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Embracing circular economy concepts in hydropower generation: A review of sustainable practices and future prospect

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Abstract. The continuous growth in global energy demand and the escalating environmental issues make the search for sustainable and environmentally friendly energy solutions an urgent task in today's era. In the face of this challenge, hydropower, as a primary representative of renewable energy, shoulders the responsibility of meeting the ever-growing demand. This review will delve into the significance of introducing the concept of a circular economy in hydropower and the potential benefits it may bring

Keywords: hydropower, circular economy, sustainability.

1. Introduction

In a global context, population growth and economic prosperity have led to a continuous surge in energy demand. However, traditional energy resources are gradually depleting, and excessive exploitation exacerbates adverse environmental impacts. Additionally, carbon emissions and environmental pollution pose significant threats to climate and ecosystems. Under this energy crisis, the concept of a circular economy has gained prominence. This idea aims to construct sustainable closed-loop systems, injecting new development impetus into the energy industry by maximizing resource utilization and minimizing environmental pollution.

Hydropower, as a leading position in the energy sector, emerges as an ideal choice for realizing the circular economy due to its renewable and clean characteristics. A profound understanding of the core concept of the circular economy, which involves recycling resources through closed-loop systems, provides a sustainable development path for the energy sector. In this process, the operational mechanisms of hydropower systems offer rich potential for circular economy applications, encompassing elements such as water resources, construction materials, turbine design, and more. By tapping into these potentials, this review hopes to contribute to the sustainable development and environmental protection of the global energy industry.

In the upcoming review, we will dive into the specific applications of the circular economy in hydropower, drawing insights from existing research and practical experiences in projects. Simultaneously, we will conduct an in-depth examination of the challenges and issues that may arise during this transformation, guiding the direction for future sustainable energy development. Through comprehensive research, this review aims to provide a profound understanding of circular economy

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practices in the hydropower sector, facilitating the energy industry's transition toward a more sustainable future.

2. Hydropower Overview

2.1. Basic Principles of Hydropower Generation

The fundamental principle of hydropower generation involves converting the kinetic energy of water into electrical energy. By directing the flow of water to drive a turbine, the kinetic energy of water transforms into mechanical energy. The turbine is connected to a generator, converting mechanical energy into electricity. In this process, the crucial factors influencing generation efficiency are the height difference and velocity of the water flow. Hydropower systems rely on this mechanism of converting water kinetic energy into electricity, providing a reliable and clean source of power for renewable energy.

2.2. Existing Hydropower Systems and Practices

Traditional hydropower systems typically consist of dams, reservoirs, turbines, and generators. Dams accumulate water, create reservoirs, and control the release of water flow to drive turbines. The turbines, in turn, power generators for electricity generation. This system is known for its high efficiency and stability, but the construction process may impact the surrounding environment, leading to issues such as ecosystem disruption and changes in land use.

To address the environmental impacts of traditional hydropower systems, research highlights projects and studies dedicated to enhancing the sustainability of hydropower. Firstly, through intelligent reservoir management systems, there is a focus on maximizing water resource utilization to optimize hydropower potential. This strategy aims for efficient power generation while emphasizing environmentally friendly recycling of water resources. Secondly, in terms of material and energy management, projects adhere to circular economy principles by using renewable and recyclable construction materials. The goal is to reduce adverse environmental impacts and improve the efficiency of dam and hydropower equipment construction. Finally, innovations in turbine design aim to enhance the efficiency of hydropower systems and prioritize eco-friendliness within aquatic ecosystems. Environmental design elements, such as reducing water flow disturbance and optimizing turbine structures, contribute to a more efficient system while positively impacting fish migration. These innovative approaches collectively drive the hydropower sector towards a more sustainable and environmentally friendly direction.

3. Application of Circular Economy in Hydropower Generation

3.1. Strategy for the Circulatory Utilization of Water Resources

Traditional hydropower faces a prominent issue, namely, the outflow and evaporation of water that may lead to a decline in the water level of reservoirs, thereby affecting the efficiency of hydropower generation. Faced with this challenge, the circular economy provides an innovative solution. Through the application of intelligent reservoir management and water circulation systems, the use of water resources can be optimized, ensuring the maximum utilization of hydropower potential while reducing the demand for fresh water. This sustainable management approach is expected to effectively address the issues faced by traditional hydropower generation, providing a new direction for the sustainable development of the energy industry.

In the current field of hydropower research, scholars are actively exploring innovative applications of intelligent reservoir management and water circulation systems. A key study done by Ming et al. emphasizes the integration of dispatchable hydropower generation with non-dispatchable photovoltaic generation, optimizing the efficiency of large-scale hydropower-photovoltaic hybrid stations through the establishment of adaptive operational rules [1]. This innovative integration helps ensure the maximum utilization of hydropower potential and the cyclical use of water resources. Additionally, another study from Tournier et al. delves into the negative impacts of sedimentation in reservoirs on water resource management, offering solutions, especially in the management practices of the Nathpa

Jhakri hydroelectric project in the Indian state of Himachal Pradesh. By addressing sedimentation issues in reservoirs, the active storage capacity of reservoirs can be maintained, ensuring sustained support for hydropower generation [2]. In terms of water resource utilization, the performance testing of the CSS algorithm its potential application in highly nonlinear real-value mathematical models provides a new approach to solving water resource management problems [3]. The application of this algorithm helps optimize water resource utilization strategies. Simultaneously, another study from Fang, Karki, and Prasanna Piya focuses on minimizing the adverse impacts of energy uncertainty under climate hydrological changes by integrating probability methods [4]. This integration is applied to the planning and operation of riverine and reservoir-type hydropower stations through daily, seasonal, and annual energy management strategies, ensuring optimal efficiency under various climatic conditions. In studies involving the maximization of hydropower potential, Zhou et al. propose an artificial intelligence-based water-floating photovoltaic power generation system, achieving multi-objective optimization through the Grasshopper optimization algorithm [5]. This innovative approach contributes to maximizing hydropower potential. Finally, a study on reducing the demand for freshwater introduces a novel photovoltaic-pumped storage microgrid design, which is more cost-effective compared to traditional photovoltaic battery systems [6]. The results indicate that by incorporating irrigation and water management, stored water resources can be more effectively utilized. This design not only helps maximize hydropower potential but also reduces the demand for fresh water.

These studies collectively form a comprehensive review, highlighting that through the innovative application of intelligent reservoir management and water circulation systems, the field of hydropower is moving towards a more sustainable and efficient future. In the literature mentioned above, while there are some positive aspects, there are also areas that may be subject to criticism or require further expansion. Ming et al. and Tournier et al. emphasize the importance of hydropower projects and reservoir management; however, they appear relatively limited in providing detailed information on the specific impacts related to ecosystems and how to minimize these impacts [1,2]. In-depth research into the sustainability of ecosystems is a critical direction for future work. Additionally, Tournier et al. mention the issue of reservoir sedimentation but lack in-depth research on the impacts on local communities and potential social issues, such as the resettlement of communities [2]. Social sustainability is an integral part of the overall success of hydropower projects. More comprehensive research on social impacts will contribute to a better understanding of the roles and influences of these projects in local communities. On the other hand, descriptions regarding economic and cost-benefit aspects are relatively scarce in the literature. More detailed economic analysis and cost-benefit assessments are crucial for a comprehensive understanding of the feasibility and sustainability of these projects. Research in this area will provide decision-makers with clearer information to make wise decisions during project implementation and operation, ensuring their long-term sustainability.

3.2. Circular Economy Management of Materials and Energy

The construction of traditional dams and hydraulic equipment often involves the use of conventional building materials, which may have negative impacts on local ecosystems and land. This environmentally impactful construction may lead to ecosystem destruction, soil erosion, and adverse effects on local communities. Renewable and recyclable construction materials can be employed to address this issue. By optimizing the design of dams and hydraulic equipment, the aim is to reduce adverse environmental effects and simultaneously increase the recyclability of construction materials. This strategy seeks to drive hydropower systems towards a more environmentally friendly and sustainable direction, better balancing the relationship between energy demand and environmental protection.

Current research provides in-depth insights into the circular economy management of materials and energy. Research from Whitehead, M. focuses on demonstrating the feasibility of using recyclable and natural fiber composite materials in the manufacturing of hydraulic turbine components from a design and manufacturing perspective [7]. The study emphasizes the application of composite materials in hydropower to reduce weight, simplify the manufacturing process, and, particularly in large-scale production, lower environmental impact. Quaranta and Davies offer a comprehensive discussion on the application of emerging materials in hydraulic engineering, with a specific focus on innovations to enhance the performance, durability, and reliability of hydraulic equipment. The application of composite materials in these areas provides technical support for designing more sustainable dams and hydraulic equipment, with the potential to increase the recyclability of building materials [8]. Somberg et al. concentrate on the importance of environmentally friendly lubrication downstream of hydroelectric stations, evaluating the friction performance of Polyphenylene Sulfide (PPS) and Ultra-High Molecular Weight Polyethylene (UHMWPE)-based composite materials through experiments [9]. This is closely related to the application of sustainable building materials in dam construction, providing substantial support for achieving environmentally friendly lubrication. Prabakaran Saravanan and Emami review the application of multi-scale thermoplastic polymer composite materials in hydroelectric power plants, highlighting the importance of green or sustainable lubrication [10]. The research outcomes of these composite materials offer new perspectives for addressing friction and wear issues in hydropower generation. Finally, Güllüoğlu, Bendeş, Yılmaz, and Yıldız introduce a method of manufacturing Pelton hydraulic turbines using composite materials on a 3D printer. The study demonstrates the potential of composite materials for rapid prototyping in the manufacturing process, providing empirical evidence for cost and time savings in designing and testing energy equipment [11]. This series of literature reviews highlights the potential advantages of sustainable building materials and composite materials in hydraulic engineering, including improved performance, extended lifespan, reduced environmental impact, and minimized resource waste. These studies provide robust support for the future development of hydraulic equipment, guiding more sustainable and innovative design and manufacturing directions.

While the above studies offer valuable insights into the application of sustainable building materials and composite materials in hydraulic engineering, some critical considerations are worth noting. Firstly, the lack of unified performance standards may affect the consistency assessment of composite materials' effects. Different studies adopt different performance standards, potentially leading to difficulties in comparing and synthesizing research results. Establishing more unified testing and assessment standards is crucial for a more comprehensive understanding of the actual performance of these materials. Secondly, there is a deficiency in lifecycle analysis. Current research primarily focuses on the manufacturing and performance stages of sustainable building materials and composite materials, lacking a comprehensive analysis of their environmental and social impacts throughout their entire lifecycle. Future research can strengthen the assessment of the lifecycle impacts of these materials from mining, manufacturing, use to disposal. This will help better understand their contributions to sustainable development goals while guiding future design and manufacturing directions.

3.3. Innovative Turbine Design

Environmentally friendly turbine technology is a key solution to addressing issues in traditional hydropower generation. Traditional turbine designs pose a range of problems, especially concerning potential negative impacts on aquatic ecosystems. These issues include water flow disturbances, pressure changes, and adverse effects on aquatic life. These adverse impacts can obstruct fish migration, disrupt the aquatic ecological balance, threaten biodiversity, and pose potential threats to the sustainability of fisheries and aquatic ecosystems. The principles of the circular economy provide guidance for addressing these problems. Adopting environmentally friendly turbine designs, aligned with the principles of the circular economy, can effectively mitigate the adverse impacts of water flow on ecosystems. This design approach aims to reduce water flow disturbances, improve hydrodynamic efficiency, and make turbines more adaptable to aquatic environments through structural optimization. Through these methods, environmentally friendly turbines can not only enhance energy utilization efficiency but also contribute to the preservation of the health of aquatic ecosystems. Therefore, introducing circular economy principles in turbine design is a crucial step in addressing issues in traditional hydropower generation. This approach not only facilitates the advancement of sustainable energy development but also contributes to maintaining aquatic ecological balance and promoting the sustainable use of water resources.

Research literature covers various aspects of hydraulic turbine technology, ranging from biological performance assessment to environmentally friendly design and the adoption of innovative technologies. Richmond et al. introduce a Hydraulic Turbine Biological Performance Assessment (BioPA) method to bridge the gap between field and laboratory studies on fish injury and turbine engineering design. The BioPA method, based on simulated data from Computational Fluid Dynamics (CFD) models, calculates a range of biological performance metrics to estimate the probability of barotrauma in juvenile fish passing through hydraulic turbines [12]. By comparing the performance metric values of various turbine designs, engineers and biologists can identify more promising designs and operating conditions to minimize hydraulic conditions harmful to passing fish. Hogan, Cada, and Amaral focus on environmentally enhanced hydraulic turbines to reduce harm and mortality to downstream migrating fish and improve downstream water quality [13]. The article summarizes significant progress made in this field over the past decade, emphasizing the excellent performance of Voith Hydro’s Minimum Gap Runner turbine. While maintaining a high fish survival rate, this design is more efficient in electricity generation than traditional designs. However, similar full-scale demonstrations for Alden turbines have not been conducted, and the article mentions continuous improvements in tools for predicting and assessing the performance of new turbine designs. Olbertz, N. investigates the impact of hydroelectric power stations on ecosystems, with a particular focus on years of research into fish mortality and injury types. The article emphasizes the dangers of fast-moving turbine blades to living organisms and proposes different types of turbines developed to improve survival rates [14]. The article introduces five different turbine designs developed by various research groups and manufacturers, achieving fish survival rates ranging from 96% to 100%. Quaranta et al. provide a series of case studies for hydropower stations, covering aspects such as low-head hydraulic turbines, ecological improvement technologies, digitization, and governance systems. The article suggests that the adoption of new technologies and practices is expected to improve hydropower station efficiency and flexibility while reducing potential impacts on aquatic ecosystems [15]. The authors present some representative cases covering ecological improvements and low-head hydraulic turbine converters, water peak reduction, digitization, and governance systems, emphasizing the possibility of better balancing carbon reduction and ecosystem protection goals. Quaranta, Pérez-Díaz, Romero–Gomez and Pistocchi focus on environmentally friendly turbine technology aimed at reducing the environmental impact of hydropower stations on fish communities and water quality. The review emphasizes the effectiveness of environmentally friendly turbines, with a particular focus on Alden and Minimum Gap Runner turbines, to reduce fish injuries and improve water quality [16]. Although the article highlights the cost-effectiveness and the ability to reduce the environmental impact of environmentally friendly turbines, it also points out scientific gaps and calls for further efforts to achieve greater fish survival and water quality improvement.

These articles collectively reveal innovation and challenges in the field of hydraulic turbine technology, covering aspects of biological performance assessment, environmentally friendly design, and the adoption of new technologies and practices. They collectively emphasize the importance of striking a balance between pursuing carbon reduction and ecosystem protection goals, providing valuable insights for the future development of hydraulic turbine technology. However, at the same time, the inconsistency in evaluation criteria poses a barrier to the generalizability of the literature. Richmond et al. introduce a biological performance assessment method that calculates a range of biological performance metrics based on simulated data from Computational Fluid Dynamics (CFD) models [12]. However, different studies use different performance standards to evaluate the effectiveness of composite materials, potentially leading to inconsistency in results. Establishing more uniform testing and evaluation standards will help achieve a more comprehensive understanding of the actual performance of these materials.

4. Prospects

With continuous technological advancements and policy initiatives, the future of hydropower will witness broader sustainable practices. New development trends will encompass various aspects, with one of the primary ones being intelligent development. As technologies such as artificial intelligence and the Internet of Things continue to innovate, hydropower will achieve a higher degree of intelligence, including automation, remote operation, and precision, thereby enhancing its efficiency and reliability.

Another significant trend is diversified utilization. Future hydropower will not only focus on traditional power generation functions but will actively explore integration with fields such as tourism, irrigation, aquaculture, etc., aiming to achieve the goal of multiple uses of water and comprehensive utilization. This diversified utilization not only contributes to improving the overall benefits of hydropower projects but also brings more sustainability and innovation to social and economic development.

These development trends indicate that future hydropower will become a more intelligent and multifunctional system, providing a more comprehensive and integrated solution for the development of sustainable energy. This is not only crucial for improving the efficiency of hydropower generation but also creates broader possibilities for collaborative development in different fields.

5. Conclusion

As global energy demand continues to grow and environmental concerns become increasingly prominent, hydropower plays a crucial role as a renewable energy source that will become even more important in the future. The rise of the circular economy concept provides new perspectives and opportunities for the sustainable development of hydropower systems.

Under the guidance of the circular economy, current hydropower systems are gradually transforming, enhancing their sustainability through strategies such as the recycling of water resources and the circular management of materials and energy. Innovations in turbine design, particularly with a focus on friendly operations for aquatic life, have not only improved efficiency but have also marked a significant step forward for the hydropower industry in the direction of environmental responsibility.

Future prospects indicate that with continuous technological advancements and policy support, hydropower will embrace more widespread sustainable practices. The development of intelligence will make hydropower systems smarter and more automated and will enhance efficiency and reliability. The trend towards diversified utilization will transform hydropower into not just a tool for energy production but an integrated system combined with fields such as tourism, irrigation, and aquaculture, resulting in more comprehensive societal benefits.

Therefore, the hydropower industry is poised to integrate more effectively into the circular economy concept in its future development, promoting the sustainable utilization of renewable energy and making a more positive contribution to global energy and environmental sustainability.

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