Addressing these frontiers will unlock the full potential of hydropower digitalization, solidifying its role in building highly efficient, resilient, and environmentally sustainable global energy systems.

Author contributions

TC: Writing – original draft, Writing – review & editing. SG: Writing – original draft. XS: Writing – original draft. LM: Writing – original draft. BZ: Writing – review & editing. JZ: Writing – review & editing.

Funding

The author(s) declare that no financial support was received for the research and/or publication of this article.

Acknowledgments

We are thankful to the Western Maintenance and Testing Branch and Nanjing NARI Relay Protection Engineering Technology Co., Ltd. for the support.

Conflict of interest

TC, SG, and LM were employed by Southern Power Grid Energy Storage Co., Ltd. XS, BZ, and JZ were employed by Nanjing NARI Relay Protection Engineering Technology Co., Ltd.

Generative AI statement

The authors declare that no Gen AI was used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Ao, Y. Z., Bakar Siddik, M. A., Konar, M., and Marston, L. T. (2023). Food, energy, and water production within watersheds of the United States. *Water Resour. Res.* 59, 1–16. doi: 10.1029/2022wr034031

Bishwakarma, M. B., and Støle, H. (2008). Real-time sediment monitoring in hydropower plants. *J. Hydraul. Res.* 46, 282–288. doi: 10.1080/00221686.2008.9521862

Chalamalasetty, H. (2024). Enhancing operational data collection and risk management at hydroelectric dams by using digital twins. In Prof. Dossick's CM515 Spring 2024 Class, C. S. Dossick and L. Ray (eds), 2024 Innovation in the Construction Industry (University of Washington). Available at: https://uw.pressbooks.pub/2024innovationcm515/chapter/harikrishnas-chapterenhancing-operational-data-collection-and-risk-management-at-hydroelectric-dams/ (Accessed 26 September 2025).

Dao, F., Zeng, Y., and Qian, J. (2024). Fault diagnosis of hydro-turbine via the incorporation of bayeszian algorithm optimized CNN-LSTM neural network. *Energy* 290, 130326–130343. doi: 10.1016/j.energy.2024.130326

Ding, S. L., Pan, J. J., Wang, Y., Xu, H., Li, D. Q., and Liu, X. (2025). Developing a digital twin for dam safety management. *Comput. Geotech.* 180, 107120–107132. doi: 10.1016/j.compgeo.2025.107120

Fleming, S. W., Rittger, K., Oaida Taglialatela, C. M., and Graczyk, I. (2024). Leveraging next-generation satellite remote sensing-based snow data to improve seasonal water supply predictions in a practical machine learning-driven river forecast system. *Water Resour. Res.* 60, 1–32. doi: 10.1029/2023wr035785

Guo, Y., Xu, Y. P., Yu, X., Liu, L., and Gu, H. (2024). AI-based ensemble flood forecasts and its implementation in multi-objective robust optimization operation for reservoir flood control. *Water Resour. Res.* 60, 1–29. doi: 10.1029/2023wr035693

Guo, J., Zhang, Y., and Wang, W. (2024). Predicting hydro turbine failures through digital twin simulations of rare real-world data. *J. Comput. Methods Sci. Eng.* 2752, 1–13. doi: 10.1177/14727978241304260

Han, Z., Li, Y., Zhao, Z., and Zhang, B. (2022). An online safety monitoring system of hydropower station based on expert system. *Energy Rep.* 8, 1552–1567. doi: 10.1016/j.egyr.2022.02.040

Kumar, K., and Saini, R. P. (2022). Data-driven internet of things and cloud computing enabled hydropower plant monitoring system. *Sustain. Comput. Inform. Syst.* 36, 100823–100835. doi: 10.1016/j.suscom.2022.100823

Kumari, R., and Chelliah, T. R. (2024). Design and implementation of a redundant control system for variable speed hydro generators. *Int. J. Electr. Power Energy Syst.* 156, 109710–109722. doi: 10.1016/j.ijepes.2023.109710

Li, X., Zhang, J., Xiao, B., Zeng, Y., Lv, S., Qian, J., et al. (2024). Fault diagnosis of hydropower units based on Gramian angular summation field and parallel CNN. *Energies* 17, 3084–3102. doi: 10.3390/en17133084

Liu, D. A., Yang, Z. F., Tang, C. H., Wang, J., and Liu, Y. (2004). An automatic monitoring system for the shiplock slope of Wuqiangxi hydropower station. *Eng. Geol.* 76, 79–91. doi: 10.1016/j.enggeo.2004.06.007

Mishra, P., and Singh, G. (2023). Energy management systems in sustainable smart cities based on the internet of energy: a technical review. *Energies* 16, 6903–6938. doi: 10.3390/en16196903

Mousavi, S. J., and Ponnambalam, K. (2025). An analytical method for fast optimization of multireservoir hydropower systems operations considering risk-return tradeoffs. *Water Resour. Res.* 61, 1–18. doi: 10.1029/2024wr038520

Niu, W., Luo, T., Yao, X., Gong, J., Huang, Q., Gao, H., et al. (2024). Artificial intelligence-based response surface progressive optimality algorithm for operation optimization of multiple hydropower reservoirs. *Energy* 291, 130449–130462. doi: 10.1016/j.energy.2024.130449

Shui, J., Peng, D., Zeng, H., Song, Y., Yu, Z., Yuan, X., et al. (2024). Optimal scheduling of multiple entities in virtual power plant based on the master-slave game. *Appl. Energy* 376, 124286–124310. doi: 10.1016/j.apenergy.2024.124286

Siddik, M. A. B., Shehabi, A., Rao, P., and Marston, L. T. (2024). Spatially and temporally detailed water and carbon footprints of U.S. electricity generation and use. *Water Resour. Res.* 60, 1–13. doi: 10.1029/2024wr038350

Stouffer, K., Pillitteri, V., Lightman, S., Abrams, M., and Hahn, A. (2015). Guide to industrial control systems (ICS) security, special publication (NIST SP). Gaithersburg, MD: National Institute of Standards and Technology.

Sun, L., Xia, J., and She, D. (2024). Integrating model predictive control with stormwater system design: a cost-effective method of urban flood risk mitigation during heavy rainfall. *Water Resour. Res.* 60, 1–18. doi: 10.1029/2023wr036495

Tan, J., Radhi, R. M., Shirini, K., Gharehveran, S. S., Parisooz, Z., Khosravi, M., et al. (2025). Innovative framework for fault detection and system resilience in hydropower operations using digital twins and deep learning. *Sci. Rep.* 15, 15669–15696. doi: 10.1038/s41598-025-98235-1

Vagnoni, E., Gezer, D., Anagnostopoulos, I., Cavazzini, G., Doujak, E., Hočevar, M., et al. (2024). The new role of sustainable hydropower in flexible energy systems and its technical evolution through innovation and digitalization. *Renew. Energy* 230, 120832–120842. doi: 10.1016/j.renene.2024.120832

Xiang, C., Xu, X., Zhang, S., Qian, H., and Duan, Z. (2024). Current situation of small and medium-sized pumped storage power stations in Zhejiang Province. *J Energy Storage* 78, 110070–110078. doi: 10.1016/j.est.2023.110070

Xie, J., Wang, X., Yang, Z., and Hao, S. (2019). Virtual monitoring method for hydraulic supports based on digital twin theory. *Min. Technol.* 128, 77–87. doi: 10.1080/25726668.2019.1569367

Yang, F., Qiu, Z., Liu, D., Xu, F., Wu, H., and Wang, X. (2023). "Monitoring the operational status of Hydropower Station equipment based on digital twin and IoT technology" in 2023 International conference on artificial intelligence and automation control (AIAC) (Piscataway: IEEE), 288–291.

Yu, X., Zhang, S., Zhang, X., Yin, X., Qiu, W., Wang, Z., et al. (2024). A review of the recent research on hydraulic excitation-induced vibration in hydropower plants. *J. Phys. Conf. Ser.* 2752, 1–12. doi: 10.1088/1742-6596/2752/1/012093

Zhang, H., Guo, P., and Sun, L. (2020). Transient analysis of a multi-unit pumped storage system during load rejection process. *Renew. Energy* 152, 34–43. doi: 10.1016/j.renene.2019.12.111

Zhang, W., and Tongji, Z. (2011). Development and application of hydropower hydro monitoring system. *Procedia Eng.* 15, 807–811. doi: 10.1016/j.proeng.2011.08.150

Zhang, L., Wang, S., Yin, G., and Guan, C. (2020). Vibration transmission path identification in a hydropower house based on a time-delayed transfer entropy method. *J. Vib. Control.* 26, 1214–1227. doi: 10.1177/1077546319894810

Zhao, Z., Li, D., She, J., Zhang, H., Zhou, Y., and Zhao, L. (2021). "Construction and application of digital twin model of hydropower plant based on data-driven" in 2021 3rd international workshop on artificial intelligence and education (WAIE), 60–64.

Zhou, Y., Zhu, Y., Luo, Q., Wei, Y., Mei, Y., and Chang, F.-J. (2024). Optimizing pumped-storage power station operation for boosting power grid absorbability to renewable energy. *Energy Convers. Manag.* 299, 117827–117839. doi: 10.1016/j.enconman.2023.117827