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Sustainable utilization of water resources: Hydropower and ocean energy

Akshay Chavan[1*], Shubham Jadhav[2], Atish Mote[3]
[1] Department of Environmental Science, School of Earth Science, Punyashlok Ahilyadevi Holkar Solapur University, Solapur, Maharashtra, India
[2] Infront of Vima Office, Damani Nagar, Solapur, Maharashtra, India
[3] Shreeram Govardhan House, Jadhav Plots, Vairag State Highway, Narkhed, Mohol, Solapur, Maharashtra, India

Abstract
Sustainable utilization of water resources through hydropower and ocean energy plays a crucial role in advancing global renewable energy transitions. Hydropower remains the most widely adopted water-based energy technology, offering reliable power generation, irrigation benefits, and flood control, while ocean energy represents an emerging field with vast untapped potential in wave, tidal, and thermal energy systems. Technological advancements such as eco-enhanced turbines, fish-friendly hydraulic designs, and modular wave and tidal converters have improved efficiency and reduced ecological impacts. Nevertheless, both hydropower and ocean energy face challenges, including environmental disturbances, high capital costs, site-specific constraints, policy fragmentation, and social acceptance issues. Comparative analysis shows that while hydropower has matured into a globally competitive energy source, ocean energy remains at the experimental and demonstration stage, requiring stronger R&D, supportive governance, and international cooperation. The paper reviews the advantages, challenges, innovations, and policy frameworks surrounding hydropower and ocean energy, emphasizing that integrated planning, ecological monitoring, and benefit-sharing arrangements are critical for balancing energy production with socio-environmental sustainability.

Keywords: Hydropower, ocean energy, tidal power, wave energy, renewable energy and eco-enhanced turbines

Introduction

Sustainable use of water resources is an urgent issue in the transition to trustworthy and eco-friendly energy systems. Hydropower and ocean energy are two renewable energy technologies that exploit the natural dynamics of water movements for electricity generation and fossil fuel displacement. These technologies help to decrease greenhouse gas emissions and increase energy independence in the context of addressing the rapidly increasing demand for energy of various nations. Their implementation are part of global initiatives developing clean energy technologies that protect the natural environment and secure long-term resource use. Hydropower and ocean energy are thus important for the future of energy systems and the opportunities and responsibilities provided by the sustainable use of water resources.

Hydropower: Advantages and Disadvantages

The main advantage of hydropower comprises the ability to generate a steady energy supply using a renewable energy source. Hydropower makes a significant contribution to energy production globally (Silva, Sebastian Naranjo & Castillo, Javier Álvarez del, 2021) [12]; with most current practices located within the Omo-Turkana basin with around 4700 MW of official installed capacity. (Zaniolo *et al.*, 2021) [15]. Hydropower plants transform plant energy from moving water to electrical energy. Besides, the facilities provide additional services such as irrigation and flood defense. While hydropower bypasses pollution from the fossil fuel plant, developmental projects can still modify river biologically and physically and modify hydrological cycles. The possible impact on rapid land changes and migration to vulnerable communities fosters opposing parties to justify the energy production against preserving downstream habitat and the livelihoods already established. Thus making the operational policy and sustainability assessment measures at the hydropower energy infrastructure facilities for long-term development have to cater for the benefits and negative phenomena expected from the development phases. Hydropower and ocean energy each present unique opportunities and barriers in the global renewable energy transition. As outlined in Table 1, hydropower offers reliable, low-cost energy with additional socio-economic benefits such as irrigation, flood control, and rural electrification, while new turbine designs enhance environmental compatibility. Similarly, ocean energy provides immense untapped renewable potential, particularly in coastal and island settings, where tidal and wave systems can deliver stable baseload power and stimulate local economies.

Table 1: Opportunities and Advantages of Hydropower and Ocean Energy

Technology	Advantages
Hydropower	Reliable baseload power; Long lifespan and low operating costs; Flood control and irrigation benefits; Rural electrification; Competitive return on investment; Eco-enhanced turbine designs reduce fish mortality; Integration with water management systems
Ocean Energy	Vast untapped resource potential (wave, tidal, OTEC); Low-carbon and renewable; Stable baseload generation; Enhances coastal/island energy autonomy; Job creation in coastal regions; Innovations in WECs/TECs improve efficiency and durability

Additionally, existing hydropower plants across the globe illustrate the successes and challenging realities of sustainable energy production. Improved operational performance has been recorded by plants with low-head and ecologically improved turbines in Italy and France, whereby their adopted protection measures for water species and river continuity reduced fish mortality (Quaranta *et al*., 2020) [9]. Contrastingly, major developments in the Lower Mekong River Basin that generated a plenteous supply of hydroelectricity require continual evaluations away from their direct footprint impacts on food security and traditional economic activities because of resource availability shifts related to altered riparian systems (Intralawan *et al*., 2019) [4]. Evidently, while the hydropower industry drives operational efficiency through its technological upgrades, directed governance improves plant longevity and energy generation, its socio-ecological impacts remain. Therefore, improving hydropower plant construction, operation, and integration within societies continues beyond its engineering design improvements and innovations to capture addressing of well-being and ecological concerns.

Moreover, contemporary innovations in hydropower technology include an effort to improve the efficiency of turbines and to minimize the damaging effects of hydropower plants on aquatic species. Eco-enhanced turbines (EETs) technologies, such as Alden and Minimum Gap Runner designs, have identified hydraulic efficiencies up to 93.6%, as well as fish passage survival rates for small fish higher than 98% (Quaranta *et al*., 2021) [10]. These modern turbines not only enable generating energy at rates similar to other technologies but also contribute to solving the problems related to fish mortality and water quality by providing self-aerating and self-lubricating systems. It is vital to utilize the fish-monitoring data in the interpretation form to allow turbine operators to manage the e-operation schedules to limit the impact on local species (Quaranta *et al*., 2021) [10]. The possible implementation of the innovations in hydropower technology allows achieving the balance of energy-generating targets and environmental efforts, which may influence the design of future projects.

Economic issues still are very important to the sustainable development hydropower, especially in what relates to the economic attractiveness of the projects and their investment potential. As compared to many other electricity generation sources, hydropower projects usually can offer competitive operating costs over their lifetime, resulting from the reduced fuel costs and long lifetimes of physical assets while they can offer good return on investment (Zaniolo *et al*., 2021) [15]. In addition, many hydropower systems offer such additional benefits as flood control, irrigation and improvements to rural electrification, which can indirectly assist their development in local economies and accessibility to infrastructure (Zaniolo *et al*., 2021) [15]. Benefit sharing arrangements have been proposed as mechanisms for distributing the economic benefits to the communities affected by the hydropower operations, in order to, ideally, promote their development and welfare without significant negative impacts (Schulz & Skinner, 2022) [11]. The ability to achieve the above goals in benefit sharing arrangements is primarily determined by the governance mode and encompassing institutional arrangements, which affect the economic attractiveness and public acceptance of hydropower projects.

Hydropower development is therefore contingent on policy measures that promote consistency in regulatory frameworks and incentives for site development and implementation. Proper planning should include assessments of climate and complete site investigations to ensure limited interference with river development by controlling the socio-economic benefits against the social and ecological impact, besides trying to strike a fair balance (Almeida *et al*., 2022) [1]. However, policy-related issues tend to arise due to contradictory claims and an apparent lack of assessment methodology to evaluate the economic and social impact of the hydropower projects, as noted by the disparities in impact assessments from the Lower Mekong River Basin (Intralawan *et al*., 2019) [4]. Standardized methodologies for assessing project outcomes can create the potential to achieve coherence in the decision-making procedure based on the perceived impact and expected benefits while ensuring accountability among the stakeholders. The cultivation of a clear roadmap detailing the distribution of benefits, transparent permitting, and dynamic adaptive management process is crucial to ensure a regulatory framework balancing economic interests with ecological and social demands needed to bring hydropower development in sync with sustainability and localized priorities.

Ocean Energy: Potential and Development

Aside from hydroelectric power generation, ocean energy also represents an alternative resource for generating sustainable electricity, with both kinetic and thermal energy from their movements being directly exploitable. Emerging technologies that make use of electricity generation based on tides, wave movements, and thermal gradients have a place in expanding the alternative supply of renewable energy for generation outside of inland waterway flows. As countries strive to satisfy increasing consumption demands through low-impact alternatives, the adaptable use of ocean energy — tidal barrages, wave energy converters, direct expansion heat pumps, etc. — have considerable potential for incorporation into regional and global networks (Wilberforce *et al*., 2019) [14]. However, many marine-based energy technologies are still in an experimental stage and require significant improvements for greater efficiency and durability, as well as for the adaptive environmental monitoring of their operations beyond deployment. Experimental and investigation activities remain ongoing to evaluate the technical parameters, economic viability and ecological aspects that determine the future development possibilities and applications of ocean energy in the context of the overall sustainable energy mix (Wilberforce *et al*., 2019) [14].

In line with this, the ocean energy also presents various opportunities that make it as a potential candidate for further sustainable electricity generation. First, the magnitude of the energy resources in the ocean, particularly wave and tidal energy, allows a significant possibility of increased capacity without additional emissions of carbon dioxide into the atmosphere which greatly aids in decarbonizing (Paredes *et al*., 2019) [8]. A study conducted in Greece on the applications of wave energy technology revealed lower greenhouse gas emissions from the implementation of the energy system against traditional energy resources, as well as additional advantages such as energy autonomy and job generation in vulnerable island and coastal areas (Lavidas, 2019) [6]. Life cycle analysis of ocean energy technologies shows that its direct emissions during operational phases are relatively low and thus, presents itself as a potential low-carbon technology in the energy industry (Paredes *et al*., 2019) [8]. Ocean energy technologies provide stable baseload power and can enhance social and economic resiliency, characteristics that make it a promising agent in achieving further interventions for decarbonization and support for human development.

Ocean energy has significant potential, therefore, many barriers remain to prevent its full commercialization and to make it accessible and inexpensive, especially technological barriers. The lack of scalable, efficient, long-lasting prototypes, compatible with increasingly variable and harsh marine conditions, continues to be the most important barrier to the commercialization of ocean energy technologies. This aspect continues to be under priority R&D activity for cost improvements (Trivedi *et al*., 2023) [13]. Analysis of ocean energy development in India indicates other barriers. Certain technological barriers and limitations also encompass inadequate policy support, R&D funding, and a lack of skilled technical workforce to operate and maintain the new system, etc. (Trivedi *et al*., 2023) [13]. The deployment of ocean energy devices may impact marine ecology, sediment transport, local fisheries, etc. These aspects also deserve impact analysis and reactive mitigation measures. All these barriers are interrelated, indicating that continued ocean energy development requires an approach where the government responsible for R&D activities, adequacy and active workforce for offshore energy development is interconnected.

One example is the Mutriku wave energy farm in Spain. This demonstration plant helps in progressing the use of ocean energy technologies. It has an estimated annual generation of 600 MWh and has been integrated to the grid under actual coastal conditions. This commercial plant which started operation in 2011 serves not just as a source of renewable electricity but also as data about real sea and operational conditions that will be used to enhance wave energy converter designs. In India, demonstration tidal and wave energy projects pointed out the need for a clear regulatory mechanism and financial incentivization for achieving dependable energy performance. Another finding was the necessity to upskill the local workforce (Chakraborty *et al*., 2021) [2]. The learnings from these demonstration projects are that beyond the technical breakthroughs, there is a need for securing policies vital for its success. These policies include socializing evacuation costs and demand incentives for its sustainability. Moreover, the projects show that funding requires stability and the active engagement of the local community and industries across all phases is necessary for its roll out (Chakraborty *et al*., 2021) [2].

Moreover, development of ocean energy technologies has focused on continued improvements of wave and tidal energy conversion devices (WECs and TECs) to enhance their conversion efficiencies and reliability. Innovations include dual-axis wave energy converters and modular tidal stream turbines capable of prolonged and constant operations despite extreme sea conditions (Wilberforce *et al*., 2019) [14]. Advancements in material engineering have enabled improved corrosion resistance and design lifetimes, which decrease the maintenance frequency of WECs and TECs. Currently, active pilot projects are generating operational data for analyzing efficiency and reliability, although long-term performance evaluation studies remain to be documented (Wilberforce *et al*., 2019) [14]. Research and development to further overcome these technical challenges could establish the commercial viability of wave and tidal energy technologies as the major components of future clean energy networks.

The technological and economic prospects of ocean energy are closely interconnected and hinge heavily on economic factors. The main economic factor is the high capital cost of development and installation of ocean energy technologies, where uncertainty regarding the cost of ocean thermal energy conversion (OTEC) and marine energy systems depends on both development and operation variables, which are often location-specific factors the determine the project viability (Langer *et al*., 2020) [5]. There is still a potential for market competitiveness as the technological innovation have successfully lowered the cost of OTEC to be at par with the fossil-based energy developments in electricity markets. However, economic factors such as high borrowing interest and the narrow use of economic analysis technologies is a financial barrier to further investment and development in ocean energy (Langer *et al*., 2020) [5]. Although compounded by the financial barriers, ocean energy development still requires an organized research program to further assess the economic factors that influence its market competitiveness through thorough economic assessment and modeling to provide clarity on the potential market pathways for ocean energy to aid investment and policy decision-making.

On the policy front, ocean energy would require international coordination, flexible regulation, and full-fledged governance mechanism frameworks that can expedite the technology's journey into commercialization from test projects. International cooperation is essential in matters such as common marine resources, uniformity in technical and environmental standards, and lowering barriers to entry to new markets (Cui & Zhao, 2023) [3]. Regulatory issues often stem from divergence in project permitting, ambiguities in financial mechanisms, inconsistent guidelines, and ultimately lead to project delays and difficulty in securing funding. In this regard, India's experience with ocean energy shows that the successful execution of ocean energy projects relies on specific government assistance, organized financial mechanisms, simplified evacuation cost sharing, and the establishment of research and training infrastructure within the industry (Chakraborty *et al*., 2021) [2]. Hence, labour mobility and harmonized regulatory benchmarks through international cooperation can enhance opportunities for policymakers to enable ecosystems for encouraging the proliferation of ocean energy technologies that align with economic and environmental goals.

Environmental Effects of Hydropower and Ocean-Based Energy

When assessing the environmental dimensions of hydropower, the critical issue remains the ecosystem interference directly linked to dam construction and operation. The large-scale hydroelectric plants might significantly change river habitats, water regimes, and terrestrial and aquatic biodiversity, resulting in natural habitat loss and local community displacement (Silva, Sebastian Naranjo & Castillo, Javier Álvarez del, 2021) [12]. The interference with water quality and changing sediment transfer patterns affect nutrient cycles, possibly resulting in increased organic materials with further implications to ecological equilibrium (Silva, Sebastian Naranjo & Castillo, Javier Álvarez del, 2021). Modern planning increasingly requires climate change implications to reduce the cumulative impacts of rivers and the related ecosystems (Almeida *et al*., 2022) [1]. With an emphasis on rigorous site assessment combined with sustainability-oriented decision-making frameworks, hydropower projects can mitigate adverse impacts and maintain ecosystem integrity with less interference while achieving energy goals (Almeida *et al*., 2022) [1].

Table 2: Challenges and Barriers of Hydropower and Ocean Energy

Technology	Challenges
Hydropower	Ecosystem alteration (river flow, biodiversity, sediment cycles); Community displacement; Policy conflicts and weak governance; High upfront capital costs; Climate vulnerability (droughts, seasonal variability)
Ocean Energy	Still in experimental stage; High development and installation costs; Harsh marine environment reduces durability; Limited skilled workforce; Inadequate policy support and R&D funding; Environmental risks to marine ecosystems (noise, species collision, sediment disruption)

However, as highlighted in Table 2, hydropower faces ecological concerns such as biodiversity loss and river system alteration, coupled with social displacement and governance challenges. Ocean energy, on the other hand, struggles with technological immaturity, high costs, and vulnerability to harsh marine conditions, while raising ecological concerns about marine species and habitats. Together, these insights emphasize that sustainable deployment of hydropower and ocean energy requires balancing technological innovations with environmental safeguards, robust governance, and long-term economic planning.

The introduction of ocean energy technologies similarly leads to a range of environmental impacts where habitat loss and interactions have been highlighted. The various infrastructures for energy-harvesting devices such as tidal turbines and wave energy converters act as stressors causing disruptions in the dynamics of the natural marine systems through noise, altered hydro-sedimentary characteristics, and wave climate (Martínez *et al*., 2021) [7]. Collisions and disturbances may be experienced by marine mammals, fish stocks, benthic and pelagic organisms, and seabirds due to operational and maintenance processes associated with the device (Martínez *et al*., 2021) [7]. Literature suggests that these impacts can influence marine renewable energy development to a degree that species distribution patterns may be altered, behaviors modified, and in some instances, habitat loss – justifying the need for adaptive and comprehensive management practices (Cui & Zhao, 2023) [3]. Environmental monitoring and appropriate mitigation practices therefore represent potential practices that can be made in an effort to minimize ecological disturbances, enhance species resilience and support the sustainable development of ocean energy practices (Cui & Zhao, 2023) [3].

A comparison of the life cycle impacts of the two energy technologies shows some common issues, as well as some impacts that are particular to each technology. The use of dam-based hydropower has historically raised significant impacts on the aquatic environment, change of natural flow pattern regimes, etc., but applications of ecologically optimized turbines and control strategies show promising results in reducing fish kill rates and habitat interruptions (Quaranta *et al*., 2020) [9]. Alternately, ocean-based energy technologies primarily raise their most burdensome impacts during raw material extraction, manufacturing, and shipping stages, where specific life cycle impact assessment revealed the stages that must be targeted to prevent ocean-related climate change and positively impact sustainability (Paredes *et al*., 2019) [8]. Related mitigation strategies are in play in both energy sectors today: hydropower developers increasingly re-use existing water management systems to reduce additional habitat impacts, while ocean energy innovators promote technological and environmental management practices to mitigate production-related impacts (Quaranta *et al*., 2020) [9]. To overcome challenges and boost additional shrinking of the environmental impact of both developments, a focus on targeted cooperation, discovery, training, monitoring, restoration, and adaptive operation practices is required.

Technological Advancements and Innovations

Improvements of the efficiency and notation on the ecodynamic aspects in the use of hydropower and ocean energy simply cannot happen without the active spread of the latest technology. First of all, technology breakthroughs have occurred in hydropower development, such as the cutting-edge environment-enhanced turbines (Alden turbine, Minimum Gap Runner turbine) that secure hydraulic efficiency of 93.6% and considerably enhanced fish passage survival (Quaranta *et al*., 2021) [10]. Such technology spread includes self-aerating and self -lubricating turbines where quality of water was retained without excessive side effects and harmful substances, thus matching the proposed landscape where energy production and ecologic boundaries are matched (Quaranta *et al*., 2021) [10]. Continuous interpretation of ecology metrics using fish-monitoring data has become an essential part of the operational strategy. Such data monitoring allows hydropower plants to optimally schedule wind turbines and secure lowest possible impact on fish life. Achievement of such harmony demonstrates how engineering effort and data monitoring continue to push the frontier of water-based renewables while delivering on sustainability goals with intensive support of the latest technology.

In addition, the continuing funding and investment of R&D have supported the technological advancement of renewable energy sources, especially those harnessing water. Many innovations, such as ecologically improved and low-head turbines, were made possible through intensive R&D focused on optimizing performance and addressing environmental challenges. For example, case studies from different countries show that R&D investment dedicated to ocean and water-based systems have helped researchers and engineers reduce fish deaths and habitat loss while also optimizing performance (Quaranta *et al*., 2020) [9]. Digitalized control systems, as well as the recycling of existing hydraulic systems, also emerged from continuous investment collaborations and innovations in the R&D sector. These further emphasize the importance of R&D for the sustainable development of hydropower and ocean energy technologies that can adapt to the increasing complexity of ecological, technical, and economical requirements (Quaranta *et al*., 2020) [9].

Case in point is the Swansea Bay Tidal Lagoon project in the United Kingdom, which deploys best-in-class tidal energy conversion systems to showcase scalable and environmentally-friendly marine power solutions. Implementation of modular designs and building practices, together with innovative turbine technologies, enables the project to adapt operations to changing coastal conditions. Pilot tests on similar wave and tidal energy devices in Europe and Asia are known to result in quantifiable gains in operational effectiveness and grid performance under varying marine conditions (Wilberforce *et al*., 2019) [14]. Besides the technical milestones, these projects are also recognized for their industry knowledge contributions, particularly the generation of operational data necessary for engineering optimization and evaluations. Stakeholders capitalize on the documentation of experiences from the trailblazing projects to improve on marine energy initiatives, troubleshoot technical challenges, and establish institutional credibility for the widespread adoption of ocean renewable energy technologies (Wilberforce *et al*., 2019) [14].

Economic and Policy factors

As with all emerging technologies, it is important to evaluate the economic potential of hydropower and the ocean energy through cost, indirect value, and financing prospects for operators. Hydropower is likely to have favorable net costs than ocean energy in the long run due to low operating costs, long lifespans, and indirect values such as flood control and rural electrification in projects in the Omo-Turkana basin (Zaniolo *et al*., 2021) [15]. In contrast, uncertainty in capital and operational costs, volatile interest rates, and installation costs that vary by site are characteristic during development of oceanic thermal energy conversion and similar marine technologies (Langer *et al*., 2020) [5]. Such knowledge gaps are exacerbated when assessing costs by individual pilot plants as opposed to integration at the system and scaling levels that drive beyond plant configurations. Effective economic analysis and a wide array of financing options such as public-sector spending, private-sector lending, and multiparty grants are imperative for making future hydropower and ocean energy competitive in the energy market (Zaniolo *et al*., 2021) [15].

On this note, the integration of policy frameworks into government interventions also plays a critical role in determining the extent and speed of deployment of emerging renewable energy technologies. The regulatory framework along with funding arrangements and fiscal measures deployed by the national governments determine the direct correlates of investment on projects and initiatives such as the research of ocean energy, their integration into grid systems and the skill-sets development. Recent efforts to develop marine energy in India for example have implemented this policy drive (Chakraborty *et al*., 2021) [2]. Furthermore, policy interventions at the international levels such as multilateral agreements and collaborative cross-border initiatives allow for the technical standards development, environmental safeguards coordination and best practice advancement across countries. These enable new technologies diffusion across borders with lesser hurdles (Wilberforce *et al*., 2019) [14]. The existence of such policy interventions allows a relatively stable investment environment, promotion of local capacities on the emerging technologies and supports their long-term integration into the energy options of the country. Targeted and well-aligned government interventions which combine best policy efforts at the global coordination level also promote not only renewable energy advancement, but paired with such actions, the technological advancements are supported with regulatory frameworks while maintaining adequate participation of all the different stakeholders (Chakraborty *et al*., 2021) [2].

Finally, scaling opportunities for hydropower and ocean energy in the future will demand key components of global aspirations for clean, reliable energy systems that can accommodate growing populations and advanced economies. These components will hinge on technological developments and operational efficiencies, as well as the establishment of inclusive benefit-sharing agreements that could support long-term engagement at the community levels with anticipated environmental and economic benefits (Schulz & Skinner, 2022) [11]. Widespread adoption of hydropower and ocean energy will also depend on the dismantling of barriers that include policy and governance shortcomings, inadequate research focus and funding, and lack of workforce education and training, as specifically highlighted in the case of ocean energy (Trivedi *et al*., 2023) [13]. Stakeholder and industry engagement and coordination will be critical in developing projects with streamlined delivery schedules, a robust regulatory environment, and institutional capabilities for adaptive management in diverse ecological and socio-ecological settings. Overall, advancing the interconnected elements highlighted above could help hydropower and ocean energy join the list of industries that can offer significant contributions to global sustainability goals while alleviating the risks associated with large-scale resource extraction and development (Trivedi *et al*., 2023) [13].

Conclusion

Hydropower and ocean energy stand as two critical pillars of water-based renewable energy systems, offering complementary pathways toward a sustainable energy future. Hydropower, as a mature and widely deployed technology, continues to provide reliable electricity, irrigation benefits, and water management functions, yet its ecological and social impacts necessitate adaptive governance and eco-sensitive innovations. Ocean energy, though still at an early stage of commercialization, holds vast potential for diversifying the global energy mix, especially in coastal and island regions where energy security is vital. The challenges of intermittency, high capital costs, environmental risks, and policy fragmentation underline the need for integrated strategies that balance energy generation with ecological conservation and community well-being. Moving forward, stronger investments in research and development, international cooperation, and inclusive policy frameworks will be essential to scale up these technologies. By harnessing the power of rivers, tides, and waves responsibly, hydropower and ocean energy can significantly contribute to global decarbonization, climate resilience, and sustainable development goals.

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