

Improvement Potential Hydroelectric Power (Hydropower) Supports Global Sustainability

Leony Ariesta Wenno, Axl J.V Ngantung, Arauna P Batudaka, Kelvinsky N Wokas, Dirly Lumempow

Politeknik Negeri Manado, Indonesia

Emails: leonywenno@elektro.polimdo.ac.id, axlNgantung34@gmail.com,
araunaputri08@gmail.com, kelvinskynatanaelwokas@gmail.com,
dirlylumempow06@gmail.com

Abstract

Hydroelectric Power Plant (PLTA) is a renewable energy source that plays an important role in fulfilling electricity needs in a sustainable way. This study aims to comprehensively analyze the development potential of hydroelectric power plants in supporting global energy sustainability by examining technical efficiency, economic viability, environmental impacts, and social implications through systematic evaluation of international best practices and mitigation strategies. The research methodology employs a systematic literature review approach, analyzing data from peer-reviewed academic journals, international energy organization reports (IEA, IRENA, WEC), and policy documents from multiple countries including Norway, Canada, Brazil, and China, with data categorized into technical, economic, environmental, and social aspects for comprehensive evaluation. Research results show that the hydroelectric power plant has superiority in provide electricity with supply stable and efficient high. Key findings demonstrate that modern hydroelectric technologies achieve remarkable performance: Kaplan and bulb turbines increase energy conversion efficiency significantly, Pumped-Storage Hydroelectricity (PSH) technology enhances system flexibility and grid stability, operational costs remain 60% lower than fossil fuel plants over long-term periods, and hydropower contributes to avoiding over 3 billion tonnes of CO₂ emissions annually while supporting flood control and water resource management. The research implications indicate that successful hydropower development requires integrated approaches combining technological innovation, supportive policies, environmental protection measures, and active community engagement to achieve optimal sustainability outcomes while maintaining economic viability and social acceptance.

Keywords: Hydroelectric Power, Potential, Sustainability, Needs, Energy

**Correspondence Author: Leony Ariesta Wenno*

Email: leonywenno@elektro.polimdo.ac.id



INTRODUCTION

Global electricity energy needs continue to experience improvement along with population growth, industrialization, and increasing economic activity (Islam et al., 2014; Scheffran et al., 2020; Stern & Kander, 2012). In recent decades, dependency on fossil fuels as the main source of electrical energy has caused various environmental problems, such as increased greenhouse gas emissions, air pollution, and global climate change (International Energy Agency, 2021). To overcome these challenges, the transition to renewable energy sources has become a main priority to create an electricity system that is more environmentally friendly, efficient, and sustainable (International Renewable Energy Agency, 2020).

Hydroelectric Power Plant (PLTA) is one of the renewable energy sources which has great potential in fulfilling electricity needs in a stable and sustainable way. Hydroelectric power works by utilizing potential and kinetic energy from water flow to move turbines, which are then converted into electrical energy through generators (World Energy Council, 2019). Based on the International Hydropower Association report (2021), hydropower contributes more than 60% of total renewable electrical energy in the world, making it the largest clean energy source compared to solar and wind power. One of the main advantages of PLTA is its ability to provide electricity continuously with high efficiency levels, different from other

renewable energy sources that tend to fluctuate because they depend on weather conditions. Besides that, pumped-storage hydroelectricity (PSH) technology enables hydroelectric power plants to store excess energy when demand is low and use it again when electricity demand increases, thus helping to increase electricity network stability (World Bank, 2021).

From an economic perspective, although the initial investment for hydroelectric power plant development is relatively large, in the long term this technology is more profitable because of its low operational costs and long operational lifespan (Pacca & Moreira, 2009). In addition, with the existence of incentive policies and subsidies from the government, the hydropower sector is increasingly attractive to investors who want to contribute to the clean energy transition (Kumar et al., 2011). However, although it has many advantages, the development of hydroelectric power plants also faces various challenges, especially related to environmental and social impacts. The construction of dams and hydroelectric power plant infrastructure can cause changes to river ecosystems, disturbing the habitat of aquatic flora and fauna, as well as affecting the lives of surrounding communities (Schweiger & Lorang, 2020). Therefore, mitigation strategies are needed such as the application of fish ladders, bypass systems, and minimum water release policies (environmental flow) to maintain aquatic ecosystem balance (Wang, Dong, & Liu, 2021). In addition, community involvement in the planning and implementation process of hydropower projects is very important to ensure that these projects can be socially accepted and run sustainably (United Nations Environment Programme, 2022).

The urgency of developing sustainable hydroelectric power has become increasingly critical due to several converging global factors. First, the accelerating pace of climate change requires immediate and substantial reductions in greenhouse gas emissions, making renewable energy deployment essential for achieving the Paris Agreement targets of limiting global warming to 1.5°C. Second, the growing global energy demand, projected to increase by 50% by 2050, necessitates massive expansion of clean energy capacity to meet this demand while simultaneously phasing out fossil fuels. Third, increasing extreme weather events and water scarcity issues highlight the need for integrated water-energy management solutions that hydropower can provide through its dual function as energy generator and water resource management system.

Previous research has established a substantial foundation for understanding hydropower's role in sustainable energy systems. Kumar et al. (2011) conducted comprehensive analysis of hydropower's contribution to climate change mitigation through the IPCC Special Report, demonstrating significant potential for emission reductions. Pacca and Moreira (2009) developed models for sustainable hydropower generation, establishing frameworks for balancing energy production with environmental protection. Zarfl et al. (2015) analyzed the global boom in hydropower dam construction, revealing both opportunities and challenges in large-scale deployment. Recent studies by Wang, Dong, and Liu (2021) examined China's large-scale hydropower implementation and its role in achieving carbon neutrality, providing valuable insights into policy frameworks and technological innovations. Schweiger and Lorang (2020) investigated environmental impacts, highlighting the importance of comprehensive mitigation strategies for ecosystem protection.

However, significant research gaps remain in current hydropower literature. Most existing studies focus on individual aspects such as technical efficiency, economic analysis, or environmental impacts in isolation, lacking comprehensive integration of all sustainability dimensions. Limited research has systematically evaluated the synergistic effects of combining advanced hydropower technologies with innovative environmental mitigation strategies and community engagement approaches. Furthermore, there is insufficient analysis of how different national policy frameworks and geographical contexts influence hydropower sustainability outcomes.

The novelty of this research lies in its comprehensive, multi-dimensional approach to analyzing hydropower sustainability that integrates technical efficiency, economic viability, environmental protection, and social acceptance as interconnected components of sustainable development. This study fills the research gap by providing systematic comparative analysis of international best practices and developing an integrated framework for evaluating hydropower projects across multiple sustainability criteria.

The primary objective of this research is to analyze the development potential of Hydroelectric Power Plants (PLTA) as sustainable energy sources, considering technical, economic, environmental, and social aspects comprehensively. Secondary objectives include evaluating the efficiency of hydropower technology in electricity systems, identifying advantages and challenges in implementation, reviewing environmental and social mitigation strategies needed to increase hydropower sustainability, and developing recommendations for optimal and sustainable hydropower development. The research benefits include providing evidence-based guidelines for policymakers and investors in hydropower development, contributing to global sustainable energy transition strategies, offering frameworks for balancing energy production with environmental and social responsibility, and supporting the achievement of United Nations Sustainable Development Goals related to clean energy and environmental protection. The implications of this study extend to informing international energy policy, supporting climate change mitigation efforts, and promoting sustainable development practices in the energy sector.

This study aims to analyze the development potential of Hydroelectric Power Plants (PLTA) as sustainable energy sources, considering technical, economic, environmental, and social aspects. In addition, this research also aims to evaluate the efficiency of hydropower technology in electricity systems, identify advantages and challenges in its implementation, as well as review environmental and social mitigation strategies needed to increase hydropower sustainability. By understanding various aspects, this research is expected to provide deeper insights about the role of hydropower in future energy systems as well as provide recommendations for more optimal and sustainable hydropower development.

RESEARCH METHOD

This study uses a descriptive qualitative method with a literature study approach to analyze Hydroelectric Power Plant (PLTA) development in the context of global sustainability. This approach was chosen because it allows deep exploration of various sources of information related to hydroelectric power, including technical, economic, environmental and social aspects, as well as to identify existing trends, challenges and opportunities. Literature studies allow researchers to collect data from various trusted sources, such as scientific journals from academic platforms (ScienceDirect, IEEE Xplore, Springer, Google Scholar), energy industry reports from international institutions (IEA, IRENA, WEC), as well as government policies and documents from organizations such as UNEP, UNDP, and the World Bank.

Data collection was carried out systematically through several stages, starting with the selection of relevant literature using special keywords such as "sustainability of hydroelectric power plants", "renewable energy policy", and "hydropower economic feasibility". The collected data was then classified into four main categories, namely technical, economic, environmental and social, to facilitate further analysis. To ensure data quality, verification was carried out to ensure that the sources used were credible and reliable publications.

Technical analysis covers evaluation of energy conversion system efficiency, environmentally friendly turbine technology, as well as implementation of pumped-storage hydroelectricity (PSH) systems. On the economic side, this research studies development costs, operations, and comparison of the Levelized Cost of Energy (LCOE) of hydroelectric power

plants with other energy sources. In environmental aspects, this research evaluates the impact of hydropower on river ecosystems and biodiversity, as well as mitigation efforts implemented, such as fish ladders. From a social perspective, this research studies local community involvement and social impacts related to resident relocation as well as potential conflicts in the use of water resources.

As part of the analysis, this research also compares hydropower development policies in countries such as Norway, Canada, Brazil and China that have succeeded in optimizing sustainable hydropower. By using this literature study approach, the research aims to provide a deep understanding of the factors that influence hydropower development and its contribution to efficient and socially sustainable energy management in various countries.

RESULTH AND DISCUSSION

Research results show that Hydroelectric Power Plant (PLTA) has great potential in supporting global sustainability through the utilization of sophisticated technology, economic efficiency, as well as its contribution in reducing carbon emissions. From the technical aspect, innovations like Kaplan turbines and bulb turbines have increased the efficiency of converting water energy into electricity. Besides that, the application of pumped-storage hydroelectricity (PSH) has been proven effective in maintaining energy supply balance, while the integration of automation based on artificial intelligence (AI) in hydropower operations is capable of increasing efficiency and optimizing energy production. From the economic aspect, although the initial investment of hydroelectric power plants is classified as large, its operational costs are lower compared to electricity generators based on fossil fuels. The Levelized Cost of Energy (LCOE) calculation shows that in the long term, hydropower plants are more economical and can produce significant benefits, especially with the existence of government incentives and renewable energy policies that support investment in this sector.

From the environmental aspect, research shows that hydropower contributes significantly in reducing greenhouse gas emissions and supporting clean energy transition. From the social side, community engagement in planning and management of hydroelectric power plants becomes an important factor in ensuring project sustainability. Some countries that have succeeded in developing hydroelectric power plants, such as Norway, Canada, Brazil, and China, show that the right policies as well as the implementation of modern technology are capable of increasing hydroelectric power efficiency while maintaining environmental balance and social welfare.

Discussion

Hydroelectric Power Plant (PLTA) represents a critical renewable energy source that plays an important role in fulfilling electricity needs sustainably. This research comprehensively analyzes the development potential of hydroelectric power in supporting global energy sustainability across technical, economic, environmental and social dimensions using descriptive qualitative methodology based on systematic literature studies.

Technical Excellence and Technological Innovation

Research results demonstrate that hydroelectric power plants possess superiority in providing electricity with stable supply and high efficiency. Advanced turbine technologies, particularly Kaplan and bulb turbines, have significantly enhanced energy conversion efficiency from water flow to electricity generation. The implementation of Pumped-Storage Hydroelectricity (PSH) technology has revolutionized system flexibility by enabling energy storage during low-demand periods and release during peak demand, thereby stabilizing electrical grid operations. Furthermore, the integration of artificial intelligence (AI)-based automation systems in hydropower operations has dramatically improved operational

efficiency and energy production optimization through predictive maintenance, real-time monitoring, and adaptive control systems.

Economic Viability and Long-term Profitability

From an economic perspective, while initial investment for hydroelectric power plant development requires substantial capital, the long-term operational costs remain significantly lower compared to fossil fuel-based electricity generation. Comprehensive Levelized Cost of Energy (LCOE) analyses demonstrate that hydropower plants achieve superior economic performance over their operational lifetime, typically 50-100 years, providing stable and predictable energy costs. Government incentive policies, including feed-in tariffs, tax credits, and streamlined permitting processes, have made hydropower investments increasingly attractive to both public and private investors seeking to contribute to clean energy transition while achieving profitable returns.

Environmental Contributions and Mitigation Strategies

Research findings reveal that hydropower provides substantial environmental benefits while presenting manageable challenges through appropriate mitigation strategies. Hydroelectric power plants contribute significantly to greenhouse gas emission reduction by avoiding over 3 billion tonnes of CO₂ annually through displacement of fossil fuel-based electricity generation. This contribution is essential for achieving Net-Zero Emission (NZE) targets by 2050 as outlined in the Paris Agreement.

However, environmental challenges require systematic mitigation approaches. The construction of dams and reservoirs can alter river ecosystems, affecting aquatic habitat connectivity and biodiversity. Effective mitigation strategies have been successfully implemented, including: (1) Fish ladder systems that enable fish migration past dam structures, resulting in population recovery rates of up to 20% in documented cases; (2) Bypass systems that maintain natural river flow patterns while allowing continued ecosystem function; (3) Environmental flow policies ensuring minimum water release to preserve downstream ecosystem health; (4) Advanced reservoir management using AI-based systems to optimize water temperature and dissolved oxygen levels.

Social Impacts and Community Engagement Strategies

The social dimension of hydropower development encompasses both significant benefits and challenges requiring careful management. Positive social impacts include substantial job creation during construction and operational phases, with large projects generating tens of thousands of employment opportunities. Rural electrification through hydropower development has increased electrification rates in developing regions, improving quality of life and supporting economic development.

However, social challenges, particularly population relocation due to reservoir creation, require comprehensive mitigation strategies. Successful approaches implemented in various countries include: (1) Meaningful community consultation throughout project planning and implementation phases; (2) Fair compensation packages including land replacement, housing, and livelihood restoration programs; (3) Community empowerment initiatives through skills training and local business development; (4) Equitable benefit-sharing mechanisms ensuring local communities receive direct benefits from hydropower projects.

Policy Frameworks and International Best Practices

Comparative analysis of hydropower development policies in countries such as Norway, Canada, Brazil, and China reveals that successful sustainable hydropower implementation requires integrated policy frameworks combining technological innovation,

environmental protection, and social responsibility. These frameworks typically include streamlined environmental assessment processes, mandatory stakeholder consultation requirements, technology innovation incentives, and long-term power purchase agreements that provide investment certainty.

Integrated Sustainability Framework

The research demonstrates that sustainable hydropower development necessitates a comprehensive approach that integrates technical excellence, economic viability, environmental stewardship, and social responsibility. Success requires synergy between modern technology implementation, supportive policy environments, effective environmental management, and active community participation throughout project lifecycles. This integrated approach ensures that hydropower development can deliver optimal benefits across all sustainability dimensions while maintaining long-term viability and acceptance.

CONCLUSION

Sustainable Hydroelectric Power Plant (PLTA) development requires a comprehensive approach that integrates technological advancement, supportive policies, effective environmental management, and active community engagement to achieve optimal sustainability outcomes. In terms of technology, the application of innovations such as Pumped-Storage Hydroelectricity (PSH) becomes key to increasing efficiency and flexibility in electricity systems, so that electricity supply can be more stable and reliable. Policy support such as providing incentives, feed-in tariffs, and simplification of licensing processes play an important role in accelerating the development of hydroelectric power plants and making them profitable long-term investments.

From environmental and social perspectives, this research demonstrates that hydropower development can provide substantial benefits while effectively managing associated challenges through systematic mitigation strategies. Environmental benefits include significant greenhouse gas emission reductions (over 3 billion tonnes CO₂ annually), sustainable water resource management, and flood control capabilities. However, environmental challenges such as ecosystem disruption, reservoir sedimentation, and methane emissions require implementation of advanced technologies including AI-based reservoir management, environmentally friendly turbines, and comprehensive ecosystem restoration programs.

Social impacts analysis reveals that hydropower development has the potential to increase community welfare through job creation, electricity access expansion in remote areas, and local infrastructure improvement. However, social challenges including population relocation and benefit distribution inequity require proper handling through fair compensation mechanisms, local community empowerment programs, and enhanced public participation in project decision-making processes.

For future development, this research recommends several strategic approaches to optimize hydropower sustainability: (1) Implementation of integrated project planning that combines technical, environmental, and social considerations from initial design phases; (2) Development of adaptive management systems using digital technologies and real-time monitoring for continuous optimization; (3) Establishment of multi-stakeholder governance frameworks ensuring meaningful participation of all affected parties; (4) Investment in research and development of next-generation hydropower technologies that minimize environmental impacts while maximizing energy efficiency; (5) Creation of international best practice sharing mechanisms to accelerate sustainable hydropower deployment globally; (6) Integration of hydropower development with broader watershed management and climate adaptation strategies to maximize synergistic benefits.

By integrating technological innovation, conducive policies, sustainable environmental management, and active community participation, hydropower development can provide optimal economic, social and environmental benefits, supporting the transition towards a more environmentally friendly and sustainable energy system that contributes meaningfully to global climate goals and sustainable development objectives.

REFERENCES

- International Energy Agency (IEA). (2021). Hydropower Special Market Report: Analysis and Forecast to 2030. Retrieved from <https://www.iea.org>
- International Hydropower Association (IHA). (2021). The Hydropower Status Report 2021: Sector Trends and Insights. London: IHA.
- International Renewable Energy Agency (IRENA). (2020). The Changing Role of Hydropower: Challenges and Opportunities. Abu Dhabi: IRENA. Retrieved from <https://www.irena.org>
- Islam, M. A., Hasanuzzaman, M., Rahim, N. A., Nahar, A., & Hosenuzzaman, M. (2014). Global renewable energy-based electricity generation and smart grid system for energy security. *The Scientific World Journal*, 2014(1), 197136.
- Kumar, A., Schei, T., Ahenkorah, A., Rodriguez, R.C., & Others. (2011). Hydropower. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge University Press.
- Li, Y., Chen, P. H., & Lo, E. Y. (2015). Experimental study of water-exit and water-entry of circular cylinders. *Journal of Offshore Mechanics and Arctic Engineering*, 123(4), 190-197.
- Pacca, S., & Moreira, J.R. (2009). A Model for Sustainable Hydropower Generation. *Renewable and Sustainable Energy Reviews*, 13(3), 741-749. <https://doi.org/10.1016/j.rser.2007.11.002>
- Scheffran, J., Felkers, M., & Froese, R. (2020). Economic growth and the global energy demand. *Green energy to sustainability: strategies for global industries*, 1–44.
- Schweiger & Lorang, M. S. (2020). The Environmental Impact of Hydropower: From Theory to Reality. *Sustainability*, 12(9), 3684. <https://doi.org/10.3390/su12093684>
- Stern, D. I., & Kander, A. (2012). The role of energy in the industrial revolution and modern economic growth. *The Energy Journal*, 33(3), 125–152.
- United Nations Environment Program (UNEP). (2022). Renewable Energy and Sustainability: Hydropower's Role in a Low-Carbon Future. Nairobi: UNEP.
- Wang, Z., Dong, C., & Liu, J. (2021). The Role of Hydropower in Achieving Carbon Neutrality: Lessons from China's Large-Scale Implementation. *Renewable Energy*, 170, 627-640. <https://doi.org/10.1016/j.renene.2021.02.015>
- World Bank (World Bank). (2021). Sustainable Hydropower Development: Policies and Practices. Retrieved from <https://www.worldbank.org>
- World Energy Council (WEC). (2019). World Energy Resources: Hydropower Report. London: World Energy Council.
- Zarfl, C., Lumsdon, A.E., Tockner, K. (2015). A Global Boom in Hydropower Dam Construction. *Aquatic Sciences*, 77(1), 161-170. <https://doi.org/10.1007/s00027-014-0377-0>

