

SUSTAINABILITY ASSESSMENT OF HYDROPOWER: A COMPREHENSIVE SYSTEMATIC LITERATURE REVIEW OF ENVIRONMENTAL, SOCIAL, ECONOMIC, AND TECHNICAL DIMENSIONS

BONO PRANOTO^{1,2*}, EDY HARTULISTIYOSO³, MUHAMMAD NUR AIDI⁴, DEWAYANY SUTRISNO⁵, HARI SOEKARNO², LISNA EFIYANTI⁶, DIAN ANGGRAINI INDRAWAN^{1,6}, YULIZAR IHRAMI RAHMILA^{1,7}, MAYRIANTI ANNISA ANWAR^{1,8}, YOHANES GUNAWAN⁹ AND MIRA YULIANTI⁷

¹Natural Resources and Environmental Management, Graduate Study Program, IPB University, Jl. Pajajaran, IPB Baranangsiang Campus, 16144 Bogor, West Java, Indonesia. ²Research Center for Limnology and Water Resources, National Research and Innovation Agency, KST Soekarno, 16911 Bogor, West Java, Indonesia. ³Department of Mechanical and Biosystems Engineering, Faculty of Agricultural Engineering and Technology, IPB University, 16680 Bogor, West Java, Indonesia. ⁴Department of Statistics and Data Science, Faculty of Mathematics and Natural Sciences, IPB University, 16680 Bogor, West Java, Indonesia. ⁵Research Center for Conservation of Marine and Inland Water Resources, National Research and Innovation Agency, 16911 Bogor, West Java, Indonesia. ⁶Research Center for Biomass and Bioproduct, National Research and Innovation Agency, KST Soekarno, 16911 Bogor, West Java, Indonesia. ⁷Research Center for Ecology and Ethnobiology, National Research and Innovation Agency, KST Soekarno, 16911 Bogor, West Java, Indonesia. ⁸Executive Secretariat of National Research and Innovation Agency, 10340 Jakarta, Indonesia. ⁹Polytechnic of Energy and Mineral Akamigas, Ministry of Energy and Mineral Resources, 58315 Blera, Central Java, Indonesia.

*Corresponding author: bono001@brin.go.id

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Abstract: Hydropower is a critical renewable energy technology with the potential to contribute significantly to the global clean energy transition. However, despite its many advantages, hydropower development faces complex sustainability challenges, including environmental degradation, social displacement, and fluctuating economic returns. These challenges highlight the need for a comprehensive assessment of hydropower projects across multiple dimensions of sustainability. This study aims to evaluate the sustainability of hydropower by conducting a Systematic Literature Review (SLR) of 65 peer-reviewed articles published between 2012 and 2022. It follows Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) standards to analyse key environmental, social, economic, technical, and policy barriers to sustainable development. The review systematically examines findings from these studies, identifying recurrent themes and critical barriers. The results reveal that while hydropower can enhance energy security and reduce carbon emissions, its implementation often leads to ecological disruption, community displacement, and varying economic benefits. The study underscores the necessity for robust policy frameworks, advanced technologies, and greater stakeholder engagement to mitigate these negative impacts and promote the sustainable development of hydropower.

Keywords: Environment, economic, social, assessment, hydropower, systematic literature review.

Introduction

Globally, hydropower stands out as a leading renewable energy technology globally, offering substantial potential for clean electricity generation (Geller & Meneses, 2016; Mao *et al.*, 2017; Singh & Singal, 2018; Xue & Sun, 2018; Adamu *et al.*, 2018; Kuniyal *et al.*, 2019). Due to its ability to harness the kinetic energy

of flowing or falling water such as rivers and dams, hydropower is widely recognised for its sustainability (Geller & Meneses, 2016). Hydropower sustainability is paramount across various industries, particularly in achieving environmental and economic goals.

Meanwhile, hydropower offers promising sustainability prospects. However, its development is riddled with challenges that demand attention. Environmental concerns arise from the construction of large-scale projects, including dams and reservoirs, leading to ecosystem alterations, habitat destruction, and disruptions in natural river flows (de Pádua Andrade *et al.*, 2012; Erlewein, 2013; Scherer & Pfister, 2016; Tedjio *et al.*, 2016; Vougioukli *et al.*, 2017; Dorber *et al.*, 2019; Ma *et al.*, 2019; César *et al.*, 2020; Cesoniene, *et al.*, 2021; Hamidifar *et al.*, 2022; van Treeck *et al.*, 2022; Dechasa *et al.*, 2022). Social displacement further complicates matters as local communities, particularly Indigenous groups, face displacement and loss of livelihoods due to project implementations (Kumar & Katoch, 2015; Voegeli *et al.*, 2019; Mishra *et al.*, 2020; Azubuike *et al.*, 2022).

Moreover, upstream and downstream water management issues compounded by climate change-induced water resource variability, pose significant operational and ecological challenges (X. Liu & He, 2012; Rambo *et al.*, 2017; Voegeli *et al.*, 2018; Khakzad, 2019; Xu *et al.*, 2020; Mitrovic *et al.*, 2021; Nowak *et al.*, 2022; Dechasa *et al.*, 2022). The ageing infrastructure and maintenance requirements and the imperative of Indigenous and stakeholder engagement add complexity to hydropower sustainability (Erlewein, 2013; Su *et al.*, 2015; Sul Khanishvili, 2015).

Several review studies have delved into the sustainability of renewable energy sources, particularly focusing on hydropower energy. Gayen *et al.* (2024) extended the discussion to encompass the environmental impacts of renewable energy for sustainable development by examining wind, solar, hydropower, and biomass energy. They also explore innovative technologies inspired by these sources while analysing global obstacles in advancing renewable energy. Adhikari *et al.* (2024) zoom in on Nepal, reviewing renewable energy technologies and challenges and focusing on hydropower in electricity generation. They

underscore policy issues, technical gaps, and human resource scarcity as primary hurdles. On the other hand, Shu *et al.* (2018) shifted their focus to climate change impacts on hydropower development, proposing mitigation strategies and emphasising site-specific research for better analysis. Suárez-Gómez *et al.* (2021) explore territorial factors in hydropower sustainability through a Systematic Literature Review (SLR), highlighting governance regimes, stakeholder collaboration, and adaptive mechanisms. Finally, Zhang *et al.* (2021) proposed a new method for assessing hydropower sustainability based on various indicators utilising advanced modelling techniques. However, limitations such as a lack of in-depth studies on project aspects and subjectivity in assessment methods persist across these reviews, indicating the need for further research and methodological refinement in the field of renewable energy sustainability, particularly in the context of hydropower.

Hydropower is a pivotal renewable energy technology with extensive global applicability for generating clean electricity. We present novel results demonstrating how hydropower can significantly contribute to sustainable energy development. The selection of our study sample and methodology is meticulously justified, emphasising their adequacy in addressing the Research Questions (RQs) posed. We discuss the comprehensive data utilised in our analysis, outlining the environmental, social, economic, and technological dimensions covered. This study makes a substantial contribution to the literature by identifying gaps and offering new insights into the sustainability of hydropower projects. Moreover, we openly discuss the limitations of our research, providing a balanced view and suggesting directions for future studies.

Materials and Methods

An SLR is a structured method for gathering, evaluating, and summarising existing research on a specific topic. It employs a transparent process to minimise bias and ensure rigorous analysis. Note that it starts with formulating a clear RQ to define the scope, followed by

developing inclusion/exclusion criteria to determine relevant studies. A comprehensive search across databases and journals used specific keywords to identify relevant studies. Screening and selection were performed based on predefined criteria, initially through titles and abstracts and then through full-text assessment. Relevant information was extracted, including study details, methodology, and key findings. The review followed Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The tools used in this review are PRISMA and Microsoft Excel.

Research Question

Few studies have examined hydropower sustainability despite the growing number of hydropower facilities worldwide. As a result, the peer-reviewed literature on hydropower sustainability is reviewed in this comprehensive literature review. The RQs that this SLR attempts to answer are listed below:

- RQ1: What are the environmental impacts and sustainability challenges associated with hydropower projects, as evidenced by the literature, and how can these impacts be effectively assessed and mitigated?
- RQ2: What are the social impacts and challenges associated with hydropower development and how can these impacts be effectively addressed to promote social sustainability and community well-being?
- RQ3: What are the economic impacts and sustainability considerations associated with hydropower development and how can policy frameworks and investment strategies be optimised to maximise benefits while addressing social and environmental costs?
- RQ4: What are the key technical, operational, policy, and risk management considerations in developing and managing hydropower resources effectively and sustainably?
- RQ5: What barriers prevent sustainable hydropower assessments from being fully implemented according to the standards?

Criteria for Inclusion

A comprehensive literature review was performed from January 1, 2012 through December 31, 2022 to find all papers on hydropower project appraisals published in English. This SLR was created and reported following the PRISMA guidelines (Page *et al.*, 2021). Comprehensive inclusion criteria were developed to identify relevant studies and remove those not related to the study of hydropower sustainability features. These papers must be peer-reviewed and concentrate on hydropower sustainability's social, economic, environmental, and technical elements. The publications reviewed are journals only, excluding proceedings, books, book chapters, and reviews. All assessments are related to hydropower, including micro hydro, Small Hydropower (SHP), and large hydropower. All assessments of potential sites, impacts, and risks associated with assessing the sustainability aspects of hydropower systems are discussed.

Literature Search Process

The keywords in the literature search were intended to locate papers about hydropower and its assessment. A synonym for Hydropower was hydroelectric and the next keyword was "evaluation". Boolean operators were utilised to find related articles (Atkinson & Cipriani, 2018). The word "AND" includes all identified keywords and "OR" is used to increase or expand our search for the same context. The following keywords were used for the search: Hydropower OR Hydroelectric AND Assessment.

A thorough search of four computerised bibliographic databases was conducted for relevant papers, as seen in Table 1. Scopus, Web of Science (WoS), JSTOR, and Google Scholar were among the databases used. Consequently, key journals with publications relating to energy, sustainability, ecology, environment, water, economy, and society were identified. Several major publishers' significant journals were

Table 1: Database and keywords

No.	Database	Access	Keywords
1	Scopus	March 1, 2023	TITLE-ABS-KEY (Hydropower OR Hydroelectric AND Assessment)
2	WoS	March 1, 2023	TOPIC (Hydropower OR Hydroelectric AND Assessment)
3	Google Scholar	March 1, 2023	(Hydropower OR Hydroelectric AND Assessment)
4	JSTOR	March 1, 2023	(Hydropower OR Hydroelectric AND Assessment)

searched, including Elsevier, MDPI, Springer, Frontier, Hindawi, and Taylor & Francis.

The main keywords were searched for in the title only with the expectation that the article would generally be about Hydropower OR Hydroelectric AND Assessment. Only the articles were published in English, with a publication period from 2012 to 2022. After collecting several articles from each database, duplicate studies were removed. The rule used is that if there are twins, then the data retained in sequential priority are Scopus, Google Scholar, WoS, and JSTOR. Microsoft Excel from Windows was used for document processing.

After duplicate removal, 278 articles remained. Figure 1 illustrates several publication keywords such as Hydropower OR Hydroelectric AND Assessment.

Coding and Analysis

All the retrieved papers were examined and screened for relevance. Sustainability

should be a fundamental filter in hydropower assessment because it ensures that projects contribute to long-term environmental, social, and economic well-being. Hydropower assessments can identify potential negative impacts such as habitat destruction, community displacement, and economic disparities by prioritising sustainability. Hence, incorporating sustainability as a filter helps to mitigate these risks, guiding decision-making toward environmentally responsible practices, equitable development, and efficient resource management. Integrating sustainability into hydropower assessment processes ensures that projects align with broader sustainability goals and contribute positively to ecosystems and communities’ overall health and resilience.

Keywords related to sustainability, the environment, the economy, and society were included to boost relevancy. First, abstracts were read and validated against the criteria mentioned above. The abstracts were divided into three categories: (1) If it was clear that the article did

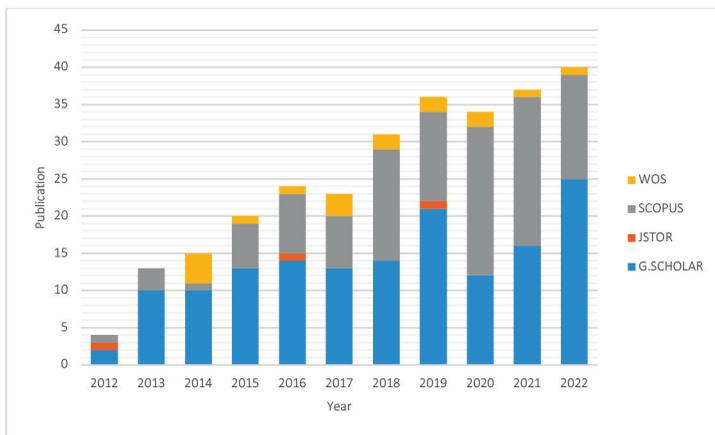


Figure 1: Number of publication keywords: Hydropower OR Hydroelectric AND Assessment

not meet the criteria, it was excluded from the SLR; (2) If it was unclear whether the article met the above criteria but the abstract still contained additional keywords, it was determined whether the article should be included in the final review; and (3) If the article appeared to meet the criteria, the whole text was studied to confirm that the concentrations in the article were not unclear. 11 researchers independently read and reviewed the publications to determine which were relevant. The final papers relevant to this SLR were chosen collaboratively by the study team. Figure 2 illustrates a summary of the papers determined through the PRISMA guidelines.

Of the 278 articles screened, 177 articles contained aspects of sustainability (Figure 3) with the following details: Six articles specifically discussed sustainability; 10 articles contained environmental, social, and economic discussions; three articles contained environmental and economic discussions; three articles contained environmental and social discussions; 19 articles contained environmental and technical discussions; 22 articles contained only discussed environment; five articles

discussed only socioeconomic aspects; eight articles contained technical and economic discussions; one article discussed only economic aspects; seven articles discussed only social aspects; and 15 articles discussed only technical aspects.

Figure 3 illustrates the number of publications related to hydropower assessment and sustainability aspects from 2012 to 2022, with the blue bars representing publications on “HydropowerAssessment”. The red line indicates those specifically addressing “Sustainability Aspects”, including environmental, economic, social, and technical considerations. Over the decade, there has been a noticeable increase in both categories of publications. The number of hydropower assessment publications shows a steady rise from four in 2012 to a peak of 40 in 2022, reflecting a growing interest in hydropower as a significant renewable energy source. This upward trend suggests that researchers and stakeholders increasingly focus on understanding various facets of hydropower development such as feasibility, design, implementation, and impact assessments.

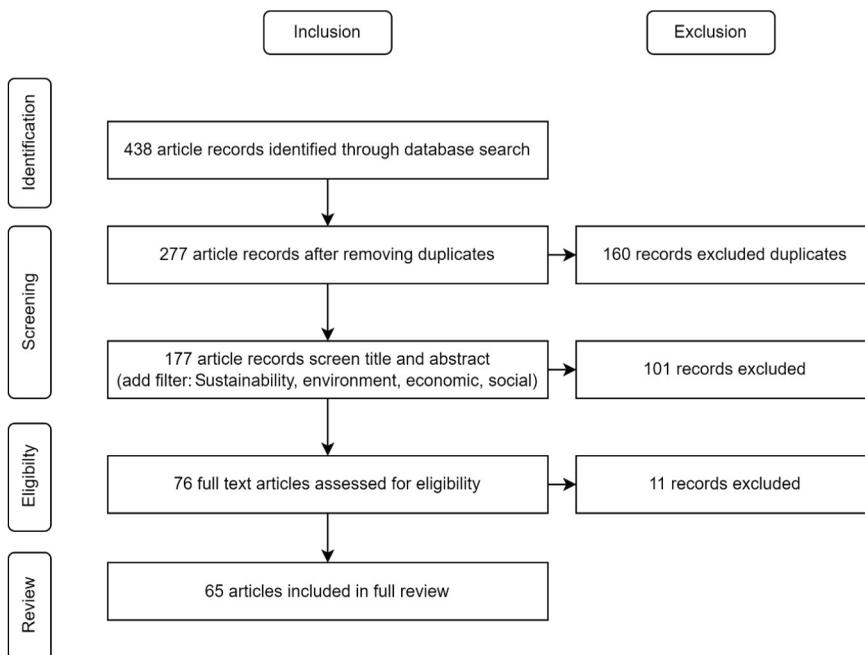


Figure 2: Summary of the papers found

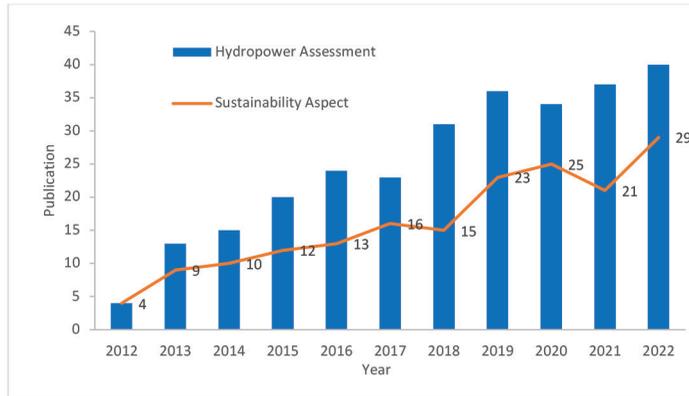


Figure 3: Number of publication keyword filter sustainability, environment, economic, social, and technical

The publications focusing on sustainability also demonstrate a consistent upward trend, highlighting the increasing importance of sustainability in hydropower research.

Starting at four in 2012, the number of sustainability-focused publications gradually increased to 16 by 2018 and rose rapidly to 29 by 2022. This trend indicates a growing awareness of the need to balance hydropower development with sustainable practices that minimise environmental and social impacts while ensuring economic and technical viability. Although there is a steady increase in both hydropower assessment and sustainability-focused publications, a gap remains throughout the period, suggesting that not all hydropower assessments explicitly focus on sustainability issues.

However, the gap has narrowed recently, particularly in 2021 and 2022, indicating a shift towards more comprehensive studies integrating sustainability concerns into hydropower assessments. Notably, significant increases in sustainability aspect publications around 2018 and 2022 may correlate with heightened global awareness and policy shifts towards Sustainable Development Goals (SDGs) and climate action. This likely drove more research attention toward environmental, social, economic, and technical sustainability aspects of hydropower projects. The increasing trend in sustainability-related publications suggests that future

research in hydropower will focus heavily on integrating sustainability aspects into project planning, assessment, and implementation. It also highlights the need for multidisciplinary approaches considering the diverse impacts of hydropower development. Overall, this figure underscores the growing emphasis on sustainability within hydropower research. This shifts towards more holistic, integrated energy planning, and management approaches to balance renewable energy development with preserving ecosystems, social equity, and economic viability.

Results and Discussion

Investigate the Characteristics, People, and Places

The research was performed in various nations and continents (Figure 4). Note that 26 of the 177 studies were conducted in China. Meanwhile, 23 studies were carried out in Brazil. 14 studies in India. Nine studies in Canada. Seven studies were conducted in Europe and the United States. Eight studies were conducted in Turkey. Six studies were in Poland—and five studies were in Italy. Four studies were conducted in Iran and Spain. Three studies were conducted in Greece, Lithuania, and Norway. Two studies were conducted in Austria, Cameroon, Ecuador, Ethiopia, Indonesia, Japan, Nigeria, Switzerland, the UK, and the USA. One study was conducted in Africa, Belarus, Belgium, Cambodia, Central

understanding and assessing hydropower from multiple perspectives, including environmental, economic, and technical dimensions.

One prominent cluster focused on environmental impacts, featuring keywords such as “rivers”, “dams”, “biodiversity”, “environmental impact assessment”, and “ecosystems”. This cluster underscores the significant attention given to mitigating the adverse effects of hydropower on natural ecosystems. The frequent co-occurrence of terms such as “environmental impact”, “water quality”, and “biodiversity” indicates a strong emphasis on promoting sustainable practices to ensure that hydropower development does not compromise environmental integrity.

Another critical cluster addresses the economic and policy dimensions of hydropower, with terms such as “economic efficiency”, “sustainable development”, “energy policy”, and “decision making”. This cluster highlights the importance of policy frameworks and economic considerations in developing and implementing hydropower projects. The presence of keywords related to decision-making and energy policy suggests a focus on balancing economic benefits with environmental and social responsibilities, which is essential for sustainable development.

The network also includes a cluster dedicated to the technical and operational aspects of hydropower, featuring keywords such as “hydrological modelling”, “water management”, “electricity generation”, and “reservoirs (water)”. This cluster reflects the critical need for precise technical planning to optimise the efficiency and sustainability of hydropower systems. The emphasis on hydrological modelling and water management indicates ongoing efforts to adapt to varying environmental conditions and enhance operational sustainability.

Additionally, the network reveals a cluster connecting hydropower with broader discussions about climate change and renewable energy. Keywords such as “climate change”, “renewable resources”, “energy transition”, and “carbon dioxide” are interconnected,

highlighting the strategic role of hydropower in reducing greenhouse gas emissions and supporting a transition to sustainable energy sources. This cluster underscores the importance of hydropower in global efforts to combat climate change.

The high degree of interconnectedness among keywords in the network suggests a well-integrated research field where various aspects of hydropower are often studied together. This integration is crucial for developing comprehensive and effective strategies for sustainable hydropower development. However, the network also reveals potential research gaps, such as the underrepresentation of topics such as social impacts and community engagement, indicating areas that may require further attention.

The co-occurrence network of hydropower keywords provides valuable insights into the main research themes and their interconnections. The prominent clusters reflect a balanced interest in environmental, economic, technical, and policy aspects, underscoring the multifaceted nature of hydropower sustainability. Therefore, addressing identified research gaps and focusing on policy implications will be critical for advancing the field and promoting sustainable practices in hydropower development. This network analysis highlights the complexity of achieving sustainable hydropower and the importance of integrated approaches considering all relevant dimensions.

Sustainability Aspect

It has been difficult to define sustainability, and no general definition exists. In 1987, the World Commission on Environment and Development emphasised the developmental aspect of sustainability. This coins the widely accepted definition of sustainable development as meeting present demands without jeopardising future generations' ability to meet their needs. Sustainability is quantified by various interdependent variables depending on the evaluation approach used. The Three Pillar Model, which encompasses economic,

social, and environmental concerns is the most well-known model. The current study defines sustainability as a hydroelectric project’s ability to continue operating for power generation while meeting technical, economic, social, and environmental objectives.

Environment Aspect

The environmental aspect of hydropower sustainability assessment aims to identify potential environmental risks and impacts associated with hydropower development. It informs decision-making processes that promote the conservation and sustainable use of natural resources. Figure 6 illustrates a collective study on the environmental aspects of hydropower sustainability.

The analysis of the environmental aspects in Figure 6 regarding hydropower projects offers valuable insights into their impacts and sustainability challenges, providing evidence to address RQ1. The thematic breakdown is as follows:

Biodiversity and Ecosystem Impact

Dam construction and reservoir formation, as highlighted by Bidoglio *et al.* (2019) and Bradford (2022), lead to significant disruptions in aquatic and terrestrial ecosystems, resulting in biodiversity loss, sedimentation, and eutrophication. Fortes Westin *et al.* (2014) also discussed the adverse effects of hydropower development on indigenous reserves and biodiversity, exacerbating environmental degradation.

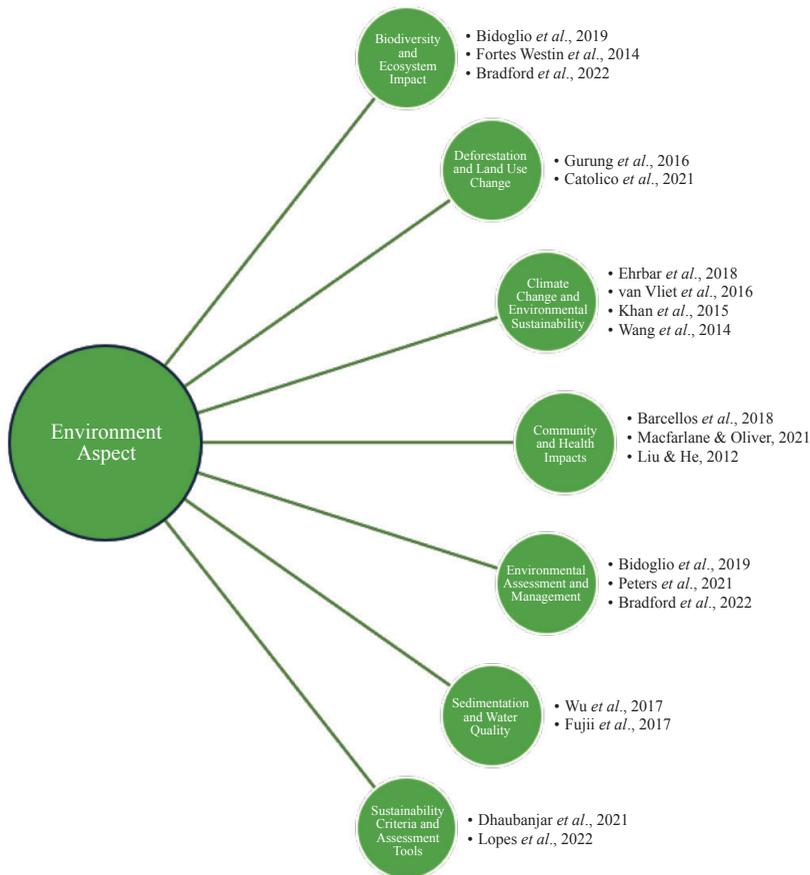


Figure 6: Environment aspect theme and references

Deforestation and Land Use Change

Catolico *et al.* (2021) noted the alarming rate of deforestation associated with hydropower projects, leading to erosion and increased extinction risks for aquatic species. The loss of floodplain forests, as emphasised by Gurung *et al.* (2016), further contributes to altered sediment transport dynamics, exacerbating environmental impacts.

Climate Change and Environmental Sustainability

van Vliet *et al.* (2016) and Ehrbar *et al.* (2018) underscore the intersection between hydropower development and climate change, highlighting challenges and opportunities. Meanwhile, Wang *et al.* (2014) and Khan (2015) advocate for sustainable practices in Small Hydropower (SHP) plants to minimise environmental impacts and enhance environmental sustainability.

Community and Health Impacts

Large hydroelectric projects, as detailed by Barcellos *et al.* (2018), disproportionately affect local communities, amplifying vulnerabilities, and increasing the risk of disease among already marginalised populations. Furthermore, Macfarlane dan Olive (2021) highlights indigenous opposition due to dam projects' significant environmental and social impacts.

Environmental Assessment and Management

Bidoglio *et al.* (2019) and Peters *et al.* (2021) emphasise the necessity of comprehensive environmental assessments to uncover the true costs and impacts of hydropower projects, stressing the importance of sustainable planning. Bradford (2022) discussed the implementation of environmental flows to maintain ecosystem services in managed rivers and proposed potential mitigative strategies.

Sedimentation and Water Quality

This study sheds light on the ecological impacts of altered sediment transport and reservoir sedimentation, which significantly affect energy production. Moreover, concerns raised by Wu *et al.* (2017) and Fujii *et al.* (2017) regarding

water quality emphasise the need for careful management during construction to preserve riverine ecosystems and maintain local water volumes.

Sustainability Criteria and Assessment Tools

Dhaubanjari *et al.* (2021) and Lopes *et al.* (2022) stress the importance of integrating sustainability criteria and assessment tools into evaluating hydropower projects to mitigate negative impacts and promote environmental sustainability.

In conclusion, the environmental aspect of hydropower sustainability is multifaceted, encompassing many challenges and considerations that must be addressed to ensure sustainable development. The thematic analysis presented in Figure 6 provides a comprehensive overview of these environmental concerns. This includes biodiversity loss, deforestation, climate change, community impacts, sedimentation, water quality, and the necessity for robust environmental assessment and management practices.

The findings underscore that while hydropower can be a renewable energy source, its development poses significant risks to ecosystems, communities, and the broader environment. To mitigate these impacts, adopting sustainable practices such as minimising land use change, implementing environmental flows, and employing thorough environmental assessments to guide decision-making is crucial. Furthermore, integrating sustainability criteria and assessment tools into hydropower project planning can help balance energy production with ecological and social preservation. By addressing these environmental challenges and leveraging innovative management strategies, hydropower development can align more closely with sustainability principles, supporting the conservation, and sustainable use of natural resources for future generations.

Social Aspect

Figure 7 outlines the social aspects of hydropower projects, emphasising the

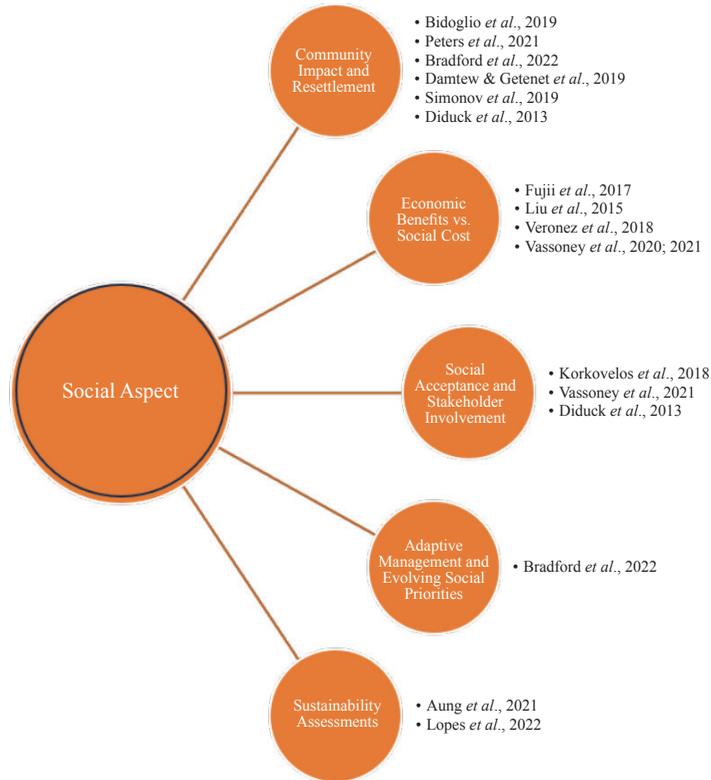


Figure 7: Social aspects and references

importance of considering both positive and negative impacts on communities, cultures, and ecosystems to answer RQ2. The references cover a broad spectrum of social dimensions related to hydropower development, including displacement, social inequalities, community engagement, cultural preservation, and social sustainability. The key themes identified include the following:

Community Impact and Resettlement

Many references such as Bidoglio *et al.* (2019), Peters *et al.* (2021), and Bradford (2022) discuss the displacement and resettlement issues arising from dam construction. Resettlement often leads to significant social upheaval, disrupting communities, and altering social networks and local economies. While some studies such as Getenet (2019) highlight the benefits of micro hydropower in rural electrification, the broader

impacts of larger projects often include a loss of livelihood, cultural displacement, and social conflicts. This can be seen in the works of Simonov *et al.* (2019) and Diduck *et al.* (2013).

Economic Benefits vs. Social Costs

Meanwhile, hydropower projects are touted for their role in economic development and sustainable energy (Y. Liu *et al.*, 2015; Fujii *et al.*, 2017) and they also have negative social impacts. These include increased access to alcohol and drugs (Veronez *et al.*, 2018), temporary employment that does not compensate for long-term unemployment (Vassoney *et al.*, 2020; 2021), and the exacerbation of social inequalities (Barcellos *et al.*, 2018). The challenge lies in balancing these economic benefits with the social costs, ensuring that local communities do not bear the brunt of negative impacts.

Social Acceptance and Stakeholder Involvement

The success of hydropower projects often hinges on social acceptance, which can be facilitated by involving stakeholders throughout the project's lifecycle (Korkovelos *et al.*, 2018; Vassoney *et al.*, 2021). This involvement helps address public concerns about environmental and social changes, ensure transparency, and increase the legitimacy of the projects. However, the case studies by Diduck *et al.* (2013) and others demonstrate that negative social impacts often outweigh the perceived benefits, leading to opposition and protests.

Adaptive Management and Evolving Social Priorities

Bradford (2022) and others have discussed the importance of adaptive management in addressing socioeconomic systems and evolving social priorities. This approach can dynamically help manage social impacts as community needs and legal frameworks change. However, the effectiveness of this adaptive management approach is contingent on the continuous engagement of all stakeholders and the ability to respond to feedback and evolving circumstances.

Sustainability Assessments

Several references emphasise the importance of comprehensive sustainability assessments that include social criteria (Aung *et al.*, 2021; Lopes *et al.*, 2022). These assessments are crucial for understanding the broader impacts of hydropower projects and ensuring that they contribute positively to social sustainability. However, how these assessments are conducted and the extent to which they influence decision-making and policy formulation remain challenges.

The analysis indicates a broad spectrum of social considerations across the life cycle of hydropower and related projects, from planning and construction to operation and beyond. The impacts are local and can have regional and even national cascading effects. The key to managing these impacts is a thorough understanding of social dynamics, effective

stakeholder engagement, and integrating social considerations into project planning and implementation phases.

The data underscore the importance of multidimensional assessments that incorporate economic and environmental factors and deeply consider the social fabric of affected communities. Ensuring that development projects contribute positively to social well-being, respect human rights, and foster socioeconomic development without exacerbating inequalities or leading to adverse social outcomes is essential for sustainable development.

In conclusion, the social aspects of hydropower sustainability are complex and encompass various impacts on communities, cultures, and socioeconomic systems. As illustrated in Figure 7 while hydropower projects can provide significant economic benefits and contribute to sustainable energy production, they often come with considerable social costs, including displacement, social inequalities, and cultural disruption. The analysis highlights that these impacts are not only local but can also have broader regional and national implications, making the management of social dimensions a critical component of sustainable hydropower development. Hence, effective stakeholder engagement and adaptive management strategies are essential for addressing these social challenges.

Involving communities and stakeholders throughout the project lifecycle can help ensure transparency, foster social acceptance, and mitigate opposition. Moreover, adaptive management allows for a flexible approach to evolve social priorities, enabling project developers to respond to change community needs and legal frameworks. These strategies must be continuously implemented and refined to be effective. Furthermore, comprehensive sustainability assessments that integrate social criteria are vital for understanding the full scope of hydropower's social impacts. This underscores the importance of a multidimensional approach to sustainability that balances economic,

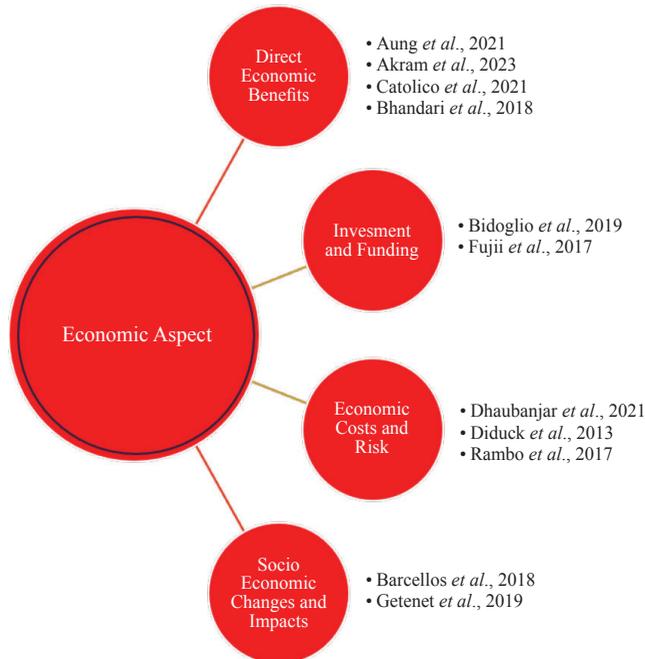


Figure 8: Economic aspects and references

environmental, and social considerations. Such an approach is crucial for achieving truly sustainable hydropower development.

Economic Aspect

The compilation of perspectives in Figure 8 comprehensively examines the economic impacts and sustainability considerations associated with hydropower development, encompassing various regions and scales to answer RQ3. This finding underscores the complex interplay between economic, social, and environmental factors in shaping the outcomes of hydropower projects.

Direct Economic Benefits

Hydropower projects often bring significant direct economic benefits, including job creation, increased revenue, and the provision of reliable electricity, which is crucial for economic development. References such as Aung *et al.* (2021), Catolico *et al.* (2021), and Akram *et al.* (2023) underscore how these projects can meet energy demands and stimulate local economies

through increased employment and company growth. However, the economic sustainability of these projects can sometimes be questionable, as noted by Bhandari *et al.* (2018), where economic sustainability scored low despite not requiring loan funding due to issues in generating sufficient revenue benefits.

Investment and Funding

The role of government incentives, grants, and private investment in fostering the development of small- to large-scale hydropower projects is significant. Fujii *et al.* (2017) and Bidoglio *et al.* (2019) highlight the positive impact of governmental financial assistance and deregulation, which encourage private investments, contributing to economic development. However, the financial viability of these projects can often hinge on substantial initial investments and favourable economic conditions, as discussed by Liu *et al.* (2015) and Igliński *et al.* (2022), where economic growth and job opportunities are tied to the accessibility of loans and funding.

Economic Costs and Risks

Hydropower development has economic risks and costs. The construction of large hydropower projects often requires significant capital investment and long lead times, which can burden project owners, as noted by Dhaubanjari *et al.* (2021). Furthermore, environmental and social opposition can lead to delays or increased costs, impacting the overall economic feasibility of projects. Diduck *et al.* (2013) and Rambo *et al.* (2017) discussed the economic losses due to environmental disruptions and social conflicts, which can offset the economic benefits and complicate the cost-benefit analysis of these projects.

Socioeconomic Changes and Impacts

The transformation of local economies and migration patterns associated with hydropower projects, described by Barcellos *et al.* (2018) and Getenet (2019). The authors illustrate the profound socioeconomic changes that can occur. These changes can have both positive and negative implications for local communities. Projects can bring about economic growth and improve living standards. However, they can also lead to increased inequality, environmental degradation, and the displacement of local populations. The challenge lies in managing these impacts to ensure that the economic benefits are equally distributed and do not come at the expense of social and environmental well-being.

In conclusion, the economic aspects of hydropower sustainability are intricate and multifaceted, involving a careful balance between the benefits of economic development and the associated costs and risks. As depicted in Figure 8, hydropower projects can provide substantial direct economic benefits such as job creation, increased revenue, and reliable electricity. This ensures the economic sustainability of these projects, which requires careful consideration of various factors. Other than that, these factors include investment and funding structures, economic costs and risks, and the broader socioeconomic changes they

induce. The analysis highlights that government incentives, private investments, and favourable economic conditions are crucial in promoting hydropower development. However, these projects also entail significant financial risks such as high initial capital costs, long lead times, and potential delays due to environmental and social opposition. Economic losses can further arise from social conflicts and environmental disruptions, complicating the overall cost-benefit analysis of hydropower projects.

The socioeconomic changes driven by hydropower development can have mixed impacts on local communities, contributing to economic growth and improved living standards. On the one hand, it potentially exacerbates inequalities, environmental degradation, and displacement. The challenge lies in managing these changes to ensure maximum economic benefits are distributed equitably without compromising social and environmental sustainability. For hydropower projects to be economically sustainable, they must be accompanied by robust economic planning, stakeholder engagement, and adaptive management strategies. Comprehensive economic assessments that account for social and environmental impacts are essential for maximising benefits and minimising adverse effects. By adopting these strategies, hydropower can continue to play a pivotal role in global sustainable energy development, balancing economic growth with the broader sustainability goals.

Technical Aspect

Technical assessment is an important aspect of the sustainability assessment of hydropower and involves evaluating the electricity use, reliability, efficiency, and technology of hydropower plants (Bhandari *et al.*, 2018). The technical assessment helps ensure that the hydropower plants are designed and operated to maximise their potential for electricity generation while minimising their environmental impact. Figure 9 illustrates the technical aspects of hydropower projects, ranging from engineering design and

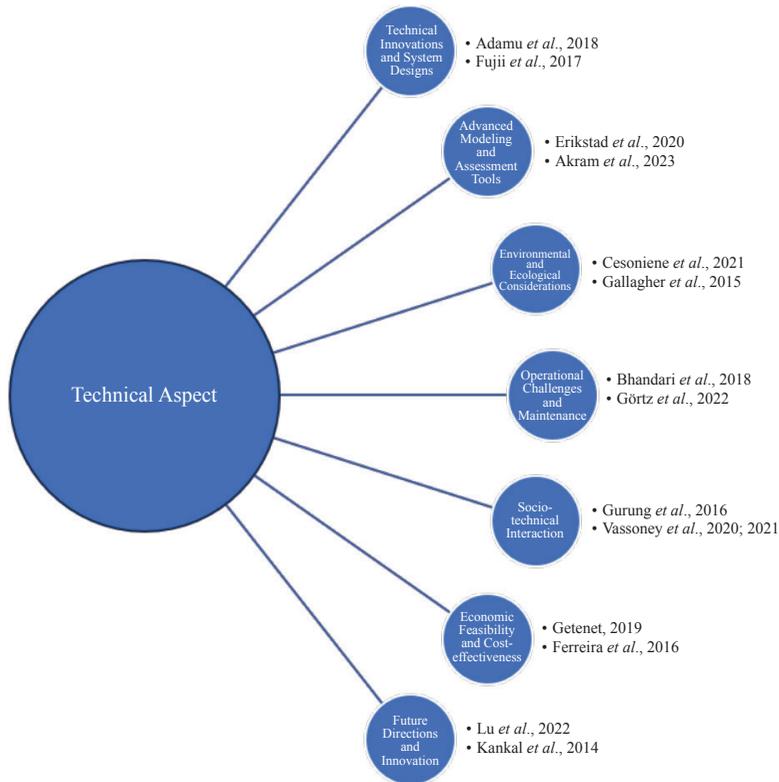


Figure 9: Technical aspect and references

turbine selection to broader environmental and ecological impacts.

The diversity of research in Figure 9 highlights the multifaceted nature of developing and managing hydropower resources effectively and sustainably to answer RQ4. Several key themes emerge from these references.

Technical Innovations and System Designs

Several studies such as Fujii *et al.* (2017) and Adamu *et al.* (2018) detail specific technological configurations optimal for small hydropower projects. This includes the choice of turbines such as Kaplan for low head conditions and system designs suited for run-off river projects. These studies emphasise the need for precise technical planning to maximise efficiency and adapt to local geographical and hydrological conditions.

Advanced Modelling and Assessment Tools

Techniques and tools for evaluating and enhancing hydropower systems are crucial. For instance, Erikstad *et al.* (2020) utilised Geographic Information Systems (GIS) and multivariate analyses for environmental impact assessments while Akram *et al.* (2023) discussed a novel fuzzy model for multiattribute group decision-making. This highlights the role of sophisticated analytical tools in optimising hydropower planning and operations.

Environmental and Ecological Considerations

The integration of environmental concerns within technical planning is evident in Cesoniene *et al.* (2021) and Gallagher *et al.* (2015), where the impact on river ecosystems and the selection of turbine types are analysed. These studies reflect an increasing trend toward environmentally sensitive hydropower

development, acknowledging the significant influence of hydropower installations on aquatic life and river physicochemical characteristics.

Operational Challenges and Maintenance

Operational sustainability, which includes serviceability, load factors, and maintenance is addressed in studies such as those of Bhandari *et al.* (2018) and Görtz *et al.* (2022). These aspects are critical for the long-term sustainability of hydropower plants, as efficient operation and regular maintenance are fundamental for achieving the desired output and extending the lifespan of the facilities.

Socio-technical Interactions

The intersection of technical and social aspects has been explored in various studies such as Gurung *et al.* (2016) and Vassoney *et al.* (2020; 2021), where social acceptance and integrated assessment tools play pivotal roles in the sustainable management of hydropower projects. These interactions underscore the importance of considering human and community factors in the technical planning and operation phases.

Economic Feasibility and Cost-effectiveness

Economic considerations are intertwined with technical assessments in determining the viability of hydropower projects. The works of Ferreira *et al.* (2016) and Getenet (2019) discuss the cost implications and financial assessments crucial for project approval and continuation. Cost management and technical assessments ensure that projects are environmentally, technically sound, and economically viable.

Future Directions and Innovation

Future-oriented studies such as those by Lu *et al.* (2022) involving advanced diagnostics and digital modelling while Kankal *et al.* (2014) focusing on sustainable energy resources, suggest a forward-looking approach to hydropower technology. These innovations aim to enhance the efficiency and sustainability of hydropower systems, pushing the boundaries of traditional methodologies.

The technical aspects of hydropower sustainability require a multidimensional approach that balances innovation with practicality and environmental stewardship with economic feasibility. The continuous evolution of technology, along with integrated environmental and socioeconomic strategies is essential for the sustainable development of hydropower. As such, ongoing research and development in this field are crucial for addressing the emerging challenges and leveraging new opportunities in hydropower generation.

In conclusion, the technical aspects of hydropower sustainability are vital for ensuring that hydropower projects are efficient, reliable, and both environmentally and economically sustainable. A comprehensive technical assessment of hydropower projects, as highlighted in Figure 9, involves diverse considerations, including engineering design, turbine selection, environmental impact, risk management, and socioeconomic integration. These elements emphasise the importance of adopting advanced technologies, innovative modelling tools, robust risk management strategies, and sustainable design practices to optimise hydropower generation while minimising adverse effects. Technical innovations, such as the development of turbines suited for specific hydrological conditions and advanced system designs, are crucial for maximising efficiency and reducing environmental impacts. The use of advanced modelling and assessment tools like GIS and multi-attribute decision-making models enhance the evaluation of environmental and social impacts, helping to mitigate risks associated with hydropower development. Integrating environmental considerations into technical planning such as designing environmentally sensitive systems and selecting appropriate turbines helps preserve river ecosystems and maintain water quality. Additionally, operational sustainability is essential for the long-term success of hydropower plants, where efficient operation and regular maintenance practices reduce the risk of unexpected failures and minimise economic and environmental losses.

Furthermore, socio-technical interactions, including community engagement and social acceptance are crucial for managing the risks associated with hydropower projects. Incorporating social factors into technical planning helps anticipate and mitigate potential conflicts, ensuring that projects are sustainable on a social level. Economic feasibility is also closely linked to technical considerations, with comprehensive cost management and financial planning essential to minimise risks related to funding, investment, and economic fluctuations.

Therefore, effective risk management is fundamental to the technical sustainability of hydropower projects. This involves identifying, assessing, and mitigating risks associated with hydrological variability, equipment failure, construction delays, regulatory changes, and environmental opposition. Advanced diagnostic tools, predictive maintenance technologies, and real-time monitoring systems can help manage these operational risks and extend the lifespan of hydropower infrastructure. Moreover, contingency planning and adaptive management strategies enable flexibility in responding to unforeseen challenges such as climate change impacts on water availability and changes in regulatory policies.

Future-oriented innovations in hydropower technology such as advanced diagnostics, digital modelling, and sustainable resource management are critical for addressing emerging challenges

and enhancing the efficiency and resilience of hydropower systems. The ongoing evolution of technology, combined with integrated environmental, social, and economic strategies is essential for the sustainable development of hydropower. By focusing on comprehensive risk management and incorporating innovative practices, hydropower can continue to play a pivotal role in global sustainable energy strategies, ensuring long-term resilience and sustainability in the face of future challenges.

Hydropower Implication

Hydropower plays a significant role in the sustainability of energy generation, focusing on balancing economic, environmental, and social considerations. The sustainability of hydropower projects involves assessing energy production and the negative social and environmental externalities associated with dams (Moran *et al.*, 2018). Meanwhile, there have been evolving viewpoints regarding the sustainability of large hydropower installations. There has been a notable increase in support for developing SHPs (Couto & Olden, 2018). Efforts are being made to move from individual assessments of hydropower projects toward energy system planning to ensure that projects align with low-carbon power generation standards (Opperman *et al.*, 2023). Table 2 is a collection of studies that discuss the impacts of sustainable hydropower, which are grouped into sustainable aspects.

Table 2: Impact of sustainability

Sustainability Aspect	Impact	References
Economic	The primary focus here is on providing economic benefits, including job creation, financial savings, economic benefits, livelihood improvement, and overall economic development.	(Khan, 2015)
Economic and environmental	Similar to the purely economic category, this aspect emphasises economic benefits but suggests a linkage with environmental considerations like minimising carbon footprint and others.	(Adamu <i>et al.</i> , 2018), (Fanaian <i>et al.</i> , 2015), (Vougioukli <i>et al.</i> , 2017)

Environmental	Impacts are varied, suggesting various environmental benefits or concerns such as reducing GHG emissions, supporting ecosystem services, conservation efforts, improving water quality, addressing pollution, promoting renewable energy, and other ecological benefits.	(Bidoglio <i>et al.</i> , 2019), (Bradford, 2022), (Cesoniene, <i>et al.</i> , 2021), (Demir <i>et al.</i> , 2021), (Dhaubanjari <i>et al.</i> , 2021), (Fortes Westin <i>et al.</i> , 2014), (Herath <i>et al.</i> , 2022), (Kovalyshyna <i>et al.</i> , 2021), (Pracheil <i>et al.</i> , 2019), (Punys & Jurevičius, 2022), (Todorova <i>et al.</i> , 2016), (Tomczyk <i>et al.</i> , 2019), (Stefanyshyn & Vlasiuk, 2019), (Macfarlane & Olive, 2021), (Doria <i>et al.</i> , 2017), (Erlewein, 2013), (Fuchs <i>et al.</i> , 2013), (Geller & Meneses, 2016), (McManamay <i>et al.</i> , 2020), (Rambo <i>et al.</i> , 2017), (Scherer & Pfister, 2016)
Social	The impacts under this category are also varied, indicating a focus on social benefits or concerns such as community development, health improvements, and social well-being.	(Barcellos <i>et al.</i> , 2018), (Cortés-Borda <i>et al.</i> , 2022), (Diduck <i>et al.</i> , 2013), (Peng <i>et al.</i> , 2021), (Veronez <i>et al.</i> , 2018), (Wu <i>et al.</i> , 2017), (Wu <i>et al.</i> , 2017)
Social and economic	Various impacts likely cover social benefits like community development, employment opportunities, social welfare, improved livelihoods, and economic benefits.	(Aung <i>et al.</i> , 2021), (Catolico <i>et al.</i> , 2021), (Y. Liu <i>et al.</i> , 2015), (Ribas <i>et al.</i> , 2019), (Sgarbi <i>et al.</i> , 2019)
Social, economic, and environmental	This aspect uniquely highlights social and economic benefits and environmental concerns, suggesting projects or studies that balance economic development with environmental stewardship.	(Bakker & Hendriks, 2019), (Bhandari <i>et al.</i> , 2018), (Ehrbar <i>et al.</i> , 2018), (Igliński <i>et al.</i> , 2022), (Lopes <i>et al.</i> , 2022), (Mortey <i>et al.</i> , 2017), (Peters <i>et al.</i> , 2021), (Shi, 2022), (Vassoney <i>et al.</i> , 2020), (Vassoney <i>et al.</i> , 2021)
Social and environmental	The impacts are varied, indicating projects or studies that address social issues and environmental concerns such as community engagement in conservation efforts or the social impacts of environmental changes.	(Hanna <i>et al.</i> , 2016), (Morimoto, 2013), (Wang <i>et al.</i> , 2014)
Technical	The impacts include potential new power generation, turbines, electricity infrastructure, and technology.	(Getenet, 2019), (Fujii <i>et al.</i> , 2017), (Fujii & Sawadate, 2018), (Ferreira, <i>et al.</i> , 2016), (Görtz <i>et al.</i> , 2022), (Gurung <i>et al.</i> , 2016), (Korkovelos <i>et al.</i> , 2018), (Lucchetti <i>et al.</i> , 2013), (Lu <i>et al.</i> , 2022), (Silvério <i>et al.</i> , 2018), (Akram <i>et al.</i> , 2023), (Hatata <i>et al.</i> , 2019), (Ji <i>et al.</i> , 2015), (Punys <i>et al.</i> , 2019), (Šilinis <i>et al.</i> , 2020)

Technical and economic	The impact of such technical strategies is to obtain economic benefits.	(Gallagher <i>et al.</i> , 2015), (Gernaat <i>et al.</i> , 2017), (Kankal <i>et al.</i> , 2014), (Taus & Beer, 2022), (Tefera & Kasiviswanathan, 2022), (Tettenborn & Sartorius, 2020), (Tuna, 2013), (Soulis <i>et al.</i> , 2016)
Technical and environment	The impact of such technical strategies on obtaining environmental benefits.	(Gholami & Kaboli, 2022), (Torres-Herrera & Lozano-Medina, 2021), (Hidayani <i>et al.</i> , 2017), (Kuniyal <i>et al.</i> , 2019), (Ma <i>et al.</i> , 2019), (Meriç, 2022), (Oberle <i>et al.</i> , 2016), (Su <i>et al.</i> , 2015), (van Vliet <i>et al.</i> , 2016), (Ali Washakh <i>et al.</i> , 2019), (Xue & Sun, 2018), (L. Zhang <i>et al.</i> , 2020), (Erikstad <i>et al.</i> , 2020), (Kumar & Katoch, 2014), (Pang <i>et al.</i> , 2015), (Simonov <i>et al.</i> , 2019), (Song <i>et al.</i> , 2020), (van Treeck <i>et al.</i> , 2021), (X. Liu & He, 2012)

Table 1 reveals a diverse focus across the sustainability spectrum, particularly on environmental and technical aspects. Environmental sustainability appears to be the most researched or reported, followed closely by technical sustainability and its subsets (technical-economic and technical-environment), highlighting the critical role of technological innovation in addressing sustainability challenges. Social and integrated (social-economic-environmental) aspects also receive notable attention, underlining the importance of holistic approaches to sustainability that consider multiple dimensions.

Environmental Impact

The landscape of environmental impacts is vast and complex, encompassing various factors that interact to shape ecosystems and habitats. Each element contributes to the intricate balance of nature from deforestation to pollution and from erosion to climate change. Fish migration, habitat preservation, and aquatic life are intricately linked to water quality, sedimentation, and flow patterns, which can be disrupted by waste disposal and siltation. The consequences ripple through

ecosystems, affecting macroinvertebrates, fishery productivity, and the food web. Moreover, changes in hydrological regimes and river discharge can lead to landslides, riverbank collapse, and submergence, posing hazards to humans and wildlife alike. Climate change exacerbates these challenges, altering water temperatures and precipitation patterns, and exacerbating natural flow disruptions. In the face of such complexities, efforts toward mitigation and ecological restoration are paramount, focusing on environmental flow management, habitat conservation, and mitigating emissions.

Protecting protected areas, preserving biodiversity, and promoting sustainable land use practices are crucial steps in safeguarding the integrity of our ecosystems and mitigating environmental costs. Additionally, recognising the value of ecological services such as avoiding emissions and depleting nonrenewables underscores the importance of holistic approaches to environmental management. Fostering resilience and sustainability requires a concerted effort to address the many factors influencing ecological health, from the local to the global scale.

The social impacts of various factors on hydropower projects are diverse and multifaceted. Displacement of communities, loss of livelihoods, and disruptions to cultural identity pose significant challenges, as do concerns regarding migration and colonisation. Meanwhile, hydropower projects often bring about job creation and investment opportunities, they also entail risks such as traffic congestion, safety hazards, and conflicts over shared benefits. Additionally, water resource management, irrigation, and drought/flood protection issues highlight the complexities of balancing economic development with environmental sustainability.

Furthermore, human health, recreational opportunities, and heritage site preservation underscore the importance of holistic planning and stakeholder engagement. Public perception, acceptance, legal obstacles, and compensation fees further shape the landscape of hydropower development. Managing functional and aesthetic impacts and addressing concerns about visual impact and infrastructure development are integral to ensure the long-term success and sustainability of hydropower projects. Overall, navigating the challenges and opportunities of hydropower development requires a comprehensive understanding of stakeholder preferences, innovative approaches, and community cohesion to foster positive outcomes while mitigating potential risks.

From an economic perspective, factors such as job creation, capital and operating costs, incentives, and development periods play pivotal roles in determining project viability and sustainability. Additionally, resource availability, reduced dependency on imported energy, and regional development contribute to the broader economic impact of hydropower initiatives. Furthermore, the tourism potential of hydropower sites, alongside benefits in navigation and irrigation, underscores their significance beyond electricity generation while also considering safety and reliable service delivery. On the technical front, efficiency, proven technology, and the

life span of hydropower systems are critical factors for ensuring reliable and sustainable energy production. Moreover, considerations such as construction and maintenance costs and expensive mitigation measures must be weighed against drought, flood protection, and water supply benefits. From a financial perspective, metrics such as the Internal Rate of Return (IRR), Net Present Value (NPV), payback period, and annual benefits provide insights into hydropower projects' economic feasibility and long-term profitability. Finally, assessing the Levelised Cost of Electricity (LCOE), health costs, and energy demand can aid in understanding the overall economic and societal implications of hydropower development.

Various factors come into play in the technical development of hydropower projects, each crucial for ensuring efficient and sustainable energy production. Among these considerations are availability, feasibility, and accessibility, which dictate the practicality and accessibility of potential sites for construction. The development period is also significant, influencing the timeline and resource allocation required for project completion. Once construction begins, factors such as slope, alignment, and structure volume become essential for determining the layout and efficiency of the hydropower infrastructure. Efficiency, in particular is paramount because it directly impacts the productivity and output of the hydropower system. This efficiency is influenced by flow, discharge, and intake height, which govern the movement and utilisation of water resources.

Additionally, the typology of the hydropower system, including its design and configuration, plays a crucial role in determining its operational capabilities and flexibility. Furthermore, considerations such as head, river length, and installed capacity contribute to the overall capacity and effectiveness of the hydropower facility. As the system operates, factors such as demand response, storage capacity, and reserve capacity become vital for managing fluctuations in energy demand and ensuring grid stability. Transmission capabilities

also play a critical role in efficiently delivering hydropower-generated electricity to end-users. Finally, factors such as black-start capability and productivity impact the resilience and long-term viability of the hydropower system, ensuring its ability to recover from disruptions and maintain consistent output over time.

The Benefit of Hydropower Sustainability Implication

Hydropower presents a complex interplay of environmental, social, economic, and technical considerations that are pivotal in determining its sustainability implications. From an environmental standpoint, the development of hydropower projects poses significant challenges, particularly concerning biodiversity loss, deforestation, and alterations in water quality. The construction of dams and reservoirs disrupts aquatic and terrestrial ecosystems, adversely affecting biodiversity, sedimentation, and water quality. Note that the environmental impact extends to climate change, with hydropower development intersecting with challenges and opportunities to mitigate its effects. However, sustainable practices in SHP offer promising solutions to minimise environmental impacts and enhance sustainability.

On the social front, implementing hydropower projects has had a myriad of impacts on communities, cultures, and ecosystems. Displacement and resettlement, often associated with large infrastructure projects, raise significant social concerns such as disrupted livelihoods and cultural preservation. Moreover, the effects of these projects on migration, urbanisation, and social inequality underscore the need for effective stakeholder engagement and community participation to ensure social sustainability. Balancing economic benefits with social considerations and addressing legal and ethical implications are crucial for fostering positive social outcomes.

Economically, hydropower projects contribute significantly to economic

development through revenue generation, job creation, and infrastructure improvement. However, displacement, environmental damage, and economic sustainability must be addressed to maximise benefits and minimise adverse impacts. Comprehensive economic evaluations, including cost-benefit analyses and consideration of regional economic development, are essential for assessing the viability and sustainability of projects. Moreover, policy frameworks are crucial for incentivising sustainable development and promoting economic growth while mitigating negative impacts.

From a technical perspective, ensuring the efficiency and sustainability of hydropower projects requires addressing operational challenges and employing innovative technologies. Technical efficiency, system design considerations, and sustainability factors are critical for optimising hydropower systems and transitioning toward automation. Consequently, robust hydrological and geographical assessments and effective risk management strategies are essential for selecting suitable sites and mitigating project risks.

The sustainability implications of hydropower development are multifaceted and require integrated approaches that consider environmental, social, economic, and technical aspects. By adopting sustainable practices, engaging stakeholders effectively, and implementing robust management strategies, policymakers and stakeholders can work toward maximising the benefits of hydropower while minimising its negative impacts, thus, contributing to long-term sustainability and socioeconomic development.

The Challenges

Hydropower is a significant renewable energy source, but its sustainability involves multifaceted challenges across environmental, social, economic, and technical domains. Understanding and addressing these challenges are imperative for ensuring the long-term viability of hydropower projects.

Hydropower sustainability faces environmental challenges due to its diverse impacts on ecosystems. Dam construction and reservoir formation disrupt aquatic and terrestrial ecosystems, leading to biodiversity loss, sedimentation, and eutrophication. Deforestation associated with hydropower projects exacerbates erosion and threatens species extinction. Additionally, altered sediment transport dynamics and water quality degradation compound environmental concerns. Effective environmental assessment and management are essential for understanding and mitigating these impacts, emphasising the need for comprehensive assessments and sustainable planning strategies. Hence, implementing best practices such as environmental flow management, habitat restoration, and integrated watershed management to address these environmental challenges can help mitigate adverse impacts while promoting ecosystem health.

The growth of hydropower poses social issues, including displacement, inequality, community involvement, and cultural preservation. Large-scale infrastructure initiatives frequently result in urbanisation, migration, and disrupted livelihoods, disproportionately affecting marginalised communities. Furthermore, environmental and social impacts hinder project success due to inadequate stakeholder engagement and opposition. Balancing economic benefits with social well-being and ensuring inclusive development through effective engagement and participation are crucial for enhancing social sustainability in hydropower projects. Potential solutions include early and continuous stakeholder engagement, fair compensation and resettlement plans, and incorporating traditional knowledge and cultural preservation measures in project planning to foster social acceptance and reduce conflict.

Economic considerations play a pivotal role in hydropower sustainability, with projects contributing to economic development through revenue generation, job creation,

and infrastructure improvement. However, economic sustainability challenges such as displacement, environmental damage, and the need for adaptive management highlight the complexity of balancing economic growth with environmental and social concerns. Moreover, robust economic evaluations and policy frameworks are essential for assessing project viability, promoting sustainable development, and minimising negative impacts. Implementing adaptive management practices such as flexible policy frameworks and economic incentives for sustainable practices can enhance economic resilience and reduce long-term risks.

On the technical front, ensuring the efficiency and sustainability of hydropower systems requires addressing operational challenges, hydrological assessments, and risk management. Enhancements in system design, operational efficiency, and risk assessment methodologies are crucial for optimising hydropower functionality and mitigating technical risks. Furthermore, technological advancements and policy frameworks are vital in driving sustainable energy resource development and aligning with evolving energy policies. Adopting state-of-the-art technologies like real-time monitoring systems, predictive maintenance, and improved turbine designs can help manage technical risks and enhance system reliability.

Note that addressing the challenges of hydropower sustainability requires a holistic approach that integrates environmental, social, economic, and technical considerations. Effective environmental assessment and management, inclusive stakeholder engagement, robust economic evaluations, and technological advancements are key pillars for sustainable hydropower development and management. By incorporating best practices such as adaptive management, community-based approaches, and technological innovation, stakeholders can navigate the complexities of hydropower projects more effectively and ensure their long-term success. By prioritising sustainability and adopting interdisciplinary strategies,

stakeholders can navigate the complexities of hydropower projects and ensure their long-term success.

Hydropower Sustainability Assessment

The International Hydropower Association (IHA) developed the Hydropower Sustainability Assessment Protocol (HSAP) in 2004 as part of the IHA Sustainability Guidelines, focusing on social, economic, environmental, and technical criteria for assessing hydroelectric dam projects (Mortey *et al.*, 2019; Yuguda *et al.*, 2022). The HSAP is a globally recognised tool that provides a standardised framework for evaluating the sustainability of hydropower projects throughout their lifecycle—from planning and preparation to implementation and operation. The protocol uses a set of performance criteria and indicators across four key pillars—environmental, social, technical, and economic systems to ensure comprehensive assessments that identify potential impacts, risks, and benefits associated with hydropower projects. It involves multiple stakeholders, including project developers, government agencies, local communities, and environmental experts to ensure diverse perspectives are integrated into the assessment process.

The HSAP has provided a framework for the sustainability assessment of hydropower projects, emphasising the mitigation of impacts through a comprehensive evaluation process (Doujak *et al.*, 2021; Roy & Roy, 2022). Various studies have highlighted the importance of the HSAP in promoting sustainable practices within the hydropower industry. The protocol has been utilised to develop conceptual models for mitigating impacts and ensuring sustainable water-based power sector practices (Huang *et al.*, 2018; Roy & Roy, 2022). Additionally, the HSAP has been integrated into the evaluation standards for hydropower projects, guiding assessments based on social, economic, and environmental criteria (Xu *et al.*, 2020; Teguh & Nisaa, 2021). The protocol has also been recognised for its role in benefit-sharing frameworks, contributing to the sustainability

of hydropower businesses and the well-being of communities (Jiménez-Inchima *et al.*, 2021).

Meanwhile, the HSAP offers a comprehensive framework for evaluating the sustainability of hydropower projects and answering the RQ5. Several obstacles contribute to its limited adoption:

Complexity and Resource Intensiveness

Implementing HSAP requires significant time, resources, and expertise. Many stakeholders, particularly in developing countries or smaller organisations may lack the capacity or funding to conduct thorough assessments using the protocol.

Lack of Awareness and Capacity

Despite efforts by the IHA to promote the HSAP, awareness of its existence and understanding of its value may be limited among relevant stakeholders, including government agencies, project developers, and financial institutions. Furthermore, the capacity to apply the protocol effectively may be lacking in many regions.

Resistance from Developers and Governments

Some hydropower developers and government agencies may perceive the HSAP as an additional regulatory burden or a potential barrier to project development. They may resist adopting voluntary sustainability assessment protocols if they perceive them impeding project timelines or increasing costs.

Limited Incentives for Compliance

In some cases, hydropower developers may have insufficient incentives to voluntarily comply with sustainability assessment protocols such as the HSAP. Hence, developers may prioritise cost and time savings over sustainability considerations if there are no tangible benefits or incentives for meeting sustainability standards.

Political and Institutional Challenges

Political considerations and institutional barriers can also hinder the adoption of the HSAP. Government agencies may sometimes lack the regulatory frameworks or enforcement

mechanisms necessary to incentivise or comply with sustainability standards for hydropower projects.

Contextual Challenges

The applicability of the HSAP may vary depending on the specific context of a hydropower project, including its location, scale, environmental, and social characteristics. Thus, adapting the protocol to suit diverse project contexts and stakeholder needs can be challenging.

Addressing these obstacles requires concerted efforts from international, national, and local stakeholders to raise awareness, build capacity, provide incentives, and integrate sustainability considerations into decision-making processes related to hydropower development. Additionally, fostering dialogue and collaboration among stakeholders can help overcome resistance and promote the adoption of sustainability assessment protocols such as the HSAP.

The methodology standard of the HSAP is designed to provide a rigorous and systematic framework for evaluating the sustainability of hydropower projects. The lack of standardised and internationally accepted standards was the main gap before 2021 until August of its launch at the 2021 World Hydropower Congress titled “Hydropower Sustainability Standard (HSS)” (Hydropower Sustainability Council, 2021), which is now part of a certification scheme, making it more binding than the voluntary measurements in the initial HSAP (Ramamurthy *et al.*, 2023). As this literature review is limited to the end of 2022, there are few studies on using the HSS in published journals.

The HSS of the HSAP is designed to be flexible and adaptable to different project contexts and stakeholder needs. Other than that, it guides conducting assessments using qualitative and quantitative methods, including data collection, stakeholder consultations, site visits, and expert reviews. The standard emphasises the importance of a multistakeholder

approach to ensure that diverse perspectives and interests are considered during the assessment process.

Role of Hydropower

Carbon Emissions Reduction

Hydropower’s large-scale clean electricity generation effectively reduces carbon emissions, facilitating the transition to a low-carbon future. Hydropower decarbonises the energy sector and mitigates climate change by displacing fossil fuel-based generation. Alsaleh and Abdul-Rahim (2022) carbon dioxide release in EU28 nations can be effectively reduced by increasing hydropower output and good governance. The study revealed that the growth of the hydropower industry has a significant negative association with carbon dioxide released in the EU28 region. Increasing hydropower energy production by one leads to a decrease in carbon dioxide release of 0.809. However, the study has limitations in that the research utilised panel data from EU28 nations, which may not fully capture each country’s diversity and unique characteristics.

Energy Transition

Hydropower’s reliability, grid stability, and ability to provide baseload and dispatchable power make it an integral part of the energy transition. Baseload power is the consistent, unvarying electricity supply required to meet the minimum demand on the grid, provided by power plants that run continuously at a steady rate. Dispatchable power, on the other hand is a flexible power supply that can be adjusted or dispatched as needed to match demand fluctuations. It is essential to balance supply and demand on the grid and support the integration of renewable energy sources. It complements other renewable sources, helping to overcome the intermittency challenges associated with solar and wind power. Alternatively, Gonzalez *et al.* (2023) highlighted the importance of reservoir hydropower as a cost-effective technology for providing the flexibility required to accommodate intermittent renewables. The

author also acknowledges the negative impacts of hydropower operations on river ecosystems and the potential for multisector conflicts. Hence, the combination of hydropower with emerging technologies such as energy storage can further enhance the flexibility and reliability of the energy system.

Economic Development

Hydropower projects have the potential to drive economic growth by creating jobs, attracting investments, and generating revenue. The income generated from hydropower can be reinvested in local communities, supporting infrastructure development, education, healthcare, and other socioeconomic initiatives. Alsaleh and Abdul-Rahim's (2021) findings emphasise the need for investment in the growth of the hydropower industry, which can create job opportunities and stimulate economic activity in the renewable energy sector. This paper also establishes the importance of considering water resource conservation and sustainability in hydropower production, contributing to EU economies' overall environmental and economic well-being.

Finding

Hydropower has emerged as a promising contender for pursuing sustainable energy solutions, offering clean and renewable electricity generation. Nonetheless, as we harness the power of water to fuel our progress, it is imperative to acknowledge and mitigate the potential for disasters that can jeopardise the long-term viability of these projects. Disaster potential assessment is pivotal to broader sustainability evaluations for hydropower initiatives.

The importance of disaster potential assessment in hydropower sustainability cannot be overstated. It is a proactive measure for identifying, understanding, and mitigating the risks associated with natural disasters and other unforeseen events. Such assessments delve into the vulnerabilities of the project site, considering factors such as geological conditions, seismic activity, flood patterns (Kuniyal *et al.*, 2019),

and climate change projections (Nguyen-Tien *et al.*, 2018). By analysing disaster potential, developers and policymakers can gain insights into potential weak points and areas that require reinforcement, thus, enabling the implementation of robust preventive measures.

A disaster in the context of hydropower can have cascading effects on environmental, social, and economic fronts. Floods, earthquakes, landslides, or dam failures can lead to extensive damage (King *et al.*, 2017), loss of life, displacement of communities, and energy supply disruption. These incidents not only impede progress but can also incur exorbitant costs for rehabilitation and recovery. Disaster potential assessment acts as a shield, ensuring that hydropower projects are equipped to withstand natural forces and recover swiftly in the aftermath of an event.

Furthermore, integrating disaster potential assessments into broader sustainability evaluations aligns with responsible and adaptive development principles. This underscores the need to create synergy between human aspirations and the ecosystem's resilience. By considering disaster scenarios, the assessment prompts incorporating strategies that enhance the project's capacity to coexist harmoniously with its surroundings. These strategies can include engineered flood management (Nowak *et al.*, 2022), early warning systems, and designing infrastructure that accommodates changing water levels and extreme weather patterns.

In the era of climate change, disaster potential assessment is not a mere formality but rather a strategic imperative. As the frequency and intensity of extreme events increase, the resilience of hydropower projects becomes a determining factor in their long-term success. Correspondingly, developers and stakeholders demonstrate their commitment to adaptability, accountability, and future-proofing by integrating potential disaster assessments with sustainability evaluations. In the last decade, only 10 studies mentioned disasters in sustainability assessments (Table 3), of which only three out of 177 (1.7%) sustainability

Table 3: Several sustainability assessment studies related to disasters in 2012 to 2022

Authors	Hazard	Main Object
Yu <i>et al.</i> (2012)	Floods	Flood control
Hidayani <i>et al.</i> (2017)	Floods	Flood control
King <i>et al.</i> (2017)	Earthquakes	Dam safety simulation
Nguyen-Tien <i>et al.</i> (2018)	Climate change	Environment impact
Kuniyal <i>et al.</i> (2019)	Floods, landslides, earthquakes	Potential assessment
Ali Washakh <i>et al.</i> (2019)	Floods	Potential assessment
Dhaubanjari <i>et al.</i> (2021)	Landslides, earthquake	Potential assessment
Nowak <i>et al.</i> (2022)	Floods	Flood impact
Lazo-Vásquez <i>et al.</i> (2022)	Floods	Reservoir flooding
Hamidifar <i>et al.</i> (2022)	Floods	Reservoir flooding

assessment studies considered the potential for recurrent disasters to occur.

Several hydropower sustainability assessment studies have delved into the potential occurrence of hazards, particularly geohazards. Notably, the works of Ali Washakh *et al.* (2019), Kuniyal *et al.* (2019), and Dhaubanjari *et al.* (2021) stand out in this domain. Note that geohazards encompass natural events such as floods, landslides, and earthquakes. These studies collectively contribute to a comprehensive understanding of the vulnerability and resilience of hydropower projects in the face of these hazards.

Focusing on specific elements within geohazards, landslides, and earthquakes warrants distinct attention. Kuniyal *et al.* (2019) and Dhaubanjari *et al.* (2021) offered insights into assessing potential landslides and earthquakes. These two studies meticulously examined the geological and seismic conditions surrounding hydropower projects, highlighting the significance of evaluating these specific hazards.

An evolution in disaster risk assessment is evident, emphasising the interconnectedness of vulnerability, capacity, and hazards. The concept of vulnerability has evolved beyond being solely defined by exposure to hazards. Rather, it encompasses the capacity to cope, endure, and recover from their impacts. This shift is reflected

in the risk equation, where vulnerability now interacts with capacity, effectively depicted as $\text{Risk} = \text{Hazard (H)} \times \text{Vulnerability (V)} / \text{Capacity (C)}$. Recognising capacity as a pivotal component acknowledges the role of human capabilities in mitigating hazard effects (UNDRR, 2004).

However, there is a notable gap in sustainability assessments related to disasters—the absence of comprehensive risk assessments that incorporate disaster capacity evaluation. Meanwhile, numerous studies have explored the potential occurrence of hazards and their associated vulnerabilities. However, the inclusion of disaster capacity assessments remains relatively limited. The integration of capacity assessment is crucial for a holistic understanding of a hydropower project's resilience to disasters. As the field progresses, bridging this gap in sustainability assessments could enhance the accuracy and effectiveness of risk evaluations (UNDRR, 2004).

Conclusions

An SLR on hydropower sustainability reveals a multifaceted landscape of benefits and challenges associated with hydropower development. Analysing peer-reviewed articles from 2012 to 2022 provides comprehensive insights into hydropower sustainability's environmental, social, economic, and technical aspects.

Environmental Impacts and Sustainability Challenges (RQ1)

Hydropower projects while beneficial for clean energy generation and carbon emissions reduction, pose significant environmental risks, including biodiversity loss, ecosystem disruption, sedimentation, and water quality degradation. Hence, effective environmental assessment and management strategies are critical for mitigating these impacts and promoting the sustainable use of natural resources.

Social Impacts and Challenges (RQ2)

Developing hydropower projects often leads to social challenges such as community displacement, loss of livelihoods, and cultural disruptions. Addressing these issues requires comprehensive social impact assessments, stakeholder engagement, and policies that promote social equity and community well-being.

Economic Impacts and Sustainability Considerations (RQ3)

Hydropower significantly contributes to economic development, particularly through job creation, infrastructure improvement, and the provision of a reliable energy supply. However, economic sustainability is challenged by high initial investments, operational costs, and potential economic disparities. Policy frameworks and investment strategies must balance economic benefits with social and environmental costs to maximise sustainability.

Technical, Operational, Policy, and Risk Management Considerations (RQ4)

Technical innovations, system design optimisations, and robust risk management practices are essential for the sustainable operation of hydropower plants. Integrating advanced modelling tools, efficient turbine technologies, and adaptive management strategies can enhance the sustainability of hydropower projects.

Barriers to Sustainable Hydropower Assessments (RQ5)

The implementation of comprehensive sustainability assessments is hindered by factors such as the complexity and resource intensiveness of protocols such as the HSAP, lack of awareness, resistance from developers, and insufficient incentives for compliance. Addressing these barriers requires concerted efforts to build capacity, raise awareness, and provide incentives for sustainable practices.

Conclusions, Policy Implications, and Recommendations

The findings highlight the need for enhanced regulatory frameworks, greater stakeholder engagement, and the adoption of advanced technologies to mitigate negative impacts while maximising the benefits of hydropower. Policymakers, industry stakeholders, and the research community are urged to adopt and implement the proposed assessment framework to facilitate the development of hydropower projects that exemplify sustainability.

The sustainable development of hydropower necessitates an integrated approach that considers environmental, social, economic, and technical dimensions. The hydropower industry can contribute significantly to the global transition toward a more sustainable and equitable energy future by embracing comprehensive assessment frameworks and robust policy measures. In addition to disaster potential assessments of sustainability, evaluations are crucial for ensuring the resilience and long-term viability of hydropower projects in the face of natural and anthropogenic challenges. Future research and policy development should continue to address these challenges to enhance the sustainability of hydropower globally.

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Conflict of Interest Statement

The authors declare that they have no conflict of interest.

References

- Adamu, V. H., Nana, A., Jati, A. P. P., Tulabing, R., & Luis, R.-S. S. (2018). Technical-economic prefeasibility assessment of an Off-Grid Mini-hydropower Plant for an agribusiness resort in Kaduna Nigeria BT - Exergy for a better environment and improved sustainability 2: Applications. In F. Aloui & I. Dincer (Eds.), *Green energy and technology* (pp. 1193-1203). Springer International Publishing. https://doi.org/10.1007/978-3-319-62575-1_83
- Adhikari, D. R., Techato, K., & Jariyaboon, R. (2024). A systematic literature review on renewable energy technologies for energy sustainability in Nepal: Key challenges and opportunities. *International Journal of Renewable Energy Development*, 13(2), 206-222. <https://doi.org/10.61435/ijred.2024.60032>
- Akram, M., Naz, S., Feng, F., & Shafiq, A. (2023). Assessment of hydropower plants in Pakistan: Muirhead Mean-Based 2-Tuple Linguistic T-spherical Fuzzy Model combining SWARA with COPRAS. *Arabian Journal for Science and Engineering*, 48(5), 5859-5888. <https://doi.org/10.1007/s13369-022-07081-0>
- Ali Washakh, R. M., Chen, N., Wang, T., Almas, S., Ahmad, S. R., & Rahman, M. (2019). GLOF risk assessment model in the Himalayas: A case study of a hydropower project in the upper Arun River. *Water (Switzerland)*, 11(9), 4-7. <https://doi.org/10.3390/w11091839>
- Alsaleh, M., & Abdul-Rahim, A. S. (2021). Moving toward sustainable environment: The effects of hydropower industry on water quality in EU economies. *Energy & Environment*, 33(7), 1304-1325. <https://doi.org/10.1177/0958305X211039452>
- Alsaleh, M., & Abdul-Rahim, A. S. (2022). The pathway toward pollution mitigation in EU28 region: Does hydropower growth make a difference? *Renewable Energy*, 185, 291-301. <https://doi.org/https://doi.org/10.1016/j.renene.2021.12.045>
- Atkinson, L. Z., & Cipriani, A. (2018). How to carry out a literature search for a systematic review: A practical guide. *BJPsych Advances*, 24(2), 74-82. <https://doi.org/10.1192/bja.2017.3>
- Aung, T. S., Fischer, T. B., & Azmi, A. S. (2021). Social impacts of large-scale hydropower project in Myanmar: A social life cycle assessment of Shweli hydropower dam 1. *International Journal of Life Cycle Assessment*, 26(2), 417-433. <https://doi.org/10.1007/s11367-021-01868-3>
- Azubuikwe, S. I., Nakanwagi, S., & Dike, S. C. (2022). Utilising sustainability assessment framework to obtain a social license to operate in renewable energy projects: The case of Murchison Hydropower Project in Uganda. In G. Woods, J. Górski & G. Mete (Eds.), *The Plaggrave handbook of social license to operate and energy transitions* (Palgrave Studies in EnergyTransitions ed.) (pp. 1-22). Palgrave Mcmillan.
- Bakker, K., & Hendriks, R. (2019). Contested knowledges in hydroelectric project assessment: The case of Canada's Site C Project. *Water (Switzerland)*, 11(3). <https://doi.org/10.3390/w11030406>
- Barcellos, C., Xavier, D. R., Bulcão, J. A. S., de Oliveira Silva, H. V, Luigi, G., da Silva, D. D. S., Moura, F. H., & Rovere, E. L. L. (2018). Health risk assessment associated with the implementation of the Madeira Hydroelectric Complex, Brazilian Amazon. *Ambiente e Sociedade*, 21. <https://doi.org/10.1590/1809-4422ASOC0019R1VU18L4FT>

- Bhandari, R., Saptalena, L. G., & Kusch, W. (2018). Sustainability assessment of a micro hydropower plant in Nepal. *Energy, Sustainability and Society*, 8(3). <https://doi.org/10.1186/s13705-018-0147-2>
- Bidoglio, G., Berger, M., & Finkbeiner, M. (2019). An environmental assessment of small hydropower in India: The real costs of dams' construction under a life cycle perspective. *The International Journal of Life Cycle Assessment*, 24(3), 419-440. <https://doi.org/10.1007/s11367-018-1458-4>
- Bradford, M. J. (2022). Assessment and management of effects of large hydropower projects on aquatic ecosystems in British Columbia, Canada. *Hydrobiologia*, 849(2), 443-459. <https://doi.org/10.1007/s10750-020-04362-3>
- Catolico, A. C. C., Maestrini, M., Strauch, J. C. M., Giusti, F., & Hunt, J. (2021). Socioeconomic impacts of large hydroelectric power plants in Brazil: A synthetic control assessment of Estreito hydropower plant. *Renewable and Sustainable Energy Reviews*, 151, 111508. <https://doi.org/https://doi.org/10.1016/j.rser.2021.111508>
- César, G. C. L., Keles, J. A., Cordeiro, J., & Lage, M. A. (2020). Assessment of water quality in the reservoir of the peti hydroelectric plant, Minas Gerais. *Geociencias*, 39(3), 817-829. <https://doi.org/10.5016/geociencias.v39i03.15064>
- Cesoniene, L., Dapkiene, M., & Punys, P. (2021). Assessment of the impact of small hydropower plants on the ecological status indicators of water bodies: A case study in lithuania. *Water (Switzerland)*, 13(4). <https://doi.org/10.3390/w13040433>
- Cesoniene, L., Dapkiene, M., Punys, P., Česonienė, L., Dapkienė, M., & Punys, P. (2021). Assessment of the impact of small hydropower plants on the ecological status indicators of water bodies: A case study in lithuania. *Water (Switzerland)*, 13(4). <https://doi.org/10.3390/w13040433>
- Cortés-Borda, D., Polanco, J. andrés, & Escobar-Sierra, M. (2022). Social perception assessment of hydropower sustainability: A stepwise logistic regression modelling. *Environmental Science & Policy*, 134(April), 108-118. <https://doi.org/https://doi.org/10.1016/j.envsci.2022.03.026>
- Couto, T. B. A., & Olden, J. D. (2018). Global proliferation of small hydropower plants – Science and policy. *Frontiers in Ecology and the Environment*, 16(2), 91-100. <http://www.jstor.org/stable/44990898>
- de Pádua Andrade, D., Paschoal, L. R. P., de Sá, O. R., & França, N. (2012). Water quality assessment of fifth-order tributaries of the reservoir at the Marechal Mascarenhas de Morais Hydroelectric power station in the Rio Grande watershed (state of Minas Gerais, Brazil). *Acta Limnologica Brasiliensia*, 24(3), 326-337. <https://doi.org/10.1590/S2179-975X2013005000002>
- Dechasa, A., Aga, A. O., & Dufera, T. (2022). Erosion risk assessment for prioritisation of conservation measures in the watershed of Genale Dawa-3 Hydropower Dam, Ethiopia. *Quaternary*, 5(4). <https://doi.org/10.3390/quat5040039>
- Demir, S., Demirel, Ö., & Okatan, A. (2021). An ecological restoration assessment integrating multi-criteria decision analysis with landscape sensitivity analysis for a hydroelectric power plant project: The Tokat-Niksar case. *Environmental Monitoring and Assessment*, 193(12), 818. <https://doi.org/10.1007/s10661-021-09573-2>
- Dhaubanjhar, S., Lutz, A. F., Gernaat, D. E. H. J. D. E. H. J., Nepal, S., Smolenaars, W., Pradhananga, S., Biemans, H., Ludwig, F., Shrestha, A. B., & Immerzeel, W. W. (2021). A systematic framework for the assessment of sustainable hydropower potential in a river basin – The case of the upper Indus. *Science of the Total Environment*, 786, 147142. <https://doi.org/10.1016/j.scitotenv.2021.147142>

- Diduck, A. P., Pratap, D., Sinclair, A. J., & Deane, S. (2013). Perceptions of impacts, public participation, and learning in the planning, assessment and mitigation of two hydroelectric projects in Uttarakhand, India. *Land Use Policy*, 33, 170-182. <https://doi.org/https://doi.org/10.1016/j.landusepol.2013.01.001>
- Dorber, M., Mattson, K. R., Sandlund, O. T., May, R., & Veronesi, F. (2019). Quantifying net water consumption of Norwegian hydropower reservoirs and related aquatic biodiversity impacts in life cycle assessment. *Environmental Impact Assessment Review*, 76, 36-46. <https://doi.org/10.1016/j.eiar.2018.12.002>
- Doria, H. B., Voigt, C. L., de Campos, S. X., & Randi, M. A. F. (2017). Metal pollution assessment in a Brazilian Hydroelectric Reservoir: *Geophagus brasiliensis* as a suitable bioindicator organism. *Revista Ambiente e Agua*, 12(4), 575-590. <https://doi.org/10.4136/ambi-agua.2061>
- Doujak, E., Hočevár, M., Pummer, E., Federico, V. Di, & Finger, D. C. (2021). A concept for sustainable and digitalized hydropower going beyond the sustainable hydropower sustainability tool. *EGU General Assembly 2021*, online. <https://doi.org/10.5194/egusphere-egu21-6629>
- Ehrbar, D., Schmocker, L., Vetsch, D. F., & Boes, R. M. (2018). Hydropower potential in the periglacial environment of Switzerland under climate change. *Sustainability (Switzerland)*, 10(8). <https://doi.org/10.3390/su10082794>
- Erikstad, L., Hagen, D., Stange, E., & Bakkestuen, V. (2020). Evaluating cumulative effects of small scale hydropower development using GIS modelling and representativeness assessments. *Environmental Impact Assessment Review*, 85(April), 106458. <https://doi.org/10.1016/j.eiar.2020.106458>
- Erlewein, A. (2013). Disappearing rivers — The limits of environmental assessment for hydropower in India. *Environmental Impact Assessment Review*, 43, 135-143. <https://doi.org/https://doi.org/10.1016/j.eiar.2013.07.002>
- Fanaian, S., Graas, S., Jiang, Y., & van der Zaag, P. (2015). An ecological economic assessment of flow regimes in a hydropower dominated river basin: The case of the lower Zambezi River, Mozambique. *Science of the Total Environment*, 505, 464-473. <https://doi.org/10.1016/j.scitotenv.2014.10.033>
- Ferreira, J. H. I., Camacho, J. R., & Malagoli, J. A. (2016). A contribution to the study of the estimate hydroelectric potential for small hydropower plant. *IEEE Latin America Transactions*, 14(7), 3215-3224. <https://doi.org/10.1109/TLA.2016.7587623>
- Ferreira, J. H. I., Camacho, J. R., Malagoli, J. A., & Júnior, S. C. G. (2016). Assessment of the potential of small hydropower development in Brazil. *Renewable and Sustainable Energy Reviews*, 56, 380-387. <https://doi.org/https://doi.org/10.1016/j.rser.2015.11.035>
- Fortes Westin, F., Santos, M. A. Dos, & Duran Martins, I. (2014). Hydropower expansion and analysis of the use of strategic and integrated environmental assessment tools in Brazil. *Renewable and Sustainable Energy Reviews*, 37, 750-761. <https://doi.org/10.1016/j.rser.2014.04.071>
- Fuchs, M., Weilguni, H., Lagler, M., Tensch, R., & Beurteilung, Z. (2013). Wasserkraftprojekte. *Wasserkraftprojekte*, 163-164. <https://doi.org/10.1007/978-3-658-00996-0>
- Fujii, M., & Sawadate, T. (2018). Assessment of potential small hydropower generation: A case study in Otsuchi, Iwate Prefecture, Japan. In Endo, A., & Oh, T. (Eds.), *The water-energy-food Nexus Human - Environmental security in Asia-Pacific ring of fire* (pp. 21-31). Singapore: Springer. https://doi.org/10.1007/978-981-10-7383-0_2

- Fujii, M., Tanabe, S., Yamada, M., Mishima, T., Sawadate, T., & Ohsawa, S. (2017). Assessment of the potential for developing mini/micro hydropower: A case study in Beppu City, Japan. *Journal of Hydrology: Regional Studies*, *11*, 107-116. <https://doi.org/10.1016/j.ejrh.2015.10.007>
- Gallagher, J., Harris, I. M., Packwood, A. J., McNabola, A., & Williams, A. P. (2015). A strategic assessment of micro-hydropower in the UK and Irish water industry: Identifying technical and economic constraints. *Renewable Energy*, *81*, 808-815. <https://doi.org/10.1016/j.renene.2015.03.078>
- Gayen, D., Chatterjee, R., & Roy, S. (2024). A review on environmental impacts of renewable energy for sustainable development. *International Journal of Environmental Science and Technology*, *21*(5), 5285-5310. <https://doi.org/10.1007/s13762-023-05380-z>
- Geller, M. T. B., & Meneses, A. A. D. M. (2016). Life cycle assessment of a small hydropower plant in the Brazilian amazon. *Journal of Sustainable Development of Energy, Water and Environment Systems*, *4*(4), 379-391. <https://doi.org/10.13044/j.sdwes.2016.04.0029>
- Gernaat, D. E. H. J. D. E. H. J., Bogaart, P. W., Vuuren, D. P. V. V., Biemans, H., & Niessink, R. (2017). High-resolution assessment of global technical and economic hydropower potential. *Nature Energy*, *2*(10), 821-828. <https://doi.org/10.1038/s41560-017-0006-y>
- Getenet. (2019). Assessment of hydropower potential of selected rivers in North Shoa Zone, Amhara Regional State, Ethiopia. *American Journal of Energy Research*, *7*(1), 15-18. <https://doi.org/10.12691/ajer-7-1-2>
- Gholami, N., & Kaboli, H. S. (2022). A comparative framework to impact assessment of objective function structure and supply/demand scenario on hydropower operation. *Water Supply*, *22*(1), 833-899. <https://doi.org/10.2166/ws.2021.226>
- Gonzalez, J. M., Tomlinson, J. E., Martínez Ceseña, E. A., Basheer, M., Obuobie, E., Padi, P. T., Addo, S., Baisie, R., Etichia, M., Hurford, A., Bottacin-Busolin, A., Matthews, J., Dalton, J., Smith, D. M., Sheffield, J., Panteli, M., & Harou, J. J. (2023). Designing diversified renewable energy systems to balance multisector performance. *Nature Sustainability*, *6*(4), 415-427. <https://doi.org/10.1038/s41893-022-01033-0>
- Görtz, J., Aouad, M., Wieprecht, S., & Terheiden, K. (2022). Assessment of pumped hydropower energy storage potential along rivers and shorelines. *Renewable and Sustainable Energy Reviews*, *165*. <https://doi.org/10.1016/j.rser.2021.112027>
- Gurung, A. B., Borsdorf, A., Füreder, L., Kienast, F., Matt, P., Scheidegger, C., Schmocker, L., Zappa, M., & Volkart, K. (2016). Rethinking pumped storage hydropower in the European Alps. *Mountain Research and Development*, *36*(2), 222-232. <https://doi.org/10.1659/MRD-JOURNAL-D-15-00069.1>
- Hamidifar, H., Akbari, F., & Rowiński, P. M. (2022). Assessment of environmental water requirement allocation in anthropogenic rivers with a hydropower dam using hydrologically based methods—Case study. *Water (Switzerland)*, *14*(6). <https://doi.org/10.3390/w14060893>
- Hanna, P., Vanclay, F., Langdon, E. J., & Arts, J. (2016). The importance of cultural aspects in impact assessment and project development: Reflections from a case study of a hydroelectric dam in Brazil. *Impact Assessment and Project Appraisal*, *34*(4), 306-318. <https://doi.org/10.1080/14615517.2016.1184501>
- Hatata, A. Y., El-Saadawi, M. M., & Saad, S. (2019). A feasibility study of small hydro power for selected locations in Egypt. *Energy Strategy Reviews*, *24*(April 2018), 300-313. <https://doi.org/10.1016/j.esr.2019.04.013>

- Herath, I. K., Wu, S., Ma, M., & Ping, H. (2022). Heavy metal toxicity, ecological risk assessment, and pollution sources in a hydropower reservoir. *Environmental Science and Pollution Research*, 29(22), 32929-32946. <https://doi.org/10.1007/s11356-022-18525-3>
- Hidayani, F., Sardjono, Y., Fandeli, C., & A.R., R. (2017). Creative environmental energy technology assessment hydroelectric power plant (Case study of Wonogiri Reservoir). *Indonesian Journal of Physics and Nuclear Applications*, 2(3), 101. <https://doi.org/10.24246/ijpna.v2i3.101-110>
- Huang, L., Huang, J., & Wang, W. (2018). The sustainable development assessment of reservoir resettlement based on a BP Neural Network. *International Journal of Environmental Research and Public Health*. <https://doi.org/10.3390/ijerph15010146>
- Hydropower Sustainability Council. (2021). *Hydropower Sustainability Standard version 2.1 draft* (Issue June). https://static1.squarespace.com/static/5c1978d3ee1759dc44fbd8ba/t/60ddb3a844b5887d18fe2341/1625142194189/HS+Standard_July+2021.pdf
- Igliński, B., Krukowski, K., Mioduszewski, J., Pietrzak, M. B., Skrzatek, M., Piechota, G., & Wilczewski, S. (2022). Assessment of the current potential of hydropower for water damming in Poland in the context of energy transformation. *Energies*, 15(3). <https://doi.org/10.3390/en15030922>
- Ji, Y., Huang, G. H., & Sun, W. (2015). Risk assessment of hydropower stations through an integrated fuzzy entropy-weight multiple criteria decision making method: A case study of the Xiangxi River. *Expert Systems with Applications*, 42(12), 5380-5389. <https://doi.org/https://doi.org/10.1016/j.eswa.2014.12.026>
- Jiménez-Inchima, I., Polanco, J., & Escobar-Sierra, M. (2021). Good living of communities and sustainability of the hydropower business: Mapping an operational framework for benefit sharing. *Energy Sustainability and Society*. <https://doi.org/10.1186/s13705-021-00284-7>
- Kankal, M., Bayram, A., Uzlu, E., & Satılmış, U. (2014). Assessment of hydropower and multi-dam power projects in Turkey. *Renewable Energy*, 68, 118-133. <https://doi.org/10.1016/j.renene.2014.01.031>
- Khakzad, H. (2019). A framework for cost-benefit assessment of alternative sediment management strategies in Dez Hydropower Reservoir: A probabilistic approach. *Water Practice and Technology*, 14(4), 783-801. <https://doi.org/10.2166/wpt.2019.063>
- Khan, R. (2015). Small hydro power in India: Is it a sustainable business? *Applied Energy*, 152, 207-216. <https://doi.org/10.1016/j.apenergy.2014.11.063>
- King, L. M., Simonovic, S. P., & Hartford, D. N. D. D. (2017). Using system dynamics simulation for assessment of hydropower system safety. *Water Resources Research*, 53(8), 7148-7174. <https://doi.org/10.1002/2017WR020834>
- Korkovelos, A., Mentis, D., Siyal, S. H., Arderne, C., Rogner, H., Bazilian, M., Howells, M., Beck, H., & De Roo, A. (2018). A geospatial assessment of small-scale hydropower potential in sub-saharan Africa. *Energies*, 11(11). <https://doi.org/10.3390/en11113100>
- Kovalyshyna, S., Chuzhekova, T., Grandova, M., Onishchenko, E., Zubcov, E., Ukrainskyy, V., Goncharov, O., Munjiu, O., Nabokin, M., & Ene, A. (2021). Ecological conditions of the lower dniester and some indicators for assessment of the hydropower impact. *Applied Sciences (Switzerland)*, 11(21). <https://doi.org/10.3390/app11219900>
- Kumar, D., & Katoch, S. S. (2014). Harnessing 'water tower' into 'power tower': A small hydropower development study from an Indian prefecture in Western Himalayas. *Renewable and Sustainable Energy Reviews*, 39, 87-101. <https://doi.org/https://doi.org/10.1016/j.rser.2014.07.052>

- Kumar, D., & Katoch, S. S. (2015). Small hydropower development in Western Himalayas: Strategy for faster implementation. *Renewable Energy*, *77*, 571-578. <https://doi.org/10.1016/j.renene.2014.12.058>
- Kuniyal, J. C., Jamwal, A., Kanwar, N., Chand, B., Kumar, K., & Dhyani, P. P. (2019). Vulnerability assessment of the Satluj catchment for sustainable development of hydroelectric projects in the Northwestern Himalaya. *Journal of Mountain Science*, *16*(12), 2714-2738. <https://doi.org/10.1007/s11629-017-4653-z>
- Lazo-Vásquez, D., Urbina, C., & Rivela, B. (2022). On the potential environmental repercussions of hydroelectricity: A contribution based on life cycle assessment of Ecuadorian hydropower plants. *Revista Virtual de Química*, *14*(1), 50-55. <https://doi.org/10.21577/1984-6835.20210098>
- Liu, X., & He, D. (2012). A new assessment method for comprehensive impact of hydropower development on runoff and sediment changes. *Journal of Geographical Sciences*, *22*(6), 1034-1044. <https://doi.org/10.1007/s11442-012-0981-7>
- Liu, Y., Ma, J., Wang, H., Yan, D. H., Lv, Y. K., & Deng, W. (2015). Multi-dimensional assessment of socioeconomic impacts of hydropower development—A case in the Upper Chuan River. *Science China Technological Sciences*, *58*(7), 1272-1279. <https://doi.org/10.1007/s11431-015-5844-x>
- Lopes, P. V. F., Costa, C. M. da S. B., Almeida, A. K., & de Almeida, I. K. (2022). Sustainability assessment model for Brazilian hydroelectric projects using multicriteria analysis. *Sustainable Energy Technologies and Assessments*, *51*(February 2021), 101851. <https://doi.org/10.1016/j.seta.2021.101851>
- Lu, S., Wei, W., Zhu, Z., Liang, Y., & Liu, H. (2022). Operation risk assessment of hydroelectric energy storage based on data visualisation and convolutional neural network. *Frontiers in Energy Research*, *9*(January), 1-12. <https://doi.org/10.3389/fenrg.2021.827942>
- Lucchetti, E., Barbier, J., & Araneo, R. (2013). Assessment of the technical usable potential of the TUM Shaft Hydro Power Plant on the Aurino River, Italy. *Renewable Energy*, *60*, 648-654. <https://doi.org/10.1016/j.renene.2013.06.015>
- Ma, L., Wang, H., Qi, C., Zhang, X., & Zhang, H. (2019). Characteristics and adaptability assessment of commonly used ecological flow methods in water storage and hydropower projects, the case of Chinese River Basins. *Water*, *11*(10), 1-15. <https://doi.org/10.3390/w11102035>
- Macfarlane, D., & Olive, A. H. (2021). Whither Wintego: Environmental impact assessment and indigenous opposition in Saskatchewan's Churchill River Hydropower Project in the 1970s. *The Canadian Historical Review*, *102*, 620-646.
- Mao, G., Wang, S., Teng, Q., Zuo, J., Tan, X., Wang, H., & Liu, Z. (2017). The sustainable future of hydropower: A critical analysis of cooling units via the Theory of Inventive Problem Solving and Life Cycle Assessment Methods. *Journal of Cleaner Production*, *142*, 2446-2453. <https://doi.org/https://doi.org/10.1016/j.jclepro.2016.11.031>
- McManamay, R. A., Parish, E. S., DeRolph, C. R., Witt, A. M., Graf, W. L., & Burtner, A. (2020). Evidence-based indicator approach to guide preliminary environmental impact assessments of hydropower development. *Journal of Environmental Management*, *265*. <https://doi.org/10.1016/j.jenvman.2020.110489>
- Meriç, B. T. (2022). Environmental flow methodology approach based on ecological impact assessment for hydroelectric power plants and hydraulic structures on stream ecosystems in Turkey. *Environmental Monitoring and Assessment*, *194*(6), 455. <https://doi.org/10.1007/s10661-022-10100-0>

- Mishra, S. K., Veselka, T. D., Prusevich, A. A., Grogan, D. S., Lammers, R. B., Rounce, D. R., Ali, S. H., & Christian, M. H. (2020). Differential impact of climate change on the hydropower economics of two river basins in high mountain Asia. *Frontiers in Environmental Science*, 8. <https://doi.org/10.3389/fenvs.2020.00026>
- Mitrovic, D., Chacón, M. C., García, A. M., Morillo, J. G., Diaz, J. A. R., Ramos, H. M., Adeyeye, K., Carravetta, A., & McNabola, A. (2021). Multi-country scale assessment of available energy recovery potential using micro-hydropower in drinking, pressurised irrigation and wastewater networks, covering part of the eu. *Water (Switzerland)*, 13(7). <https://doi.org/10.3390/w13070899>
- Moran, E. F., Lopez, M. C., Moore, N., Müller, N., & Hyndman, D. W. (2018). Sustainable hydropower in the 21st century. *Proceedings of the National Academy of Sciences of the United States of America*, 115(47), 11891-11898. <https://www.jstor.org/stable/26564475>
- Morimoto, R. (2013). Incorporating socio-environmental considerations into project assessment models using multi-criteria analysis: A case study of Sri Lankan hydropower projects. *Energy Policy*, 59, 643-653. <https://doi.org/10.1016/j.enpol.2013.04.020>
- Mortey, E. M., Kouassi, K. L., Diedhiou, A., Anquetin, S., Genoud, M., Hingray, B., & Kouame, D. G. M. (2019). Sustainable hydroelectric dam management in the context of climate change: Case of the Taabo dam in Côte D'Ivoire, West Africa. *Sustainability (Switzerland)*, 11(18). <https://doi.org/10.3390/su11184846>
- Mortey, E. M., Ofofu, E. A., Kolodko, D. V., & Kabobah, A. T. (2017). Sustainability assessment of the bui hydropower system. *Environments - MDPI*, 4(2), 1-25. <https://doi.org/10.3390/environments4020025>
- Nguyen-Tien, V., Elliott, R. J. R., & Strobl, E. A. (2018). Hydropower generation, flood control and dam cascades: A national assessment for Vietnam. *Journal of Hydrology*, 560, 109-126. <https://doi.org/10.1016/j.jhydrol.2018.02.063>
- Nowak, B., Andrzejak, A., Filipiak, G., Ptak, M., & Sojka, M. (2022). Assessment of the impact of flow changes and water management rules in the dam reservoir on energy generation at the Jeziorsko Hydropower Plant. *Energies*, 15(20). <https://doi.org/10.3390/en15207695>
- Oberle, P., Ikhwan, M., Stoffel, D., & Nestmann, F. (2016). Adapted hydropower-driven water supply system: Assessment of an underground application in an Indonesian karst area. *Applied Water Science*, 6(3), 259-278. <https://doi.org/10.1007/s13201-016-0425-0>
- Opperman, J. J., Carvallo, J. P., Kelman, R., Schmitt, R. J. P., Almeida, R., Chapin, E., Flecker, A., Goichot, M., Grill, G., Harou, J. J., Hartmann, J., Higgins, J., Kammen, D., Martin, E., Martins, T., Newsock, A., Rogéliz, C., Raeppele, J., Sada, R., Thieme, M. L., & Harrison, D. (2023). Balancing renewable energy and river resources by moving from individual assessments of hydropower projects to energy system planning. *Frontiers in Environmental Science*, 10. <https://doi.org/10.3389/fenvs.2022.1036653>
- Page, M. J., Mckenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-wilson, E., Mcdonald, S., McGuinness, L. A., Stewart, L. A., Thomas, J., Tricco, A. C., Welch, V. A., Whiting, P., & Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ*, 1-11.
- Pang, M., Zhang, L., Wang, C., & Liu, G. (2015). Environmental life cycle assessment of a small hydropower plant in China.

- The International Journal of Life Cycle Assessment*, 20(6), 796-806. <https://doi.org/10.1007/s11367-015-0878-7>
- Peng, S., Shi, G., & Zhang, R. (2021). Social stability risk assessment: Status, trends and prospects — A case of land acquisition and resettlement in the hydropower sector. *Impact Assessment and Project Appraisal*, 39(5), 379-395. <https://doi.org/10.1080/14615517.2019.1706386>
- Peters, R., Berlekamp, J., Lucia, A., Stefani, V., Tockner, K., & Zarfl, C. (2021). Integrated impact assessment for sustainable hydropower planning in the Vjosa Catchment (Greece, Albania). *Sustainability (Switzerland)*, 13(3), 1-18. <https://doi.org/10.3390/su13031514>
- Pracheil, B. M., McManamay, R. A., Parish, E. S., Curd, S. L., Smith, B. T., DeRolph, C. R., Witt, A. M., Ames, S., Day, M. B., Graf, W., Infante, D., McCoskey, D. N., Rugani, K., Vezina, C., Welch, T., & West, A. (2019). A checklist of river function indicators for hydropower ecological assessment. *Science of the Total Environment*, 687, 1245-1260. <https://doi.org/10.1016/j.scitotenv.2019.06.049>
- Punys, P., & Jurevičius, L. (2022). Assessment of hydropower potential in wastewater systems and application in a Lowland Country, Lithuania. *Energies*, 15(14). <https://doi.org/10.3390/en15145173>
- Punys, P., Kvaraciejus, A., Dumbrasukas, A., Šilinis, L., & Popa, B. (2019). An assessment of micro-hydropower potential at historic watermill, weir, and non-powered dam sites in selected EU countries. *Renewable Energy*, 133, 1108-1123. <https://doi.org/10.1016/j.renene.2018.10.086>
- Ramamurthy, R., Bleser, J., Konradsen, F., Kibret, S., Opperman, J., You, L., Sloff, K., McCartney, M., Fèvre, E. M., & Boelee, E. (2023). Human health impacts of dams and reservoirs: Neglected issues in a one health perspective. *Aquatic Ecosystem Health & Management*. <https://doi.org/10.14321/ahm.026.02.096>
- Rambo, C. L., Zanotelli, P., Dalegrave, D., De Nez, D., Szczepanik, J., Carazek, F., Franscescon, F., Rosemberg, D. B., Siebel, A. M., & Magro, J. D. (2017). Hydropower reservoirs: Cytotoxic and genotoxic assessment using the Allium Cepa Root Model. *Environmental Science and Pollution Research International*, 24(9), 8759-8768. <https://doi.org/10.1007/s11356-017-8509-4>
- Ribas, J. R., Arce, M. E., Sohler, F. A., & Suárez-García, A. (2019). Multi-criteria risk assessment: Case study of a large hydroelectric project. *Journal of Cleaner Production*, 227, 237-247. <https://doi.org/10.1016/j.jclepro.2019.04.043>
- Roy, N. C., & Roy, N. (2022). Paradigm shift in the sustainability of water-based power sector – An application of hydropower sustainability assessment protocol. *Social Responsibility Journal*. <https://doi.org/10.1108/srj-05-2020-0214>
- Scherer, L., & Pfister, S. (2016). Global water footprint assessment of hydropower. *Renewable Energy*, 99(February), 711-720. <https://doi.org/https://doi.org/10.1016/j.renene.2016.07.021>
- Sgarbi, F. de A., Uhlig, A., Simões, A. F., & Goldemberg, J. (2019). An assessment of the socioeconomic externalities of hydropower plants in Brazil. *Energy Policy*, 129, 868-879. <https://doi.org/https://doi.org/10.1016/j.enpol.2019.02.072>
- Shi, J. (2022). Assessment framework of Green Intelligent Transformation of small hydropower in China. *Energy Engineering: Journal of the Association of Energy Engineering*, 119(2), 681-697. <https://doi.org/10.32604/ee.2022.014942>
- Shu, J., Qu, J. J., Motha, R., Xu, J. C., & Dong, D. F. (2018). Impacts of climate change on hydropower development and sustainability: A review. *IOP Conference*

- Series: Earth and Environmental Science*, 163(1). <https://doi.org/10.1088/1755-1315/163/1/012126>
- Šilinis, L., Punys, P., Radzevičius, A., Kasiulis, E., Dumbrasukas, A., & Jurevičius, L. (2020). An assessment of hydropeaking metrics of a large-sized hydropower plant operating in a Lowland River, Lithuania. *Water (Switzerland)*, 12(5). <https://doi.org/10.3390/w12051404>
- Silvério, N. M., Barros, R. M., Tiago Filho, G. L., Redón-Santafé, M., Santos, I. F. S. D. I. F. S. dos, & Valério, V. E. de M. V. E. D. M. (2018). Use of floating PV plants for coordinated operation with hydropower plants: Case study of the hydroelectric plants of the São Francisco River basin. *Energy Conversion and Management*, 171(June), 339-349. <https://doi.org/10.1016/j.enconman.2018.05.095>
- Simonov, E. A., Nikitina, O. I., & Egidarev, E. G. (2019). Freshwater ecosystems versus hydropower development: Environmental assessments and conservation measures in the transboundary Amur River basin. *Water (Switzerland)*, 11(8). <https://doi.org/10.3390/w11081570>
- Singh, V. K., & Singal, S. K. (2018). Application of MADM for assessment of parameters for optimum operation of small hydropower plants. *IASH Journal*, July 2017.
- Song, Z., Liu, Q., Hu, Z., Zhang, C., Ren, J., Wang, Z., & Tian, J. (2020). Construction diversion risk assessment for hydropower development on sediment-rich rivers. *Energies*, 13(4), 938.
- Soulis, K. X., Manolakos, D., Anagnostopoulos, J., & Papantonis, D. (2016). Development of a geo-information system embedding a spatially distributed hydrological model for the preliminary assessment of the hydropower potential of historical hydro sites in poorly gauged areas. *Renewable Energy*, 92, 222-232. <https://doi.org/10.1016/j.renene.2016.02.013>
- Stefanyshyn, D. V., & Vlasiuk, Y. S. (2019). Some critical comments on the quality of environmental impact assessment reports for small hydropower plants in Ukraine. *Environmental Safety and Natural Resources*, 32(4), 43-59.
- Su, H., Hu, J., Yang, M., & Wen, Z. (2015). Assessment and prediction for service life of water resources and hydropower engineering. *Natural Hazards*, 75(3), 3005-3019. <https://doi.org/10.1007/s11069-014-1445-4>
- Suárez-Gómez, J. D., Polanco, J. A., & Escobar-Sierra, M. (2021). Understanding the role of territorial factors in the large-scale hydropower business sustainability: A systematic literature review. *Energy Reports*, 7, 3249-3266. <https://doi.org/10.1016/j.egy.2021.05.026>
- Sul Khanishvili, N. (2015). Strategic environmental assessment of Aragvi River Basin. *American Journal of Environmental Protection*, 4(3), 34. <https://doi.org/10.11648/j.ajep.s.2015040301.16>
- Tauš, P., & Beer, M. (2022). Evaluation of the hydropower potential of the Torysa River and its energy use in the process of reducing energy poverty of local communities. *Energies*, 15(10). <https://doi.org/10.3390/en15103584>
- Tedjio, R. C., Talla, E. T., & Nana, E. D. (2016). Complementarity of two impact assessment tools: The case of a hydroelectric power plant in one of Africa's last hardwood forests in Eastern Cameroon. *Impact Assessment and Project Appraisal*, 34(3), 261-266. <https://doi.org/10.1080/14615517.2016.1184503>
- Tefera, W. M., & Kasiviswanathan, K. S. (2022). A global-scale hydropower potential assessment and feasibility evaluations. *Water Resources and Economics*, 38, 100198. <https://doi.org/https://doi.org/10.1016/j.wre.2022.100198>

- Teguh, N. A., & Nisaa, A. F. (2021). Hydropower Sustainability Assessment Protocol (HSAP) implementation in Indonesia: A mini-review. *Journal of Infrastructure & Facility Asset Management*. <https://doi.org/10.12962/jifam.v3i1.13463>
- Tettenborn, F., & Sartorius, C. (2020). Nachhaltigkeitsbewertung für Kleinwasserkraftwerke in China. *Zeitschrift Für Energiewirtschaft*, 44(1), 31-37. <https://doi.org/10.1007/s12398-020-00268-8>
- Todorova, Y., Lincheva, S., Yotinov, I., & Topalova, Y. (2016). Contamination and ecological risk assessment of long-term polluted sediments with heavy metals in small hydropower cascade. *Water Resources Management*, 30(12), 4171-4184. <https://doi.org/10.1007/s11269-016-1413-8>
- Tomczyk, P., Wiatkowski, M., & Gruss, Ł. (2019). Application of macrophytes to the assessment and classification of ecological status above and below the barrage with hydroelectric buildings. *Water (Switzerland)*, 11(5). <https://doi.org/10.3390/w11051028>
- Torres-Herrera, H. J., & Lozano-Medina, A. (2021). Methodological proposal for the assessment potential of pumped hydropower energy storage: Case of Gran Canaria Island. In *Energies* (Vol. 14, Issue 12). <https://doi.org/10.3390/en14123553>
- Tuna, M. C. (2013). Feasibility assessment of hydroelectric power plant in ungauged river basin: A case study. *Arabian Journal for Science and Engineering*, 38(6), 1359-1367. <https://doi.org/10.1007/s13369-013-0590-5>
- UNDRR. (2004). Risk awareness and assessment. *Living with Risk: A Global Review of Disaster Reduction Initiatives*, 36-78.
- United Nation. (2022). *World Economic Situation and Prospects (WESP) Country Classification*.
- van Treeck, R., Radinger, J., Noble, R. A. A., Geiger, F., & Wolter, C. (2021). The European Fish Hazard Index – An assessment tool for screening hazard of hydropower plants for fish. *Sustainable Energy Technologies and Assessments*, 43(June 2020), 100903. <https://doi.org/10.1016/j.seta.2020.100903>
- van Treeck, R., Radinger, J., Smialek, N., Pander, J., Geist, J., Mueller, M., & Wolter, C. (2022). Comparative assessment of hydropower risks for fishes using the novel European Fish Hazard Index. *Sustainable Energy Technologies and Assessments*, 51. <https://doi.org/10.1016/j.seta.2021.101906>
- van Vliet, M. T. H., van Beek, L. P. H., Eisner, S., Flörke, M., Wada, Y., & Bierkens, M. F. P. (2016). Multi-model assessment of global hydropower and cooling water discharge potential under climate change. *Global Environmental Change*, 40, 156-170. <https://doi.org/10.1016/j.gloenvcha.2016.07.007>
- Vassoney, E., Mammoliti Mochet, A., & Comoglio, C. (2020). Multicriteria analysis for the assessment of flow release scenarios from a hydropower plant in the Alpine Region. *Water Resources Management*, 34(2), 637-651. <https://doi.org/10.1007/s11269-019-02459-6>
- Vassoney, E., Mammoliti Mochet, A., Desiderio, E., Negro, G., Pilloni, M. G., & Comoglio, C. (2021). Comparing Multi-Criteria Decision-Making Methods for the assessment of flow release scenarios from small hydropower plants in the Alpine area. *Frontiers in Environmental Science*, 9. <https://doi.org/10.3389/fenvs.2021.635100>
- Veronez, D. V., Abe, K. C., & Miraglia, S. G. E. K. (2018). Health impact assessment of the construction of hydroelectric dams in Brazil. *Chronicles of Health Impact Assessment*, 3(1), 11-36. <https://doi.org/10.18060/21777>
- Voegeli, G., Gaudard, L., Romerio, F., & Hediger, W. (2018). Framework for decision-making process in granting rights

- to use hydropower in the European context. *Water (Switzerland)*, 10(7). <https://doi.org/10.3390/w10070930>
- Voegeli, G., Hediger, W., & Romerio, F. (2019). Sustainability assessment of hydropower: Using causal diagram to seize the importance of impact pathways. *Environmental Impact Assessment Review*, 77, 69-84. <https://doi.org/10.1016/j.eiar.2019.03.005>
- Vougioukli, A. Z., Didaskalou, E., & Georgakellos, D. (2017). Financial appraisal of small hydro-power considering the cradle-to-grave environmental cost: A case from Greece. *Energies*, 10(4), 1-20. <https://doi.org/10.3390/en10040430>
- Wang, B., Nistor, I., Murty, T., & Wei, Y.-M. M. (2014). Efficiency assessment of hydroelectric power plants in Canada: A multi criteria decision making approach. *Energy Economics*, 46, 112-121. <https://doi.org/10.1016/j.eneco.2014.09.001>
- Wu, Y., Wang, Y., Chen, K., Xu, C., & Li, L. (2017). Social sustainability assessment of small hydropower with hesitant PROMETHEE method. *Sustainable Cities and Society*, 35, 522-537. <https://doi.org/10.1016/j.scs.2017.08.034>
- Xu, Z., Niu, Y., Liang, Y., Li, Z., & Iftikhor, A. (2020). The Integrated Hydropower Sustainability Assessment in Tajikistan: A case study of Rogun Hydropower Plant. *Advances in Civil Engineering*, 2020. <https://doi.org/10.1155/2020/8894072>
- Xue, B., & Sun, Z. (2018). Economics of hydropower energy: A critical assessment. *Energy Sources, Part B: Economics, Planning, and Policy*, 13(1), 33-36. <https://doi.org/10.1080/15567249.2017.1402102>
- Yu, T., Xiaohui, L., Qian, Y., & Jialan, S. (2012). Research on power benefits assessment of SiPing Hydropower Station under the operation of Sanliping Hydropower Station. *Physics Procedia*, 24, 512-517. <https://doi.org/10.1016/j.phpro.2012.02.074>
- Yuguda, T.K., Imanche, S.A., Tian, Z., Akintunde, T. Y., & Luka, B. S. (2022). Hydropower development, policy and partnership in the 21st century: A China-Nigeria Outlook. *Energy & Environment*. <https://doi.org/10.1177/0958305x221079423>
- Zhang, L., Chai, J., Zhu, J., & Zhao, Z. (2020). Dynamic simulation and assessment of the ecological benefits of hydropower as an alternative energy for thermal power under ecological civilisation construction: A case study of Fujian, China. *Energy Science and Engineering*, 8(7), 2426-2442. <https://doi.org/10.1002/ese3.677>
- Zhang, Y., Ma, H., & Zhao, S. (2021). Assessment of hydropower sustainability: Review and modelling. *Journal of Cleaner Production*, 321(June), 128898. <https://doi.org/10.1016/j.jclepro.2021.128898>