Climate Change and the Future of Bhutan's Hydropower: *A Review of Literature*

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Abstract

Bhutan's hydropower sector, vital to its economy and sustainability goals, faces increasing threats from climate change. This review examines its vulnerabilities to glacial retreat, glacial lake outburst floods (GLOFs), erratic rainfall and fluctuating river flows, emphasising socio-economic and environmental impacts.

Bhutan's reliance on run-of-river hydropower, highly sensitive to seasonal variability, leads to energy shortages and import dependence. Weak enforcement of environmental policies and a lack of climate-integrated planning exacerbate these risks. Despite policies like the Bhutan Sustainable Hydropower Development Policy (SHDP) 2021, adaptation challenges persist.

The slow transition to reservoir-based hydropower, limited investments in alternative energy, and weak early warning systems threaten energy security. Infrastructure remains vulnerable to extreme weather events, requiring improved flood-resistant designs, predictive climate models, and nature-based solutions.

This study highlights the urgent need for policy reforms, technological innovations, and energy diversification to strengthen hydropower resilience. By enhancing climate-adaptive infrastructure, enforcing environmental regulations, and fostering regional co-operation, Bhutan can maintain sustainable hydropower development amid climate uncertainties.

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Introduction to Bhutan's Hydropower Sector

Bhutan, a small Himalayan country, is water-abundant with 94,508 cubic metres per capita available per annum. It is divided into five major hydrological basins covering 38,000 square kilometres (km^2) (WWF Bhutan, 2021). Its freshwater rivers and basins are fed by monsoon rains and supplemented by glaciers and snow, contributing 2-12% and 2% respectively (WWF Bhutan, 2021).

Hydropower in Bhutan depends on these water resources. This industry is a major driver of the country's economy and one of the principal sources of foreign exchange and clean energy development across the South-Asian region (Tariq et al., 2021).

Hydropower in Bhutan has been termed a strategic and renewable energy resource in ensuring energy security, with the country boasting a clean energy potential of over 35,000 megawatts (MW) from more than 150 sites, of which only seven percent of the potential is tapped. Yet the sector already accounts for 40 percent of the national revenue and 20 percent of the national economy (Almulhem, 2023).

Climate Change Impact on Hydropower

Bhutan is identified as exceptionally vulnerable to climate change impact, affecting the hydrological regime and electricity generation (Mahanta et al., 2018). Hydropower is a climate-sensitive industry, as it relies on river flows and water levels. Yangzom and Choden (2021) report that from 1976 to 2005, there were increasing trends of temperature and decreasing levels of precipitation at mean annual scales with high variability. The trends of annual rainfall indicate a decrease in the total rainfall and water discharge.

Conversely, hydrological models project that the total annual flow in the river basins will increase in the future and will be available until the end of the century. However, such scenarios of a bell-shaped flow regime can impede hydropower development, as the higher flow during monsoons will only spill over, while the generation will be negative during the lean season (NEC, 2020a).

It is predicted that temperatures in the northern parts of the country will continue to rise, accelerating the rate of snow and glacier melt. This increased melting will, in turn, peak river discharge and result in floods and GLOFs (Aryal et al., 2023).

Global warming and climate change have accelerated the melting of glaciers at rates higher than the global average (Bajracharya et al., 2014; Mahanta et al., 2018). Interestingly, it is predicted that one-fourth of the total mountain glaciers may disappear by the end of 2050, and 50 percent of the loss might be reached by the end of the 21st century (IPCC, 1996).

Bajracharya et al. (2014) reported that the glacialised area in Bhutan decreased by 23.3 percent between 1977 and 2010, while the number of glaciers significantly increased from 771 in the 1970s to 885 in 2010. Although the exact number of glaciers in Bhutan is unknown, Aryal et al. (2023) estimate around 1583 glaciers today. This increase can be attributed to the shrinkage and fragmentation of glaciers leading to the loss of glacial area.

Rinzin et al. (2023) identify four potentially dangerous glacial lakes, namely Bechung Tsho, Raphstreng Tsho, Thorthomi Tsho, and Luggye Tsho, located in the Lunana Glacial Complex of the Phochu Basin in Bhutan. Shrinkage and intensified retreat of glaciers, and expansion and formation of new glacial lakes, add to the increased risks of GLOFs discharging huge amounts of water and debris. This can lead to the destruction of public infrastructure, agricultural land and hydropower systems, and loss of human lives (Bajracharya et al., 2014).

Socio-Economic Implications

The commissioning of the 336 MW Chukha hydropower project in 1986-88 contributed to the country's socio-economic development, with 75 percent of the generated electricity exported to India. Since the Eighth Five-Year Plan (1997-2002), electricity exports to India have played a crucial role in financing Bhutan's current and capital expenditures (Tshering and Tamang, n.d.). As a clean renewable resource, hydropower serves two important purposes in the Bhutanese economy - to provide safe, reliable, sufficient and affordable electricity for domestic consumption and industrial use, and as an industry for earning revenue from export of hydroelectricity (MoEA, 2021).

NEC (2020a) reports that there will be temporal and spatial variations with high flows during monsoons and low during winter seasons, which make the management of hydropower systems complex. This will adversely affect electricity production and supply to domestic and foreign markets.

Bhutan's high dependency on hydropower raises concerns over energy security. In 2018, the hydropower generation from the five major hydropower plants decreased by 10 percent from the previous year and caused a sharp decline in electricity exports by more than 16 percent due to poor hydrology (ADB, 2022). There has been a significant drop in the export of electricity over the years. In 2021, the export of electricity was valued at Nu. 24.2 billion; in 2022, it was Nu. 22.47 billion, and in 2023, it was Nu. 16.67 billion.

The demand for energy is growing rapidly. Since 2015, the domestic energy demand has risen by an average of 2.2 percent annually, reaching 374 MW of electricity in 2020. Before 2021, import of electricity was minimal; however, the boom in energy-intensive industries and the establishment of industrial parks pushed up the country's energy demand (Dema, 2023).

Peak energy demand during the winter months cannot be met, as the electricity generation from run-of-river plants drastically drops to 300 MW (lean season generation) from 2000 MW (peak monsoon season generation). To meet the domestic demand, Bhutan controls industrial loads during the lean season or imports electricity from India (ADB, 2022).

The year 2024 marked a departure from the previous decades, in which Bhutan's domestic energy consumption surpassed the traditional exports of electricity. This was attributed to the declining hydropower generation and an increase in dependence on imported electricity (NSB, 2024). The year also saw a surge in electricity imports by six-fold during the lean season.

Environmental Considerations

The Bhutan Himalayas is recognised as a biodiversity hotspot, and the mountain ecosystem faces an existential threat from erratic weather conditions and water stress. Climate change has altered the properties of water, particularly in the high mountain areas, affecting the biology of a unique mountain ecosystem (RSPN, 2011). The pressure on these natural ecosystems is exacerbated by the expansive development of hydropower projects.

Hydropower plants can potentially destroy the riparian ecosystems downstream by disrupting the periodic natural flooding and exacerbating water pollution. Further, reduction in sediment and nutrient load downstream can increase river erosion and reduce the ecological and economic viability of the river systems. Naturally adapted aquatic species cannot survive in the artificial lakes, and the deteriorated quality of water downstream - particularly with low levels of oxygen and supersaturated gas - can make the environment unsuitable for life. Hydropower plants can often fragment or destroy biodiversity altogether (World Bank, 2016).

Bhutan's hydropower systems can offset these impacts, considering its run-of-river plants with minimal inundation areas. However, it is still likely that there will be impacts on the aquatic ecosystem, due to the alteration and fragmentation of the river system. Approximately 90 percent of the river networks are free-flowing, but with the new anticipated hydropower projects, this is expected to be reduced to 50 percent (World Bank, 2016).

Since studies on aquatic biodiversity are not extensive in Bhutan, it is difficult to fully assess the impact of river fragmentation on the aquatic ecosystems. Yet, with global warming and climate change, there are concerted efforts to promote renewable energy resources, under which hydropower has gained universal acceptance (Rinzin, 2020).

As this global phenomenon elicits questions on the sustainability of the water resources that power the plants, hydropower in Bhutan can be seen as a sector that plays a significant role in mitigating climate change by leveraging on renewable resources and sustainable practices. Further, the export of surplus electricity to India can help reduce and transition from the dependence on coal and fossil fuels, thereby contributing to regional decarbonisation (Debnath, 2023).

Adaptation and Resilience Strategies

Bhutan's Sustainable Hydropower Development Policy 2021 outlines several policies and measures to strengthen resilience of the hydropower sector in the face of a changing climate and evolving energy demands. Key measures include transitioning from a run-of-river to a reservoir based system, and pump storage schemes to provide a reliable energy output during the lean seasons, building climate resilience and ensuring water security.

Additionally, diversification of energy sources, by integrating wind and solar energy, is emphasised to create a hybrid energy system that enables energy security. The policy mandates watershed and catchment area management, alongside comprehensive Environmental Impact Assessments (EIAs) (MoEA, 2021).

Bhutan's National Adaptation Programme of Action (NAPA), addresses immediate needs related to climate change adaptation. Under NAPA, early warning systems (EWS) and risk reduction strategies against climate change induced disasters, particularly GLOFs, flash floods, landslides and droughts, were put in place.

The UNDP has supported Bhutan in efforts to enhance adaptive capacity, through the implementation of NAPA, to reduce risks from GLOFs along Punakha, Wangdue Phodrang and Chamkhar Valleys. The project emphasised physically lowering the water levels of Thorthomi Lake to reduce the risk of flooding.

Bhutan has been constantly monitoring water levels in glaciers and glacial lakes since then, and has installed EWS in at-risk river systems, where hydropower facilities are proposed to be built. Further, implementing effective watershed management practices in critical areas to enhance the resilience of hydropower infrastructure and ensure sustainable water flow, was emphasised (GEF, 2016).

These efforts were subsequently strengthened with the implementation of NAPA-II. It drew attention to improving the climate resilience of hydropower through the installation of 32 automatic water level stations, three automatic river discharge systems, and four cable-way systems -

which provide critical hydrological data - and upgrading Bhutan's National Weather and Flood Forecasting and Warning Centre (NWFFWC), enhancing flood risk management. Similarly, monitoring snow and glacier behaviour benefitted hydropower (NCHM, 2018).

Gaps in Bhutan's Adaptation Approach

Limited transition to reservoir-based systems

Bhutan's hydropower sector primarily operates on run-of-river systems which are susceptible to fluctuating river flows. Unlike the reservoir-based plants, which provide stable year-round electricity generation by storing water during high-flow seasons and releasing it during the dry periods (Tsuanyo, 2023), the run-of-river projects experience seasonal variability and create energy security concerns that compel the import of electricity from India.

Despite the SHDP 2021's emphasis on transitioning to the reservoir-based systems, the transition has been slow for several reasons:

a) high capital costs, because reservoir-based projects require substantial financial investment and environmental mitigation measures;
b) environmental and social concern, because reservoirs require large inundation areas that can potentially affect biodiversity and displace local communities;
c) geological and seismic risks, because the country's mountainous terrain is prone to landslides and earthquakes that may threaten the viability of large dam structures;
d) international relations and water sharing, because the Bhutanese hydropower projects are closely linked with India through joint ventures and power purchase agreements, and shifting towards reservoir-based projects may require re-negotiation with India;
e) e-flow requirements and by-laws - hydropower policies must comply with the environmental flow (e-flow) requirements to maintain riverine ecosystems and aquatic biodiversity (Biswas, 2011; MoEA, 2020; NEC, 2007; Water Research Bhutan, 2023).

Insufficient adaptation of alternative renewable energy resources

While its policies emphasise the importance of diversification, implementation of alternative renewable energy resources, like solar and wind, remain minimal (IRENA, 2019). Rugged terrain and variable weather conditions in the country pose a significant challenge to efficiently scale up renewable energy resource projects (Cowlin & Heimiller, 2009).

Further, the World Bank (2016) notes that the national grid is primarily designed for electricity generation from hydropower, and integrating intermittent renewable sources can become costly in upgrading transmission infrastructures and storage facilities. Although the adoption of alternative renewable resources is emphasised in national policies, shortcomings in the ecosystem for renewable technology, and lack of incentivisation, expertise and policy frameworks, have impeded diversification efforts (Bhonsale, 2020).

Weak enforcement of environmental and climate-risk measures

Environmental policies and regulations have been established to mitigate the impacts of hydropower on ecosystems and communities. However, weak enforcement of these instruments has led to inconsistencies in the implementation process.

While environmental impact assessments (EIAs) and watershed management policies exist, their execution varies widely across projects, often due to resource constraints and lack of regulatory oversight (NEC, 2020b; World Bank, 2016). Weak implementation of EIA and Environmental Management Plans has resulted in inadequate quality assurance and monitoring, and inconsistent compliance across hydropower projects. Furthermore, although hydropower authorities are required to submit compliance reports periodically, regular inspections have been hampered by manpower shortages and logistical challenges (Gawel and Ahsan, 2014; NEC, 2020b).

The major concern is the cumulative impact of hydropower on the river ecosystems, as the run-of-river projects dominating the Bhutanese hydropower industry often fail to maintain sufficient e-flow. Although e-flow by-laws have been introduced, compliance has remained a big hurdle, affecting aquatic biodiversity and disruption in river ecosystems.

Bhutan has also not conducted a national-scale strategic environmental assessment for hydropower development since 2004, leaving gaps in assessing cumulative biodiversity impacts and construction-related environmental damages (NEC, 2020b).

Climate change impact and hydropower infrastructure vulnerability

Bhutan's hydropower is exposed to an increasing risk from climate change vulnerabilities. These events can severely damage the hydropower dams, disrupt power supply, and threaten critical infrastructures. Hydropower planning has historically relied on past hydrological data, instead of future climate projections (International Hydropower Association, 2019) and the limited integration of climate-resilient models can hinder long-term adaptation efforts. Bhutan's hydropower plans do not fully integrate climate risk assessments that may threaten hydropower plants, such as glacial retreat and shifting precipitation.

Bhutan lacks a comprehensive Early Warning System (EWS) for climate-induced disasters that could help mitigate infrastructure damage and operational disruptions (UNDRR, 2020). For instance, Bhutan's weather monitoring network is unreliable due to its heavy reliance on manual data collection and transmission, which results in gaps in weather records, lower forecast accuracy, and challenges in predicting extreme weather events. While automatic weather stations are in place, frequent communication and network disruptions reduce their effectiveness. High altitude regions remain under-represented in the precipitation monitoring network, and flood warning systems are limited to major rivers, leaving smaller tributaries without adequate monitoring (Tshering & Fruman, 2025).

Recommendations

The following recommendations address the existing gaps to ensure the sustainability of the Bhutanese hydropower systems.

Enhancing climate-resilient hydropower infrastructure

It is imperative that Bhutan prioritises the development of climate-resilient hydropower infrastructures to mitigate the impact of extreme weather events. Resilience measures can be achieved through reinforcement of reservoir-based dam designs.

Further, improved sediment control measures and enhanced flood management systems can be adopted to counter the risks of climate impact.

Technical upgrades, by adapting engineering techniques, such as flexible spillways and real-time water management systems, can help respond to climate uncertainties (IHA, 2023). The integration of nature-based flood stabilisation measures, such as reforestation in the upstream catchment areas, can reduce sedimentation (Molnar-Tanaka & Surminski, 2024).

Strengthening Early Warning Systems (EWS) and disaster preparedness

There is a need to establish a comprehensive EWS for hydropower-related disasters to minimise infrastructure damage and ensure continuity of operations. Investments should be made in automated weather stations across all catchment areas, in remote-sensing technologies, flood forecasting systems, and real-time hydrological and glacial lake monitoring networks to improve predictive capabilities (Tshering & Fruman, 2025; Quaranta et al., 2023). There should also be regular disaster preparedness drills and an integration of climate risks assessments with hydropower project planning.

Enhancing data collection and climate modelling for hydropower planning

Similarly, Bhutan's hydropower sector can benefit from improved climate modelling and real-time hydrological data collection to anticipate future changes in river discharge and trends in glacial retreat. Unlike the planning of hydropower projects based on historical data, expansion of automated weather stations and integration of satellite-based monitoring technologies can shift hydropower development to projection-based planning and strengthen Bhutan's capacity to make data-driven energy decisions (Tshering & Fruman, 2025). AI-powered predictive modelling tools are also recommended to further improve Bhutan's ability to develop adaptive hydropower strategies.

Energy diversification to reduce hydropower dependency

Given the vulnerability of hydropower to climate change, it is important to accelerate the integration of alternative renewable energy resources, including wind and solar power, to diversify Bhutan's energy portfolio. The hybridisation of energy sources can ensure energy security, particularly during the lean seasons and extreme weather events (ADB, 2022). Policies should advocate and encourage private sector participation through incentivising investments and subsidisation to promote grid modernisation and diversification (IRENA, 2016).

Enhancement of policy implementation and regulatory oversight
The strengthening of environmental regulations and mechanisms is critical to realise sustainable hydropower development (NEC, 2020b). The government should establish an independent regulatory body to monitor environmental compliance and over-see hydropower-related climate adaptation measures. Such an entity can conduct regular strategic environmental assessments and update EIA frameworks consistently across projects to include climate resilience considerations.

Conclusion

Hydropower has long been a backbone of the Bhutanese economy, symbolising the nation's commitment to clean energy and sustainability. It is, however, plagued by growing vulnerabilities posed by climate change, including glacial retreat, GLOFs, fluctuating river flows, and erratic rainfall patterns that necessitate a critical reassessment of the sector.

This is a moment for Bhutan to pause and re-think its hydropower-centric development model. Although a vital sector for the country, a balanced approach that reduces heavy reliance on hydropower, minimises environmental degradation, and promotes renewable energy diversification, is recommended, as uncertain and complex challenges brew in a changing climate scenario.

Such an approach would not only strengthen Bhutan's energy resilience but also set a regional example for sustainable energy policies and development. As Bhutan leads this change, it can inspire neighbouring countries to re-evaluate their approaches to hydropower in a fragile Himalayan region, mitigate ecological destruction and ensure sustainable development for future generations.

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