



COMPREHENSIVE OVERVIEW OF HYDROPOWER TECHNOLOGY

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ABSTRACT: This study provides a comprehensive overview of hydropower technology, tracing its historical evolution from ancient applications to modern developments. As the most established form of renewable energy, hydropower has significantly contributed to global energy demands. The chapter discusses the origins of hydropower in ancient civilizations, the transition to electricity generation in the late 19th century, and the massive growth of large dam constructions in the 20th century. Recent trends emphasize environmental considerations, leading to a focus on sustainable practices, innovative technologies, and smaller-scale systems such as run-of-the-river hydropower. The manuscript also highlights challenges, such as balancing energy production with ecological sustainability, and underscores the importance of community engagement and regulatory frameworks. Ultimately, the text advocates for the modernization of existing facilities and the integration of hydropower with other renewable energy sources to enhance sustainability and contribute to a resilient energy future.

KEYWORDS: *Hydropower Technologies; Renewable Energy; Environmental Sustainability; Small-scale Systems.*

1. INTRODUCTION

Hydropower is notably the most established form of renewable energy and has played a critical role in meeting global energy demands for thousands of years. This chapter elucidates the historical evolution of hydropower, from its ancient origins to the modern era. It highlights large-scale developments in the 20th century and discusses current environmental considerations impacting this vital energy source. Understanding hydropower technology not only sheds light on its operational mechanisms but also on its potential for sustainable development.

2. ANCIENT TIMES: Origins of Hydropower

The history of hydropower can be traced back to ancient civilizations over two millennia ago. One of the earliest applications of hydropower is believed to have occurred in ancient Rome, where water wheels were employed primarily for milling grain. These primitive devices harnessed the kinetic energy of flowing water to power mechanisms that ground grains into flour, demonstrating humans' innovative use of natural resources for agricultural efficiency [1].



This technology gradually spread, with significant developments arising in other civilizations, such as the Greeks and Persians, where similar techniques for irrigation and milling were adapted. The ingenuity of water wheels continued to evolve through the Middle Ages, leading to widespread adoption across Europe and Asia. This historical utilization laid the foundation for future hydropower applications and showcased the potential of hydraulic power in human society [2].

3. DEVELOPMENT IN THE 19TH CENTURY

The late 19th century marked a pivotal moment in the evolution of hydropower with advancements linked to the dawn of electricity. The transformation from mechanical to electrical applications began with the first commercial hydroelectric power plant becoming operational in 1882 in Appleton, Wisconsin. This facility utilized flowing water to spin a turbine, generating electricity and demonstrating the practical applications of hydropower in industrial development [3].

This era also witnessed significant technological advancements, leading to the establishment of more efficient and larger-scale hydropower plants. By the end of the century, hydropower was recognized as a reliable energy source, crucial for urban and industrial growth.

4. 20TH CENTURY: Growth and Large Dam Construction

The 20th century experienced unprecedented growth in hydropower, primarily fueled by the construction of large dams worldwide. The completion of the Hoover Dam in 1936 illustrated this shift; the dam serves as a symbol of engineering prowess, providing flood control, irrigation, and hydroelectric power to millions in the American Southwest.

Large dams significantly increased hydropower capacity globally, making it a major contributor to the energy mix. By the mid-20th century, hydropower accounted for a substantial share of the total electricity generated worldwide, reaching its peak during the 1970s. Important projects like the Itaipu Dam, shared by Brazil and Paraguay, began operations in 1984 and remains one of the largest hydroelectric power plants globally in terms of electricity generation [4].

Infrastructural investments extended to various continents, with large-scale dams constructed in Africa, Asia, and Europe to cater to growing energy needs. These expansive projects not only led to significant energy production but also generated socio-economic development by improving infrastructure, providing jobs, and enhancing local agricultural productivity [5].

However, the widespread construction of large hydropower projects has drawn criticism due to adverse environmental impacts, including ecosystem disruption, habitat loss, and effects on water quality and flow regimes.



5. MODERN ENVIRONMENTAL CONSIDERATIONS AND INNOVATIONS

In recent decades, heightened awareness of environmental concerns has prompted a reevaluation of large hydropower projects. The ecological consequences of dam development led researchers to focus on alternative technologies that minimize adverse effects. The spotlight has increasingly shifted to smaller-scale systems, such as run-of-the-river hydropower, which generates electricity without significant reservoir construction [6].

- **Run-of-the-River Hydropower:** Run-of-river systems utilize the natural flow of rivers to generate electricity, converting a portion of the river's energy into usable power while causing minimal disruption to the overall watercourse. These systems typically have a lower environmental footprint compared to traditional dams and can sustain river ecology, support aquatic life, and maintain downstream communities [7].
- **Environmental Impact Assessments:** Environmental Impact Assessments (EIAs) are now a crucial part of evaluating potential hydropower projects. EIAs assess the potential ecological, social, and economic impacts of proposed developments, ensuring compliance with environmental regulations and fostering sustainable practices. Recent studies emphasize the integration of socio-economic and ecological considerations into EA processes, promoting balanced and responsible hydropower development [8].
- **Innovative Technologies:** Emerging technologies in hydropower are focused on enhancing sustainability. Adaptive management approaches that involve continuous monitoring and operational adjustments based on ecological data can significantly reduce the negative impacts of hydropower facilities. Innovations such as fish-friendly turbine designs are making strides in minimizing harm to aquatic life during energy generation [9].

6. CURRENT TRENDS AND FUTURE DIRECTIONS

The transition towards low-carbon and sustainable energy solutions reinforces hydropower as a cornerstone of the renewable energy landscape. Current trends in the hydropower sector indicate a multifaceted approach that emphasizes modernization, environmental sustainability, community engagement, and technological innovation.

- **Modernization of Existing Facilities:** Many existing hydropower plants are now undergoing significant upgrades aimed at improving efficiency and operational output. Modernization initiatives often encompass retrofitting aging equipment, enhancing turbine efficiency, and integrating advanced automation and control systems. These upgrades not only increase energy production but also extend the operational lifespan of facilities [10]. Particularly, hydropower plants older than 50 years are benefiting greatly from these modernization efforts, as upgrading systems can lead to marked improvements in efficiency and reductions in operational costs compared to building new facilities [11].
- **Integration with Other Renewable Sources:** The hybridization of hydropower with other renewable energy technologies such as solar and wind is becoming increasingly prevalent. This integrated approach leverages the complementary characteristics of various energy sources, enabling hydropower systems to stabilize the intermittency associated with solar and wind energy. For example, during periods of high solar



output, surplus energy can be used to pump water back to elevated reservoirs, which can then be released during peak demand hours when other renewable sources might be underperforming [12]. Pumped-storage hydropower systems are especially important for energy storage in the context of grid management, providing flexibility in energy dispatch and contributing to grid stability as variable renewable energy sources continue to expand their presence [13], [14].

- **Enhanced Environmental Stewardship:** With a growing emphasis on environmental sustainability, the hydropower sector is increasingly adopting practices aimed at minimizing ecological disruption. Today's hydropower projects often incorporate innovative designs and technologies that prioritize environmental preservation. Measures such as fish ladders and bypass channels are designed to ensure that migratory species can safely pass through hydropower facilities, mitigating the impacts on local ecosystems [15]. Moreover, developing guidelines and best practices for the responsible operation of hydropower plants is crucial for habitat preservation and biodiversity [16].
- **Community Engagement and Social Licensing:** Community engagement has emerged as a vital aspect of successful hydropower project development. Gaining social license to operate involves public acceptance and support, which requires transparent involvement of stakeholders and effective communication strategies from project developers. Engaging with local communities helps build trust and minimizes conflict, ultimately enhancing project success [17]. In recent years, various hydropower initiatives have included community development programs that aim to empower local economies through job creation and infrastructure enhancements while ensuring that affected communities gain tangible benefits from the projects' presence.

7. CHALLENGES AND AREAS FOR IMPROVEMENT

Despite the promising outlook for modern hydropower, several challenges persist. Among them, the need to balance energy production with ecological sustainability is paramount. Addressing these challenges requires ongoing research focused on:

- **Technological Innovations:** Continuing the development of advanced turbine designs that are less harmful to aquatic life and capable of functioning in low-flow conditions.
- **Environmental Research:** Conducting comprehensive studies to evaluate the long-term ecological impacts of hydropower on fish populations and local ecosystems.
- **Regulatory Frameworks:** Ensuring that legislation and policy frameworks support sustainable hydropower development while protecting ecological integrity.

8. SUMMARY

The comprehensive overview of hydropower technology illustrates its historical significance, current advancements, and future prospects. As a key player in the renewable energy sector, hydropower stands poised to contribute to a sustainable energy future. By embracing modern technologies and practices, the hydropower industry can enhance its contributions to global energy demands while aligning with broader goals for environmental sustainability and economic resilience.



REFERENCES

- [1] C. Teodoro, "Harnessing Hydroelectric Energy from Water Irrigation Pumps: A Sustainable Lighting Solution for Agricultural Fields and Fishponds," *E3S Web Conf.*, vol. 488, Feb. 2024, doi: 10.1051/e3sconf/202448802014.
- [2] H. Ardiansyah, "Hydropower Technology: Potential, Challenges, and the Future," *Indones. Post-Pandemic Outlook Strateg. Towar. Net-Zero Emiss. by 2060 from Renewables Carbon-Neutral Energy Perspect.*, pp. 89–107, 2022, doi: 10.55981/brin.562.c6.
- [3] I. Kougias et al., "Analysis of emerging technologies in the hydropower sector," *Renew. Sustain. Energy Rev.*, vol. 113, p. 109257, 2019, doi: <https://doi.org/10.1016/j.rser.2019.109257>.
- [4] C. Llamosas and B. K. Sovacool, "Transboundary hydropower in contested contexts: Energy security, capabilities, and justice in comparative perspective," *Energy Strateg. Rev.*, vol. 37, p. 100698, 2021, doi: <https://doi.org/10.1016/j.esr.2021.100698>.
- [5] A. Bathaei and D. Štreimikienė, "Renewable Energy and Sustainable Agriculture: Review of Indicators," *Sustainability*, vol. 15, no. 19, 2023. doi: 10.3390/su151914307.
- [6] A. Elbatran, M. Refae, O. Yaakob, Y. Ahmed, and M. Ismail, "Hydro Power and Turbine Systems Reviews," *J. Teknol. (Sciences Eng.)*, vol. 74, pp. 83–90, May 2015, doi: 10.11113/jt.v74.4646.
- [7] D. Anderson, H. Moggridge, P. Warren, and J. Shucksmith, "The impacts of 'run-of-river' hydropower on the physical and ecological condition of rivers: Physical and ecological impacts of ROR hydropower," *Water Environ. J.*, vol. 29, Nov. 2014, doi: 10.1111/wej.12101.
- [8] K. Joseph, S. Eslamian, K. Ostad-Ali-Askari, M. Nekooei, H. Talebmorad, and A. Amiri, "Environmental Impact Assessment as a Tool for Sustainable Development," 2018, p. <https://link.springer.com/referenceworkentry/10.1007%2F978-3>.
- [9] A. Kuriqi, A. N. Pinheiro, A. Sordo-Ward, M. D. Bejarano, and L. Garrote, "Ecological impacts of run-of-river hydropower plants—Current status and future prospects on the brink of energy transition," *Renew. Sustain. Energy Rev.*, vol. 142, p. 110833, 2021, doi: <https://doi.org/10.1016/j.rser.2021.110833>.
- [10] D. Morgado, N. Troja, A. Kadyrzhanova, and D. Samuel, "Hydropower Modernization Needs in Asia," no. 1, pp. 1–22, 2020.
- [11] L. Chen et al., "Green building practices to integrate renewable energy in the construction sector: a review," *Environ. Chem. Lett.*, vol. 22, no. 2, pp. 751–784, 2024, doi: 10.1007/s10311-023-01675-2.
- [12] C. Hill, M. Such, D. Chen, J. Gonzalez, and W. M. Grady, "Battery Energy Storage for Enabling Integration of Distributed Solar Power Generation," *Smart Grid, IEEE Trans.*, vol. 3, pp. 850–857, Jun. 2012, doi: 10.1109/TSG.2012.2190113.
- [13] P. C. Nikolaos, F. Marios, and K. Dimitris, "A Review of Pumped Hydro Storage Systems," *Energies*, vol. 16, no. 11, 2023. doi: 10.3390/en16114516.
- [14] L. Al-Hadhrami, "Pumped hydro energy storage system: A technological review," *Renew. Sustain. Energy Rev.*, vol. 44, Apr. 2015, doi: 10.1016/j.rser.2014.12.040.
- [15] R. Panchan, P. Rauch, G. Unfer, and K. Pinter, "Downstream migration and hydropower dam passage of a Danubian cyprinid, *Rutilus meidingeri*, at the Seeache River, Austria," *J. Nat. Conserv.*, vol. 76, p. 126513, 2023, doi: <https://doi.org/10.1016/j.jnc.2023.126513>.
- [16] E. P. Framework and D. Process, "Update of Recommendations for Hydropower and the Environment," 2010.
- [17] M. Ezeh, A. Ogbu, A. H. Ikevuje, and E. George, "Stakeholder engagement and influence: Strategies for successful energy projects," *Int. J. Manag. Entrep. Res.*, vol. 6, pp. 2375–2395, Jul. 2024, doi: 10.51594/ijmer.v6i7.1330.