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Reviewing and critiquing published approaches to the sustainability assessment of hydropower

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ABSTRACT

Recognizing the multidimensional role that hydropower can potentially play in achieving a more sustainable energy supply system, this paper reviews a series of published economic, environmental and social indicators that are often used to characterize this energy source. Getting the right balance between measures assessing benefits and costs is often a challenge in complex evaluations. The current paper argues that present studies sometimes set system boundaries too narrowly so that they omit key factors associated with hydropower. In particular, the role that hydroelectric resources can play to stabilize the overall electrical grid, and thus to leverage investments in other intermittent renewables, is only rarely accounted for in sustainability assessments. Based on a broad literature review, the authors articulate two key recommendations for future assessments: first, that such assessments should reflect on policy issues as well as environmental challenges with respect to existing hydropower potential within the current framework; second, that system boundaries should be extended not only to allow broad hydrological, ecological and geological assessments, but also to reasonably estimate hydro's potential benefits to the functioning of the overall electrical grid.

Contents

1. Introduction

Robust electrical supply systems clearly play a crucial role toward achieving human well-being and can act as a foundation of economic growth and prosperity. Yet with increasing concern over global climate change and the health ramifications of using carbon-based fuels, a progressively greater use of renewable resources is seen as having distinct advantages over non-renewables [1,2]. Several studies have surveyed the environmental and climatic effects of the fossil fuel energy systems [3,4] and the benefits of a transition to a lower-pollution energy system [5–7], including both hydropower and natural gas [8,9]. Some studies have

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focused on energy-based carbon emissions [10–13], while others have traced and modeled various mechanisms that lead to environmental effects [14,15]. One obvious conclusion is that hydropower, when used well, has the potential to reduce the pollutants and carbon emission, and thus to improve environmental and climatic health. Of course, when used poorly hydropower can cause devastation to human and natural systems, as many well-known historical disasters attest [16].

Apart from its doubtless advantages, even nominally successful hydro projects are often associated with negative environmental consequences in the form of biodiversity loss, disruptions to fish migration, potentially large-scale land inundation, the disruption of human resettlement, and many others. Although early consideration and adoption of mitigation measures can limit such impacts, it is often impossible to completely eliminate or fully control the adverse influences on local ecosystems. The modern evaluation of the impact of engineering projects ideally considers – indeed, is often mandated to consider – anticipated economic, social and ecological impacts through all stages of the development. While standard environmental impact assessments may have been enough in the past, more detailed guidelines are now prescribed by many international (financial) institutions such as the World Bank, International Hydropower Association (IHA), International Energy Agency (IEA), European Bank for Reconstruction and Development (EBRD), and others. These guidelines establish a set of recommendation for impact assessment, suggesting ways to ameliorate adverse effects and criteria for the application of mitigation measures. The process in turn provides a basis for comparison between hydropower and other electricity generation sources. The need to seek a wide range of opinions during project implementation is reflected in most of the published mandates. Due to the variety of contexts and perspectives, the list and priority of proposed indicators naturally varies between the numerous published guidelines, studies, and reports. Although there is, as yet, no universally accepted standard for assessing the sustainability of hydropower projects, there is an obvious and important overlap in the obligations to consider.

All power developments, be they coal, nuclear, gas, wind or solar, offer certain benefits while possessing inherent drawbacks. Thus, when performing a sustainability assessment of a project, it is imperative to evaluate as much as possible the system as a whole, not just its individual components. But this creates ambiguity regarding the scale at which sustainability should be examined since, realistically, no power system, nor indeed any large scale human activity, is absolutely sustainable. This paper argues that while existing frameworks are quite comprehensive on a project scale, there are merits of choosing a scale that is sufficiently broad to take into account all key impacts, including those occurring at the grid level. To this end, the study first summarizes existing knowledge and compares several different sustainability approaches or guidelines.

2. Synergy between hydropower and sustainability

Sustainable development is a concept that at its core is both revolutionary and somewhat intuitive, yet incredibly difficult to comprehensively define and perhaps even more difficult to fully operationalize. In the absence of a collective, pragmatic and operational interpretation, the existing literature encompasses a variety of approaches, frameworks and models for evaluating sustainable practices [17–26]. The simplest of these approaches is perhaps the concept of the triple bottom line that recognizes that sustainability rests upon three pillars encompassing economic, environment and social domains. There is debate about who originated this approach, though it is contended by some to have been first used by Altieri [17] in relation to agricultural production. Despite being a little ambiguous, the most widely cited definition of sustainability is now decades old, stated as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [18]. By contrast, Thompson's [23] approach distinguishes between systemic and goal-directed sustainability. As a systems approach, sustainability inquires about whether a system, with defined boundaries, external inputs and self-healing capacity, can continue over a specified time scale without major degradation to its context or to itself – informally, without falling apart. Another way of assessing sustainability is to use Life Cycle Analysis (LCA), which traces relevant input-output data for the purpose of estimating resource consumption and emission from the system throughout phases of design, construction and operation.

The International Energy Agency (IEA) predicts the growth in electricity demand at an annual rate of 2.5% sustained until 2030 and that will require and commensurate energy investment up to $26 trillion [27]. Indeed, the overall context for the assessment of energy sustainability is dominantly one of growth. Using traditional fossil fuel to meet the growing power demand is both unsustainable (since these resources cannot be replenished in a reasonable time frame), and is tending to serious climate repercussions [28–30]. In this context, implementation of hydro can have the enormous benefit of reducing fossil fuel-based generation [31–33]. From a life cycle perspective, the CO_2 produced during construction and operational phase of hydro projects is seldom comparable in scale to that associated with the use of non-renewables. For example, decomposition of flooded biomass in hydro reservoir can cause emission of 4–8 g CO_2 eq./KWh [34–37] which is 36 to 167 times lower compared to that of fossil fuel-based generation [36,37]. Overall greenhouse gas emission (GHG) from a typical hydro plant ranges from 2–18 kt CO_2 eq./TWh throughout its life cycle while that of fossil fuel run plants ranges from 389 to 1272 kt CO_2 eq./TWh [38–42]. Studies have also shown that development of even half of the world's economically feasible hydropower potential could reduce GHG emissions by about 13%, and the impact on avoided SO_2 and NO_x emissions would be even greater [43,44].

Apart from using a renewable power source, hydroelectricity usually includes a capacity to store energy and thus can provide flexibility to the operation of the grid [45–47]. If leveraged well, this storage/reserve function can allow greater integration of intermittent renewables, particularly wind and solar resources [48–51]. On a community level, hydropower projects are often multipurpose in nature; serving various needs including power, flood control, water supply, and recreational benefits [52–54]. Investments in infrastructure (access roads, dams, and canals), communications, and skill building in large projects can support regional economic development. On the negative side, though, these projects often inevitably alter many environmental and social parameters due to the conversion of portions of terrestrial ecosystems into aquatic ones, whether through resettlement, restriction of navigation, modifications of local land use, loss of biodiversity, or changes in aquatic sediment composition and distribution [55–61]. Interestingly, often these effects vary from one case to the other irrespective of the project scale. Consequently, it is invariably challenging to make generalized comments regarding the impact of hydropower development on surrounding environment [62]. Even projects having the same installed capacity may have quite different environmental consequences depending on specifics of design, hydrology, geology, available field conditions, and the specific fluvial parameters.

Certainly one of the key attractions of hydropower is its occasional abundance and that it is both renewable and dispatchable; but perhaps just as obviously, the environmental and social consequences of hydro's development can range from daunting to devastating. It is also obvious that preference for hydroelectric projects, or indeed for almost any type of power project, can seldom be judged solely on its own attributes, but depends also on local system (grid) requirements, on the performance and availability of other local options and on whether the associated impacts and risks can be limited.

3. Existing frameworks and guidelines on sustainable development of hydropower

At present, nearly all countries mandate an assessment of the expected impacts of any new hydroelectric development prior to construction. Nevertheless, historically many developers have apparently perceived such requirements as mere formalities, a rather onerous but necessary steps to obtain regulatory approval with requirements to be as frequently ignored during implementation [63]. Such occurrences are perhaps even more common in developing countries [64]. Several international and financial institutions provide monetary assistance (including low interest loans) for large-scale hydropower development. In most cases, the funding is conditional on reasonable performance under agreed frameworks. The current paper reviews the major institution-specific guidelines on sustainability assessment of hydropower projects starting with the frameworks proposed by various international organizations, certification bodies and funding agencies. Latter sections aggregate other indicators extracted from research studies, project documents and expert recommendations.

3.1. *Low impact certification by LIHI*

Originating in 2000, the Low Impact Hydropower Institute (LIHI) is a US-based non-profit organization dedicated to certifying hydropower projects with reduced environmental impacts. Their stated purpose is to protect the river ecosystem and enable low impact projects to access renewable energy markets. The approach assesses hydroelectric schemes based on a number of criteria developed in eight categories: river flows, water quality, upstream fish passage, downstream fish passage and protection, watershed protection, threatened and endangered species protection, recreation, and cultural resource protection [65]. Each criterion is evaluated on a pass-fail basis, and satisfactory performance in all the criteria is required for certification.

This certification emphasizes the ecological impact with little focus on social and economic aspect of hydropower development. So far, a total of 121 projects have been certified by LIHI with 9 under review and 16 pending applications [66]. Until recently, the certification program was strictly limited to run-of-river plants and did not extend to pumped storage or projects that require construction of new dam or diversions. However, through a subsequent revision in 2016, the guidelines were extended to cover facilities with limited storage capacity [67]. The revision proposes no new criteria but offers an extended list of alternative standards to ensure compliance.

3.2. *Green hydropower certification by EAWAG*

Following a successful pilot certification, the Swiss Federal Institute of Aquatic Science and Technology (EAWAG) presented Green Hydropower Certification Scheme. It sets out the technical basis of a uniform and scientific certification process for hydropower plants. The program claims that following its stated procedure can ensure design and operation of a facility that safeguard basic features of the ecological integrity of the river system [68]. The process involves forming an environmental management matrix that accounts for direct impact on the river ecosystem and its riverine landscape. It places five management criteria in different columns describing the operational issues or aspects of construction related to hydropower development, i.e., minimum flow regulations, hydro-peaking, reservoir management, bedload management and power plant design. Environmental dimensions, such as hydrological character, connectivity of river system, solid material and morphology, landscape and biotopes, etc., are placed in separate rows and are expected to cover the most important aspects relevant to ensuring ecological viability [68]. The elements within the matrix are assigned with specific requirements and are designed to be universally applicable to all kinds of hydropower plants. As the concepts and criteria are independent of Swiss law requirements, the scheme should be applicable in principle to other countries with minor modification. However, this should not be used for licensing purposes or as a substitute to environmental impact analysis as warned by EAWAG. Similar to LIHI, the certification scheme concentrates on ecological issues with little consideration on key economic and social indicators associated with hydroelectric development.

3.3. *Hydropower sustainability assessment protocol (HSAP) by IHA*

The International Hydropower Association (IHA)'s so-called HSAP protocol is the outcome of a collective effort by Hydropower Sustainability Assessment Forum that is launched in 2008 by IHA along with its key strategic partners. Recognizing the inconsistencies in the existing approaches, the framework aims to develop an enhanced sustainability assessment tool to measure and guide performance, and to streamline the approaches for hydropower projects. It encourages or seeks a considerably high level of convergence amongst the diverse views from its members which included representatives of governments from both developed and developing countries, commercial and development banks, social and environmental NGOs, and the hydropower sector. The 2010 Protocol updates 2006 version and comprises a set of four standalone assessment frameworks: an early stage tool for assessing risk and opportunities during initial planning followed by three detailed schemes for preparation, implementation and operation stage [69]. The proposed indicators further reflect on four different sustainability perspectives - economic, environmental, social and technical. The detailed guideline is summarized here in Table 1. A 5-level scale system is used to determine the status of each criterion where level 5 describes the proven best practice, level 3 stands for basic good practice while level 1 represents significant gaps relative to accepted practices.

From a sustainability viewpoint, the protocol is unique with its handling of the issues from both a triple bottom approach and life cycle perspective. Interestingly, the protocol does not provide any specification regarding the requirements for acceptable performance on the criteria, rather relies on the institution's policies and positions to decide on such critical issues. Since its introduction, HSAP has been implemented in developing several large-scale hydropower projects including China's Three Gorges. Realizing the complex nature of the project, sustainability issues were evaluated using a triple bottom line approach, with the LCA consideration and from a systems perspective (i.e., reservoir, dam, power plant, transmission, the location of the project and the surrounding area) [70].

3.4. *Directions in hydropower by World Bank*

Recognizing its multidimensional role in poverty alleviation and sustainable development, the World Bank emphasizes on exploiting the maximum strategic value of hydropower resources in an environmentally and socially responsible manner. Directions in Hydropower [71] summarizes the key issues in scaling-up

Table 1
Hydropower Sustainability Assessment Protocol topics [69].

Technical	Environmental	Social	Economical	Integrated
Siting and design	Downstream flows	Project affected communities and livelihoods	Economic viability	Demonstrated need and strategic fit
Hydrological resource	Erosion and sedimentation	Resettlement	Financial viability	Communications and consultation
Reservoir planning, filling and management	Water quality	Indigenous peoples	Project benefits	Governance
Infrastructure safety	Biodiversity and invasive species	Cultural heritage	Procurement	Integrated project management
Asset reliability and efficiency	Waste, noise and air quality	Public health		Environmental and social issues management

hydropower projects along with setting priorities for the organization in lending and nonlending activities. Unlike the sustainability frameworks reviewed here, it discusses key challenges and both policy and regulatory issues regarding hydropower development. The directive highlights the bank's two track approach towards hydropower scale-up: first, through direct investment and second, by strengthening sectoral foundations by providing technical assistance, knowledge sharing, initiating policy dialog and several other roles. In 2014, the World Bank endorsed the Hydropower Sustainability Assessment Protocol (HSAP) as a tool for guiding hydroelectric development in client countries [72]. The relatively slow adoption of the protocol by low- and middle-income countries where much of the remaining hydropower potential exists, motivates the bank to raise awareness about the HSAP, particularly through sector-level engagement. A pilot assessment was carried out on a World Bank-supported Vietnamese hydropower storage plant to learn about the practicalities of the tool. While the protocol findings are conducive to management action, the manuals are reported to be complex and insufficient [72]. Given the Protocol documents' extreme site-specificity, the bank further emphasizes the use of accredited assessors for quality assurance.

3.5. *Hydropower implementing agreement by IEA*

The Hydropower Implementing Agreement is a collaborative program under the International Energy Agency (IEA) which aims “to improve technical and institutional aspects of the existing hydropower industry and increase future development in an environmentally and socially responsible manner” [73]. The outcome of this agreement results in several technical reports that provide a comprehensive overview in its entirety including trends in hydroelectric development, comparative analysis with other generation sources, ethical considerations, financing options, methods for education and training in hydropower etc. The first phase of the program reviews the processes and conditions which make hydroelectric projects environmentally and socially acceptable, identifies international best practices, and proposes a set of recommendations [74]. This document reflects the points of view of academic specialists and professionals from varied backgrounds and organizations from IEA member countries. Table 2 highlights the key issues discussed in the report. Following the identification of the indicators, their representativeness is verified with knowledge gathered from sixty case studies around the globe and rigorous experts' examination.

The authors of the current paper found the work of the task force under its Hydropower Implementing Agreement to be quite comprehensive, highlighting issues such as restructuring of the electricity market, reliability and backup benefits of hydroelectric resources, and credits it for avoided emission and impact on human health from LCA and environmental impacts perspective.

Table 2
List of environmental and social indicators under the IEA framework [74].

Categories	Key Issue
Biophysical environment	Reservoir impoundment Loss of biological diversity Sedimentation characteristics Water quality Hydrologic Regime Barriers for fish migration and river navigation
Socioeconomic environment	Resettlement and rehabilitation Health and safety Impacts Vulnerable community groups Land Use and cultural heritage
Sharing development benefits	Benefits due to power generation Benefits due to dam function Improvement of Infrastructure Development of Regional Industries

3.6. *Sustainable energy financing by EBRD*

The European Bank for Reconstruction and Development (EBRD), operating primarily in Central and Eastern Europe, finances hydropower projects under its Sustainable Energy Financing Facilities (SEFFs) initiative. The EBRD uses eight environmental criteria for assessing hydropower projects: environmental flow, water quality, fish passage and protection, watershed protection, threatened and endangered species, recreation, cultural and community issues [75]. Mitigation of negative impacts under these criteria is vital to complete licensing procedure and secure funding from the EBRD. Table 3 provides a list of criteria prescribed by the EBRD.

Due to its attractive simplicity and clarity, several researchers have used the guideline for evaluating hydropower projects. Kucukali [76] assessed the environmental risks associated with a small plant on the basis of EBRD standards. Each of the five criteria was scored on a scale of 1–3 on the basis of documented evidence, measured data, and observations during the operation stage of the plant. A similar study by Schmalz and Thürmer [77] found a 300 kW hydropower plant in Germany to be of low environmental risk. From a sustainability viewpoint, the existing framework by the EBRD seems to be missing a few critical environmental indicators (such as loss of biodiversity, impact on flora and fauna), and also lacks considerations of key social, economic and technical issues. Nevertheless, other impacts being negligible, this sort of simple scoring system can offer a first glimpse at project EIA during the initial planning stage.

4. Selective review of sustainability indicators

A broad list of indicators for assessing hydropower projects is now summarized based on a range of research articles. The

Table 3
Environmental criteria for hydropower projects under the EBRD [75].

Criteria	Requirement
Environmental flow	Maintains a minimum river flow accounting for seasonal fluctuations.
Water quality	Does not contribute to deterioration of upstream or downstream water quality.
Fish passage	Has minimal impact on local fish populations and provides effective fish passage.
River basin	Does not negatively impact environmental conditions in the river basin or integrity of the existing ecosystem.
Endangered species	Not constructed on a protected river and neither negatively impacts any endangered species.
Recreation	Accommodates recreational activities.
Cultural Issues	Protects archeological, paleontological, historical, religious and unique natural values.
Community Issues	Does not stop or limit local communities' ability to provide a livelihood.

selection process was guided by a systematic review where relevant materials were collected by conducting multiple search operations with designated keywords such as hydropower, sustainability, power systems etc. on major academic databases for scientific and technical research. The entries found throughout this process were first screened for relevance and their bibliographies were further scanned for related scientific resources that were missed during the initial search operations. To the best of the author's knowledge, literature on sustainable development of hydropower dates as far back as 1995. Thirty-five documents were found to be dedicated, either partially or entirely, to this issue. While a few of the selected studies primarily rank generation assets with respect to a set of criteria [46,53,78–82], the majority focused exclusively on hydroelectric power [83–102]. Table 4 provides a chronological list of research studies along with the reported technical, ecological, economic and social parameters.

Due to the complexity in quantifying social impacts, the current literature identifies it as one of the most challenging aspects of hydropower development. Indeed, the International Association for Hydro-Environment Engineering and Research (IAHR) has recently identified this topic as a real need in hydropower assessments [103]. Involuntary resettlement, relocation and rehabilitation of local indigenous community, potential conflict and increased incidence of waterborne diseases are widely identified indicators in this category. Benefits of hydroelectric development reported in these studies typically include job creation, investment in infrastructure, irrigation, recreation, tourism, navigation etc. The environmental indicators cited by most researchers usually touch on inundation, loss of biodiversity, fish migration, land use, reservoir sedimentation and water quality. A handful of studies have also included increased water temperature, lower dissolved oxygen, loss of soil fertility, soil erosion, increased salinity or lesser recognized fact of seismic activity to the list. Whereas GHG emission is considered a major criterion when comparing hydropower with other generation resources, avoided emissions is rarely identified as an environmental benefit in studies that solely focus on hydroelectric generation. Other more rarely mentioned environmental indicators include its impact on fisheries or other projects in the vicinity, aesthetics and methane emission as a result of decomposition of buried organic matter in hydro reservoirs. While social and environmental issues associated with hydropower development are widely discussed in the existing literature, economic and technical parameters have received less attention. A limited number of studies have highlighted technical issues such as efficiency, difficulty in construction, flexibility and the influence of the estimated development period. A similar practice of exclusion is observed for plant life, unit electricity cost, and presence of other infrastructure (access roads, transmission networks, etc.) which substantially affect project economies. The review process also suggests a contrast among researchers regarding the hierarchy of certain indicators. Job creation and complementary benefits of hydropower (irrigation, recreation, tourism etc.) are at times considered as social indicators while a few have placed them under economic category.

The review also sheds light on the typical methods used for assessing hydropower sustainability. Multicriteria analysis is found to be the most common among published approaches [46,53,80,83–87] with variations such as the weighted sum method (WSM), the weighted product method (WPM), the preference ranking organization method for enrichment evaluation (PROMETHEE), the elimination and choice translating reality (ELECTRE), the technique for order preference by similarity to ideal solution (TOPSIS), Analytic Hierarchy Process (AHP) being widely used. The methodology is at times complemented with stakeholders' analysis [81,83] or life cycle assessment [82]. Recent literature includes the application of relatively novel methodologies such as fuzzy mathematical functions [88], information network analysis (INA) [89] and emergy analysis [90] for evaluating non-technical and ecological impacts of hydropower construction. Many researchers provide a rather general [54,91–93] or project/country-specific narrative [57,94–100] that highlights the key issues. A few of the papers are review articles that further extend the scope by suggesting spatial design principles [101] or performing a systematic assessment of hydropower externalities [102].

5. Limitations of the existing approaches

While the guidelines created by international/financial institutions at times have limited scope or complex and insufficient manuals that act as a barrier to their adoption, the approaches published in academic papers also have limitations. The existing literature tends to evaluate hydropower sustainability from three different perspectives: the triple bottom approach, LCA and from a systems perspective. Despite their apparent comprehensive nature, these traditional approaches often miss key challenges faced by hydroelectric development. First, the growth of hydropower is largely influenced by policies and incentives provided by governing bodies. In the absence of a carbon tax sufficient to internalize the externalities of carbon-based electricity generations, future hydropower development will largely be at the mercy of policy initiatives. These policies, typically imposed for protecting environmental integrity or enhancing local conditions, exhibit a large spatial variation and can change abruptly depending on particular interests of the power regime. The situation is usually more complex for hydropower systems located at transboundary rivers. Typically, water sharing at these plants is guided by some form of international agreement. However, the jurisdictions, often having different priorities for conflicting water uses, tend to resist influence or take control over these resources. Sustainable development of remaining hydropower resources would require favorable local policies as well as international collaboration to avoid potential conflicts. Second, hydropower potential is sensitive to climate change because of its dependency on runoff [92]. Several studies have projected the impending changes in runoff pattern as

Table 4
List of hydropower sustainability indicators reported by researchers.

Reference article	Social	Environmental	Economic	Technical
Sarkar and Karagöz [57]	Resettlement, job creation, waterborne diseases, traffic, immigration, colonization	Biodiversity loss, fish migration, deforestation	Recreation, tourism navigation	
Afgan et al. [78]	Job creation, capital produced, diversity and vitality	Emission of CO_2, NO_x, SO_2, waste	Efficiency, investment per unit power, GNP per KWh	
Afgan and Carvalho [80]		CO_2 Emission, land use	Efficiency, installation cost per kWh, electricity cost	
Kaygusuz [96]	Relocation, waterborne diseases, colonization, migration, job creation, investment, traffic, recreation, tourism, navigation	Inundation, species extinction, landslides, biodiversity loss, fish migration, erosion, soil fertility & salinity	Drought & flood protection, affordable power, construction cost	
Klimpt et al. [93]	Public participation, resettlement, irrigation, heritage sites, shared benefits, human health	Hydrologic regime, biodiversity loss, fish migration, water quality, sedimentation, flood, avoided emission, seismic activity		Efficiency, flexibility, demand response, storage, black-start
Bakis and Demirbas [91]	Displacement, employment opportunities, living standards	Sedimentation, topographical & hydrological conditions, flooding, species extinction, ecosystem	Unit electricity cost, capital & maintenance cost, irrigation, water supply benefits	
Balat [99]	Visual impact, irrigation	No pollution, flooding, fishery, avoided GHG emission, air quality	Health cost, cheap power, life span, maintenance	
Evans at al. [53]	Public acceptance, displacement, flood protection, irrigation, recreation	GHG emission, inundation, land use, water consumption, siltation	Price per KWh	Availability, efficiency technological limitations
Kaygusuz [54]	Resettlement, recreation, drought & flood protection, navigation, waterborne diseases	Climate benefits, flood, DO, pH, hydrologic regimes, aquatic habitat, sedimentation, water temperatures, macro-invertebrate	Affordable power, job creation, expensive mitigation, maintenance	
Supriyasilp et al. [84]	Safety, social conflict, land use, water resource problem, legal obstacle, infrastructure	Flow pattern and amount, habitat loss, land use, river bank collapse, sedimentation, dust and noise	Project cost, IRR, NPV, cost per KWh	Feasibility, construction, slope, alignment, flow, accessibility, installed capacity, development period, transmission
Onat and Bayar [79]	Public perception, resettlement, human health, employment, agriculture, tourism	Land use, water consumption, CO_2 emission, air pollution, water quality	Unit price of energy, capital & operating cost, resource availability	Efficiency
Carrera and Mack [81]	Innovative ability, shared benefits, health concerns, functional & aesthetic Impact, conflict & catastrophic potential, public participation & perception, traffic	Land use, waste disposal		Reserve capacity, flexibility to incorporate other technologies
Kaunda et al. [92]	Involuntary resettlement, loss of livelihood and cultural identity	Inundation, air & water pollution, biodiversity loss, land use, sedimentation, aquatic weed, CO_2 & methane emission, climate benefits	Agriculture, power, mining, tourism	
Capik et al. [94]	Water supply, waterborne disease, flood control, irrigation, navigation, recreation, accessibility, improved living, relocation, job opportunities, tourism, land use	No emission, acid rain, waste, inundation, air quality, erosion, flooding, aquatic life, climate change, hydrologic regime, fish migration, sedimentation, water table	Cheap power, agricultural loss, market fluctuation, construction, O&M cost, efficiency, plant life, safety, employment, development period	
Vučijak et al. [85]		Biological indicators, morphological condition, water quality, terrestrial habitat		
Kentel and Alp [95]	Investment, aesthetic impact, impact on locals, water supply, irrigation, fishing	Dust, air pollution, noise, erosion, landslide, debris, aquatic life, pH, fish passage, sedimentation, diversion, suspended solids, deforestation	Affordable power, reduced dependency on imported energy	
Scannapieco and Belgiorno [82]	Public acceptance, employment, traffic	Global warming potential, water, land use, underground resources, waste, biodiversity, ecosystem impact, emission, landscape, hazards	Capital, O&M costs, energy demand	
Rosso et al. [83]	Compensation fees, enterprise activities, marginal area, local employment, stakeholder preferences	Protected areas, hydrological risks, environmental flow, river discharge, water quality, mitigation	Operation & investment costs, incentives, IRR compensation fees, annual benefit, payback period	River length, efficiency, productivity, discharge, intake height, typology, head, structure volume
Maxim [46]	Job creation, human health, social acceptability, external supply risk	Land use, environmental costs	Levelized cost of electricity (LCOE)	Demand response, efficiency, capacity factor
Zhang et al. [9]		Soil erosion, pollution, fish & human habitat, inundation, land productivity, sedimentation, water quality, ecological alteration, emission		
Chen et al. [89]		Food web impact, sedimentation, discharge, heavy metal pollution		
Pang et al. [90]		Natural flow disruption, land use, aquatic life,	High initial investment, low maintenance	

		biodiversity loss	
Morimoto [86]	Resettlement, loss of agricultural productivity, community cohesion, psychological distress, human health	Submergence, biodiversity loss, aquatic life, endangered and rare species, soil erosion	Average generation cost (capital + operating + resettlement + opportunity) per kWh
Yuksel [98]	Flood protection, navigation, recreation, accessibility, living conditions, livelihood, water uses	Reduced GHG emission, air quality, waste, avoided depletion in non-renewables, increased productivity	Life span, reliable service, O&M cost, proven technology, regional development, efficiency, employment
Sparkes [100]	Resettlement, livelihood, public participation, navigation, irrigation, infrastructure development, water supply, human health	Biodiversity, aquatic life, wildlife, flooding	Impact on local economy

a result of global warming (increase in some regions while decrease in others) [104,105]. This changing climate can reduce the usable capacity of hydropower plants by 61 – 74% in the next 25–50 years [106]. The likely impact of these events may require hydropower system to adjust operation or adapt through new measures [107]. Third, the consequences of extreme weather events, such as floods, ice or hailstorms or droughts, negatively impact generation by effecting water quality, quantity and damaging plant or transmission infrastructure [92,108–111]. Risk of flooding and sedimentation is also likely to increase with changes in local hydrology as a result of climate related extreme weather events [112]. Despite their functionality, current approaches rarely address these long-term environmental (climate) challenges within their frameworks that may substantially affect future hydropower generation potential. Of course, the challenges of a less predictable future are real and formidable.

From a systems perspective, the majority of the research have set boundaries that include project location and extend into the surrounding areas. Due to such restricted considerations, traditional life-cycle assessment omits some of the relevant factors and neglects some key benefits offered by hydropower. First, the value of irrigation, flood control, avoided emission from fossil fuel generation, and recreation provided by multipurpose reservoirs are sometimes ignored. Second, traditional system boundaries exclude the power grid which in turn disregards the role of pumped or hydro storage in system stabilization through ancillary services. At present, particularly with storage using batteries still awaiting major technological breakthrough, hydropower is really the one renewable source that offers an effective means of permitting demand variability. Moreover, reservoir-based hydropower is rarely credited in the existing literature for leveraging investment in intermittent renewables [113–115]. Despite being addressed by the IEA [74], indicators that reflect on the stability, flexibility and resilience offered by hydroelectric resources are rarely incorporated in the present matrices. A more detailed and complete analysis will require extending the system boundaries to include the grid, thus allowing inclusion of previously omitted parameters. Also, this line of research may also benefit from application of novel methods and approaches that integrate the disparate and currently unconnected aspects/dimensions of hydropower, environment and policy.

6. Conclusion

Hydroelectric projects, when built in the right places and following proper guidelines and with adequate mitigation measures, can bring multiple benefits to the community. Apart from providing electricity access, hydropower serves twofold purposes in climate change mitigation - as a renewable resource producing power at minimal GHG emission and as a backup facility to move the electrical grid to a low-carbon future. However, in the absence of a unified consensus or with poor safeguards and project execution, developing this potential resource in a sustainable way offers both considerable challenge and tangible risk. While environmental and social issues associated with hydropower development are often right cited with criticisms, here the core of the debate is not whether the environment is impacted, as much as to what is the degree of negative impacts that can be allowed while being sustainable. All power sources are problematic in a variety of ways, and yet the use of power brings dramatic and measurable benefits to human communities. The requirement is to determine holistic and defendable measures that evaluate pros and cons and that are open to external scrutiny and debate. Power and controversy are inevitable linked in human systems.

In a world with growing electricity demand, intermittent renewable sources pose a major predicament in terms of its impact on grid stability. The key balancing question, i.e., how much wind and/or solar can be incorporated without compromising flexibility – requires rigorous consideration of available dispatchable sources of coal, natural gas and hydropower. Now, the use of hydrocarbon-based fuel entails considerable financial risks with the growing adoption of carbon pricing mechanism. In a carbon constrained economy, hydroelectric projects can potentially be financed through carbon offsetting which may balance its typically high installation cost. This research seeks to summarize the existing state of play relating to the how sustainability is assessed for hydropower. The indicators used for these analyses are aggregated and summarized. The discussion briefly documents research methods and points out some limitations in the existing approaches. Thus, this study attempts to advance the current sustainability assessment. Two recommendations are also put forward: first, that such assessments should reflect on major environmental challenges and broad policy issues with respect to existing hydropower potential and, second, that system boundaries should be extended to allow reasonable estimation of hydro benefits on the overall grid.

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