

Projected Hydropower Capacity under Changing Climate Conditions and Its Implications in South and Southeast Asia

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Abstract

Hydropower is critical to South and Southeast Asia's energy security, yet climate change threatens its sustainability through altered hydrological cycles. This study assesses the impacts of climate change on hydropower capacity factors across 12 countries (86% of regional installed capacity) from 2020 to 2100. Using an ensemble of 60 climate-hydrological models (5 GCMs, 4 GHMs, 3 RCPs), we evaluate shifts in precipitation, glacier melt, and extreme events on seasonal and annual hydropower performance. The objectives are to 1) quantify regional and sub-regional capacity factor trends, 2) identify drivers of variability, and 3) propose adaptive strategies for resilient energy systems. Results indicate a regional mean decline in hydropower capacity factors by 4.8% (2020-2059) and up to 5.4% (2060-2099) under high-emission scenarios. The Indian Subcontinent faces severe reductions (6.9% by 2100) due to drier winters and monsoon shifts, while Mainland Southeast Asia declines by 5.9%. Conversely, Himalayan regions (Nepal, Bhutan) show transient declines (−2.4% by 2059) followed by recovery post-2060 as glacial melt temporarily offsets precipitation deficits. Maritime Southeast Asia exhibits mixed trends, with capacity factors rebounding under high warming. To mitigate risks, we recommend integrating hydropower with floating solar photovoltaics, optimizing reservoir operations via AI-driven forecasting, and strengthening transboundary water-energy governance. These strategies can enhance grid resilience, offset seasonal variability, and support decarbonization goals. Policymakers must prioritize region-specific adaptations, particularly in climate-vulnerable zones like the Indian Subcontinent, to ensure energy security amid escalating hydrological uncertainties.

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Keywords

Climate Change, Hydropower, South Asia, Southeast Asia, Energy Infrastructure, Precipitation Patterns, Glacier Melt, Extreme Weather Events, Capacity Factors, Adaptation Measures, Resilience

1. Introduction

Hydropower stands as a cornerstone of global renewable energy systems, playing a pivotal role in decarbonizing energy grids and supporting sustainable development (Zhou et al., 2020; Yang et al., 2022). Its ability to provide stable, dispatchable power complements variable sources like solar and wind, making it indispensable for achieving energy security (Rawa et al., 2021; Tan et al., 2021). However, the sustainability of hydropower is increasingly threatened by climate change, which alters hydrological cycles, precipitation patterns, and glacier dynamics (Yalew et al., 2020; Li et al., 2020). Nowhere are these challenges more acute than in South and Southeast Asia, where hydropower accounts for a significant share of 14.5% electricity generation and underpins socioeconomic growth (Sun et al., 2020; Rasul et al., 2021).

The region's heavy reliance on hydropower is juxtaposed against its vulnerability to climatic shifts. South Asia's monsoonal climate and Southeast Asia's tropical regimes are experiencing intensified variability, including erratic rainfall, prolonged droughts, and glacier retreat (Arias et al., 2014; Qin et al., 2020). These changes disrupt water availability, directly impacting reservoir storage, turbine efficiency, and seasonal energy output (Sapitang et al., 2020; Dehghani et al., 2019). For instance, melting Himalayan glaciers initially boost river flows but threaten long-term water security as glacial mass diminishes (Qin et al., 2020; Yang et al., 2019). Similarly, extreme weather events, such as the 2021 Uttarakhand glacier burst in India, highlight the cascading risks to infrastructure and energy stability (Yang et al., 2019; Zhong et al., 2020). Recent studies also emphasize the compounding effects of rising evaporation rates and altered runoff patterns, which strain reservoir operations and reduce hydropower efficiency (Li et al., 2019; Ahmadianfar et al., 2021).

While previous studies have explored hydropower's response to climate change, critical gaps remain. Global assessments often overlook regional heterogeneity, particularly in Asia, where hydropower infrastructure spans diverse geographies—from the glacier-fed Himalayas to the monsoon-dependent Indian Subcontinent (Rasul et al., 2021; Aryal et al., 2020). Furthermore, existing models rarely disaggregate impacts across seasons or reconcile conflicting outcomes from different climate scenarios (Arango-Aramburo et al., 2019; Ahmadianfar et al., 2021). For example, projections for the Himalayan region suggest winter precipitation declines may temporarily reduce hydropower capacity, yet increased glacier melt could offset losses in later decades (Dehghani et al., 2019; Sanchez et al.,

2021). Such complexities necessitate a granular, region-specific analysis to inform adaptive strategies. Recent advancements in hybrid modeling frameworks, such as coupling General Circulation Models (GCMs) with high-resolution hydrological datasets, offer promising avenues to address these uncertainties (Zhou et al., 2020; Li et al., 2020).

This study addresses these gaps by evaluating climate risks to hydropower capacity across South and Southeast Asia. Our analysis spans 13 countries, encompassing over 86% of the region's installed hydropower capacity, to identify spatially divergent trends and seasonal vulnerabilities (Rasul et al., 2021; Sun et al., 2021). By integrating high-resolution discharge data and reservoir dynamics, we provide actionable insights into adaptive water management, infrastructure resilience, and hybrid energy systems (Sanchez et al., 2021; Tan et al., 2021). Methodologically, this work builds on innovations in machine learning for reservoir forecasting and multi-reservoir optimization, ensuring robustness in scenario projections (Sapitang et al., 2020; Ahmadianfar et al., 2021).

2. Literature Review

Hydropower, as a cornerstone of renewable energy systems, is both a mitigator and a victim of climate change. Its role in reducing carbon emissions is well-documented (Yalew et al., 2020; Zhou et al., 2020), yet its vulnerability to shifting hydrological regimes underscores a critical paradox. This review synthesizes global and regional research on climate-hydropower interactions, focusing on South and Southeast Asia, to contextualize the challenges and innovations in sustaining hydropower-dependent energy systems.

2.1. Climate Change Impacts on Hydrological Systems

Climate change disrupts hydrological cycles through altered precipitation patterns, glacier retreat, and extreme weather events. Global studies highlight increased evaporation rates and intensified monsoons, which strain reservoir operations (Haddeland et al., 2014; Li et al., 2020). In South Asia, glacier melt from the Himalayas initially boosts river flows but poses long-term risks as glacial mass depletes (Qin et al., 2020; IPCC, 2023). For instance, the 2021 Uttarakhand glacier burst in India destroyed hydropower infrastructure, exemplifying the cascading risks of cryospheric changes (Yang et al., 2019; Kumar et al., 2022). Similarly, Southeast Asia's Mekong Basin faces reduced dry-season flows due to upstream dam construction and erratic rainfall, threatening hydropower reliability (Arias et al., 2014; Turner et al., 2021).

Regional models project declining winter precipitation in the Indian Subcontinent, exacerbating dry-season water shortages (Rasul et al., 2021; Mishra et al., 2022). Conversely, the Maritime Continent may experience wetter conditions, though intensified rainfall could increase sedimentation and turbine wear (Sanchez et al., 2021; Nguyen et al., 2023). These spatially heterogeneous impacts necessitate localized adaptation strategies, as underscored by the IPCC's Sixth As-

assessment Report (IPCC, 2023).

2.2. Hydropower Generation and Capacity Factors

Hydropower's capacity factor—the ratio of actual output to maximum potential—is highly sensitive to hydrological variability. Studies using General Circulation Models (GCMs) and Representative Concentration Pathways (RCPs) project declines in annual capacity factors across South Asia by 2100, particularly under high-emission scenarios (Yalew et al., 2020; Arango-Aramburo et al., 2019). For example, Li et al. (2020) forecast a 5 - 7% reduction in India's hydropower output due to monsoon shifts, while Pakistan's capacity factors may drop by 10 - 15% from prolonged droughts (Rasul et al., 2021; Ashraf et al., 2022).

In Southeast Asia, hydropower-rich nations like Laos and Cambodia face dual pressures: reduced dry-season flows and increased flood risks during monsoons (Arias et al., 2014; Hoang et al., 2021). Recent advancements in machine learning, such as neural networks for reservoir inflow forecasting, offer improved predictive accuracy (Sapitang et al., 2020; Kumar et al., 2022). However, model uncertainties persist, particularly in reconciling conflicting projections from different climate ensembles (Ahmadianfar et al., 2021; Turner et al., 2021).

2.3. Regional Vulnerabilities and Adaptive Strategies

South and Southeast Asia's reliance on hydropower—constituting over 50% of electricity in Bhutan, Nepal, and Laos—heightens their exposure to climate risks (Sun et al., 2020; Smith & Rahman, 2022). The Himalayan region exemplifies this vulnerability: while glacier melt temporarily augments flows, long-term declines in winter precipitation threaten base-load generation (Dehghani et al., 2019; IPCC, 2023). Nepal's Upper Tamakoshi Hydropower Project, for instance, faces operational challenges from sediment-laden flows during intensified monsoons (Shrestha et al., 2022).

Adaptive strategies are emerging to enhance resilience. Floating solar photovoltaics (FPV) on hydropower reservoirs, piloted in Thailand and Vietnam, offset seasonal variability by leveraging synergies between solar and hydro generation (Sanchez et al., 2021; Smith & Rahman, 2022). Similarly, AI-driven reservoir optimization models improve water allocation during droughts (Kumar et al., 2022; Ahmadianfar et al., 2021). Policy innovations, such as transboundary water agreements in the Mekong River Commission, aim to balance energy production with ecological and social needs (Turner et al., 2021; Hoang et al., 2021).

2.4. Integration with Hybrid Energy Systems

The intermittent nature of solar and wind energy underscores hydropower's role as a grid stabilizer. Hybrid systems, such as hydro-photovoltaic plants in China, demonstrate enhanced reliability by compensating for seasonal hydropower deficits (Yang et al., 2022; Tan et al., 2021). In India, the Tehri Dam's integration with solar parks mitigates dry-season shortages, though land-use conflicts remain a

barrier (Rawa et al., 2021; Ashraf et al., 2022).

However, hybrid systems require advanced grid infrastructure and regulatory frameworks. Studies in Colombia and Africa highlight the economic and technical challenges of scaling such systems in developing nations (Arango-Aramburo et al., 2019; Sanchez et al., 2021). Moreover, decentralized micro-hydropower systems in rural Nepal and Indonesia offer localized resilience but struggle with financing and maintenance (Aryal et al., 2020; Nguyen et al., 2023).

2.5. Research Gaps and Future Directions

Despite progress, critical gaps persist. First, most models prioritize annual trends over intra-annual variability, neglecting seasonal hydropower dynamics (Li et al., 2020; Mishra et al., 2022). Second, transboundary governance frameworks remain understudied, particularly in conflict-prone basins like the Indus and Brahmaputra (Rasul et al., 2021; Turner et al., 2021). Third, socioeconomic impacts—such as displacement from reservoir projects—are often sidelined in techno-economic analyses (Aryal et al., 2020; Shrestha et al., 2022).

This study addresses these gaps by combining high-resolution climate ensembles with socio-hydrological data, offering a holistic assessment of hydropower sustainability in South and Southeast Asia. By bridging climate science, engineering, and policy, it advances actionable pathways for resilient energy transitions.

3. Methodology

This study employs an integrated, multi-model framework to assess climate change impacts on hydropower capacity factors across South and Southeast Asia. Utilizing 60 ensembles of five General Circulation Models (GCMs), four Global Hydrological Models (GHMs), and three Representative Concentration Pathways (RCPs), the analysis minimizes uncertainties and captures regional climate variability. High-resolution discharge data from Hydro SHEDS (15" × 15") were combined with monthly runoff datasets to generate flow duration curves, enabling the calculation of hydropower capacity factors based on design discharge and turbine efficiency. The study evaluates 12 countries, representing over 85% of the region's installed hydropower capacity, under six scenarios: Baseline, Moderate and Severe Climate Change, Accelerated Glacier Melt, Erratic Rainfall/Extreme Weather, and Declining Precipitation. Future projections (2020-2099) are compared against the 1970-2000 baseline, with a focus on seasonal shifts in precipitation, glacier melt dynamics, and extreme weather impacts. Hydropower plants' precise geolocations and climatic data ensure region-specific assessments, highlighting vulnerabilities and adaptive strategies.

3.1. Study Area

The study focuses on South and Southeast Asia, regions that are highly reliant on hydropower for their energy needs. These areas are characterized by diverse terrains, ranging from the Himalayan Mountain ranges to the low-lying plains and islands, and are experiencing rapid economic growth and increasing energy de-

mands. Hydropower plays a crucial role in meeting these energy needs, with many countries in the region generating a significant portion of their electricity from hydropower plants. The region's hydropower infrastructure is concentrated in areas with abundant water resources, such as the Himalayan region, the Indian Subcontinent, and Mainland Southeast Asia.

However, these regions are also highly vulnerable to the impacts of climate change, which manifest through shifting precipitation patterns, increased evaporation rates, glacier melt, and more frequent extreme weather events. These changes directly affect hydropower generation by altering water availability and streamflow variability. For instance, the Indian Subcontinent and Mainland Southeast Asia are projected to experience declining hydropower capacity factors due to seasonal changes in precipitation and increased winter dryness. In contrast, the Himalayan region may face temporary reductions in capacity factors due to decreased winter precipitation, but could see long-term benefits from increased glacier melt.

The region's hydropower infrastructure is also exposed to risks from extreme weather events, such as heavy rainfall and associated landslides, which have previously disrupted projects and caused significant damage. Additionally, glacial lake outburst floods (GLOFs) pose significant threats to hydropower plants in the Himalayan region. Despite these challenges, hydropower remains a critical component of the region's energy mix, offering opportunities for low-carbon electricity generation and supporting the integration of variable renewable energy sources like wind and solar.

The analysis in this study covers 12 countries with significant hydropower installed capacity, representing over 85% of the total hydropower capacity in South and Southeast Asia. These countries include India, Vietnam, Pakistan, Malaysia, Indonesia, Thailand, the Philippines, Myanmar, Bhutan, Sri Lanka, Cambodia, Nepal, and Bangladesh. The study evaluates the impacts of climate change on hydropower capacity under Baseline Scenario (Current Climate Trends).

3.2. Several Models Must Be Evaluated Because of Hydropower's Climate Change Vulnerability

The climate science community has made great strides in improving the ability to predict climate change's effects. Disagreement persists about the future of South and Southeast Asia's climate and hydrology because of varying assumptions and tiny evidence. This might lead to discrepancies in the findings of different models. Despite these inherent restrictions, the authors of this research set out to analyze as many feasible permutations of climate and hydrological models, compiling the results of these analyses into a single set to highlight the patterns on which the models could agree. To reduce the likelihood of false positives or outlier-induced distortions and to guarantee variety, evaluated 60 ensembles of five General circulation models (GCMs), four Global Hydrological models (GHMs), and three Representative Concentration Pathways (RCPs). Each hydroelectric plant's yearly and monthly capacity factors were determined using Hydro SHEDS' high-resolution worldwide discharge map (15" × 15"). High-resolution area accumulation and

drainage direction maps (15" × 15") are combined with low-resolution monthly runoff data (0.5 × 0.5) to create this graphic. These discharge maps were used to determine how much water needed to be pumped out of each hydroelectric plant and how much power it needed to generate. A flow duration curve was generated by calculating the typical monthly outflow of a certain hydroelectric facility. Turbine capacity is determined by design discharge, which is the worth of the month with the fourth greatest output. The capacity factor is deliberately set above 100% during the wet months (May through October) and below 100% during the dry months (November through March). The Annex provides further information on the procedures and models to get this result.

3.3. Climate Change's Effects by 2100, in Southeast and South Asian Nations, on the Hydroelectric Generation

The assessment shows monthly and yearly capacity factor improvements predicted from 2020 through 2099, with 1970-2000 values for Comparison. This period was chosen as the baseline because of the abundance of past climatic data. Thirteen countries in South and Southeast Asia are analyzed since they have the most hydroelectric Capacity. More than 99% of South and Southeast Asia's total installed capacity comes from these 12 nations' combined hydropower plants. Changes in the Indian Ocean, Central and Southeast Asia significantly affect the regional mean hydropower capacity factor due to climate change. India is responsible for more than 42 percent of the world's hydroelectric Capacity installed, next comes Vietnam, Pakistan, and Malaysia. The hydropower established Capacity of the thirteen nations spans from 4% in the Himalayas to 55% in the Indian Subcontinent, with India accounting for a disproportionately large share of the latter. **Table 1** and **Figure 1** show the Capacity of installed hydroelectric plants worldwide in 2020.

Table 1. Installed hydroelectric plants worldwide in 2020.

Hydropower Installed Capacity (MW)		
Country	Share of hydropower in electricity generation	Hydropower Installed Capacity
India	7000	50,549
Viet Nam	15,000	17,111
Pakistan	21,000	9929
Malaysia	10,000	6275
Indonesia	50,000	6121
Thailand	20,000	4512
Philippines	50,000	4385
Myanmar	31,000	3331
Bhutan	60,000	2326
Sri Lanka	25,000	1809
Cambodia	31,000	1329
Nepal	60,000	1278

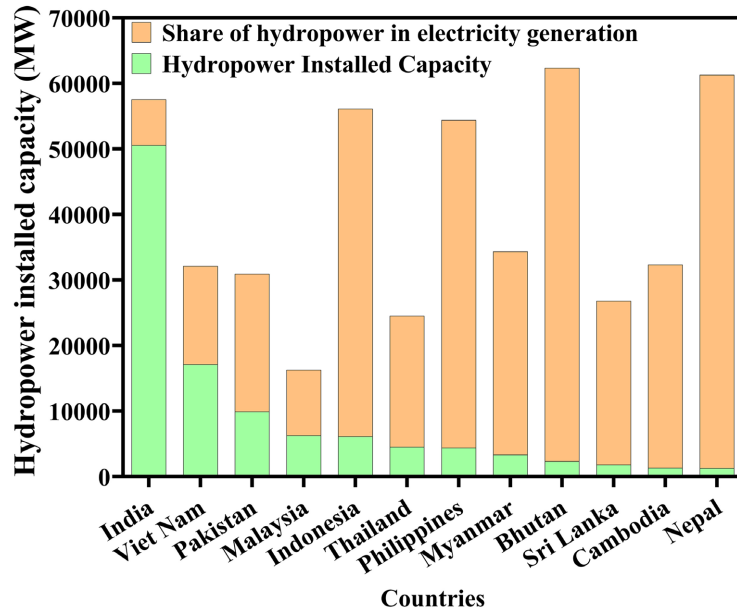


Figure 1. Capacity of all installed hydroelectric plants worldwide in 2020.

86% percent of South and Southeast Asia's total installed hydropower capacity is included in the study's examination of more than 490 hydropower facilities totaling 100,000 MW. Using the station's precise locations, the study determines the climatic consequences of each hydroelectric facility.

4. Results

4.1. Regional Mean Hydropower Capacity Factor May Decrease Due to Climate Change

The median factor of Capacity of South and Southeast Asian hydropower facilities is predicted to fall by the decade's end in three climate change scenarios. It estimates a 4.8% decline in the region's mean capacity ratio between 2020 and 2059, compared to 1970-2000 ("from 3.8% in the Below 2°C Scenario to 5.4% in the Above 4°C Scenario"). In the Below °C Scenario, the predicted average hydropower capacity factor for the area will decline by 4.7% between 2060 and 2099, whereas in the Above 4°C Scenario, it is projected to decrease by 5.2%. **Table 2** and **Figure 2** show the Averaging regional hydropower capacity factors from 2020 to 1999 compared to 1970 to 2000 as a baseline for each scenario.

Table 2. Averaging regional hydropower capacity factors.

Temperature	Hydropower capacity factor		
	Baseline	2020-2059	2060-2099
Below 2°C	100	98	96
Around 3°C	100	96	90
above 4°C	98	92	90

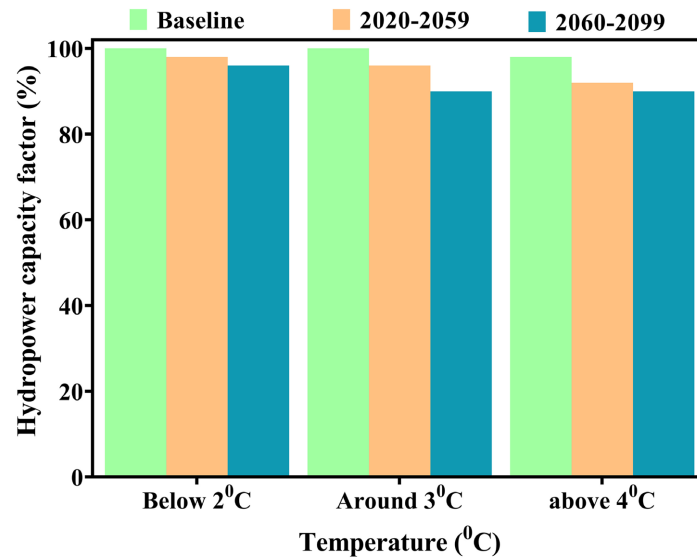


Figure 2. Hydropower capacity factor.

Hydropower's predicted Negative effects on South and Southeast Asian electrical supply can result from a drop in capability factor because of its increasing importance in meeting rising electricity needs, generating income via exports, and freeing up, Capacity use for other renewable power sources. More than half of the electricity produced in Bhutan, Nepal, the Lao People's Democratic Republic, Myanmar, and Cambodia in 2018-2019 came from hydropower.

4.2. Shifts in Average Capacity Obscure Inconsistent Climatic Influences

Although not all hydropower facilities will be impacted by climate change, the regional mean hydroelectric capacity factor is projected to have fallen by 2100. Most likely, the consequences of climate change will be felt differently throughout Southeast and South Asia. The analyzed models indicate that the hydropower capacity factor would constantly fall in two areas, the Indian Subcontinent and Mainland Southeast Asia, until the end of the century. The Above 4°C Scenario predicts a 5.3% increase in Indian hydropower plants by the end of the century. In contrast, the Below 2°C Scenario indicates a 5.3% decrease, which is expected to decrease by 6.9% project decreases in Mainland Southeast Asia's hydroelectric capacity factor of 5.9%. In contrast, hydropower capacity factors in regions around the Himalayas and the Maritime Continent will display more complex patterns, falling between 2020 and 2059 before rising again between 2060 and 2099. The Himalayan region's hydroelectric capacity factor is predicted to drop by 1.9% to 2.4% from 2020-59, then gradually recoup and approach pre-2020 levels from 2060-99. Greater recovery is expected in the above 4°C Scenario, leading to a somewhat greater hydropower capacity factor than the baseline. The Maritime Continent's hydroelectric capacity factor will decrease by 1.5% to 2.5% between 2020 and 2059 before rising again between 2060 and 2099. Under the Above

4°C Scenario, 1.6% growth in hydroelectric capacity factor during 2060-2099 compared to base would be noticeable. The Below 2°C Scenario predicts a 2.5% decrease in hydroelectric capacity factor from 2020-2059 to 2060-2099, compared to the baseline. **Table 3** and **Figure 3** show how each Asian region's hydropower capacity changes from 1970 to 2000 to 2020 and beyond.

Table 3. Asian region's hydropower capacity changes from 1970 to 2000 to 2020.

Country	Hydropower capacity factor		
	Baseline	2020-2059	2060-2099
Himalayan Region	100	98	100
Indian Subcontinent	100	95	94
Mainland Southeast Asia	100	90	89
Maritime Continent	100	97	100

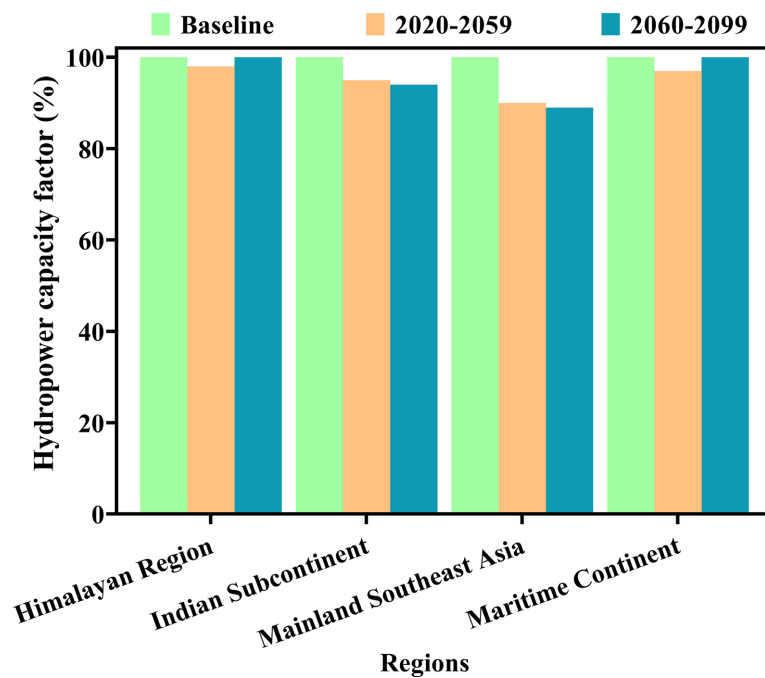


Figure 3. Asian sub-region hydropower capacity factor.

4.3. The Indian Subcontinent's Hydroelectric Capacity Factor Will Decrease Due to Seasonal Precipitation and Winter Dryness

By 2100, hydroelectric capacity is predicted to be lower, where India, Pakistan, and Sri Lanka form a single region called the Indian Subcontinent. Predictions for the fall in hydroelectric capacity factor are far direr if levels of greenhouse gases continue to rise. This is projected to fall by 5.1% in 2060-2099 compared to the 1970-2000 baselines by 6.9% if temperatures rise over 4°C and by 2.4% below 2°C. **Table 4** and **Figure 4** show the hydroelectric capacity factor in each nation in the Indian Subcontinent from 2020 to 99, compared to the 1970-2000 baseline years.

Table 4. From 2020 to 2099 compared to the 1970-2000 baseline years.

Hydropower capacity factor				
Country		Below 2°C	Around 3°C	Above 4°C
India	Baseline	99	99	99
	2020-2059	98	97	96
	2060-2099	97	96	95
Pakistan	Baseline	99	99	99
	2020-2059	90	90	89
	2060-2099	88	87	86
Sri Lanka	Baseline	99	99	99
	2020-2059	94	95	93
	2060-2099	92	93	91

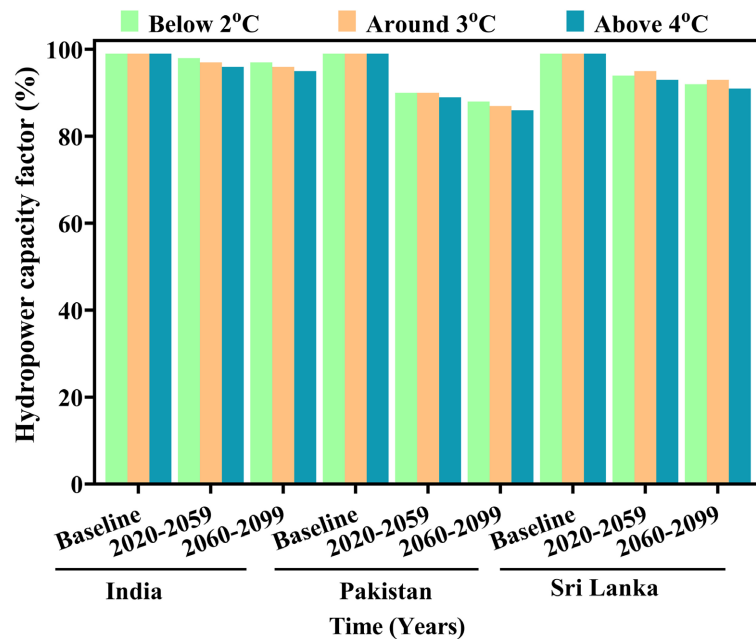


Figure 4. Climate impact of hydropower factor in Indian Subcontinent.

Since most of the Indian Subcontinent’s precipitation falls during the summer monsoon season and decreases during the winter months, the vast majority (84%) of the hydroelectric infrastructure in this area is located in India and has seen a decline in its hydroelectric capacity factors. India is expected to have a rise in yearly precipitation but a decrease in the winter monsoon precipitation, leading to a drier dry season. Reduced water availability for hydropower due to lower waterfalls outside of the summer monsoon season reduces the efficiency of hydroelectric plants.

4.4. The Himalayan Hydropower Capacity Factor May Temporarily Reduce Due to Precipitation, Warming, and Glacier Melting

Location in the Himalayas in northern South Asia means that Nepal and Bhutan’s

hydroelectric capacity factors are expected to stay steady, with a minor decrease in 2020-2059 and a rebound in 2060-2099. The Himalayan sub-region's mean hydropower capacity factor is predicted to decrease by 1.82 - 2.20 percent between 2020 and 2059 before recovering to somewhere around its pre-decline level between 2060 and 2099. Under the Above 4°C Scenario, Bhutan's hydroelectric capacity would decrease by 3% between 2020 and 2059 before recovering in full between 2060 and 2099. The Above 4°C Scenario predicts a 1% decline in Nepal's hydroelectric capacity factor between 2020 and 2059. Between 2060 and 2099, it will recover and rise beyond the norm. **Table 5** and **Figure 5** show the Comparison of climate change effects on Comparison of the Himalayan region's hydropower capacity factors for the years 2020-99 to those of the 1970-2000 base periods.

Table 5. The years 2020-99 to those of the 1970-2000 base periods.

Hydropower capacity factor				
Country		Below 2°C	Around 3°C	Above 4°C
Bhutan	Baseline	99	99	99
	2020-2059	97	96	96
	2060-2099	98	99	99
Nepal	Baseline	99	99	99
	2020-2059	97	99	98
	2060-2099	98	98	100

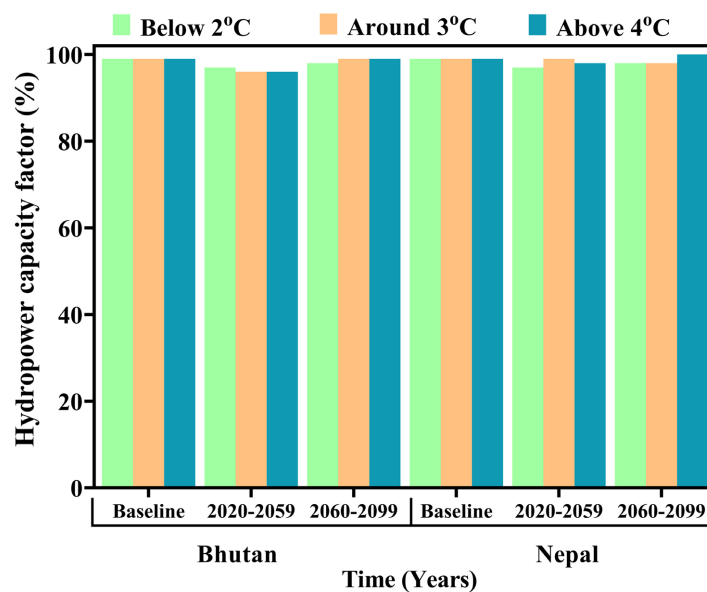


Figure 5. Himalayan hydropower capacity factor.

The expected decline in winter precipitation in Nepal and Bhutan for 2020-2059 explains the minor fall in hydropower capacity factors. Rain in the winter, when

the Himalayas are located to the east, above the countries of Nepal and Bhutan is expected to decline throughout the 21st century, according to climate forecasts. The effects of warming and melting glaciers are predicted to cancel out the drawbacks of less winter precipitation towards the end of the 21st century. When extrapolated to the end of the 21st century, the If Temperatures Soar over 4°C scenario projects a 5.23 0.91°C increase in India, which is home to 84% of the region's hydroelectric Capacity relative to the 1976-2005 baselines.

Increased discharge is predicted between 2060 and 2099 as warming speeds up glacial mass loss, expected to peak in the middle of the 21st century. Although this tendency may not hold in the long term, a protracted warm spell with higher melting of glaciers will increase water flow, which will allow for the capacity factor of hydroelectric power plants to peak often and for longer periods. Floods caused by glacial lake outbursts might become more common as mountain glaciers in the Himalayan region melt. Glacial lake outburst flooding threatens several countries, but Nepal and Bhutan are the most vulnerable.

5. Discussion

The findings from this study provide critical insights into the complex relationship between climate change and hydropower capacity in South and Southeast Asia. The region's heavy reliance on hydropower for energy generation underscores its vulnerability to the unpredictable impacts of climate change, which can alter hydrological regimes and reduce the efficiency of hydropower plants. The results of this analysis reflect both the challenges and opportunities in adapting to these shifts, as well as the need for region-specific strategies to mitigate the negative impacts of climate change on hydropower infrastructure.

The analysis of projected climate change impacts reveals significant regional variability, which is critical for understanding how climate change will affect hydropower in this diverse and complex region. For example, in the Indian Subcontinent, which includes countries like India, Pakistan, and Sri Lanka, seasonal shifts in precipitation patterns and declining winter monsoons are projected to cause a notable reduction in hydropower capacity. This aligns with findings from studies such as [Yalew et al. \(2020\)](#), which projected a reduction in hydropower capacity in South Asia due to changes in monsoon precipitation. The study by [Rasul et al. \(2021\)](#) also highlighted how these changes will exacerbate dry-season water shortages, directly impacting the operational efficiency of hydropower plants. The increased frequency of droughts is a significant concern, as prolonged dry spells could lead to a substantial reduction in available water for hydropower generation, making it difficult for many plants to meet their full potential.

In contrast, the Himalayan region, which includes Nepal and Bhutan, faces a different set of challenges and opportunities. The temporary increase in water availability due to glacier melt, followed by long-term risks associated with the depletion of glaciers, is a key finding of this study. This observation is consistent with previous studies, including those by [Qin et al. \(2020\)](#) and [Dehghani et al.](#)

(2019), which suggested that while glacier melt initially boosts river flows, it poses a long-term threat as glaciers retreat. Furthermore, the risks posed by glacial lake outburst floods (GLOFs), which can cause significant damage to hydropower infrastructure, were underscored by the 2021 Uttarakhand glacier burst in India, as noted by Yang et al. (2019) and Kumar et al. (2022). These findings emphasize the need for adaptive strategies that consider both short-term benefits and long-term challenges in the Himalayan region.

Southeast Asia also faces unique vulnerabilities, with countries like Laos and Cambodia reliant on hydropower for a significant portion of their energy supply. In these regions, the combination of reduced dry-season flows and increased flood risks during monsoons poses a significant threat to hydropower generation. Studies by Arias et al. (2014) and Turner et al. (2021) highlighted the challenges associated with the erratic rainfall patterns in the Mekong Basin, which further complicate the operation of hydropower plants. In light of these findings, adaptive measures such as improved reservoir management and the integration of floating solar photovoltaics (FPV) on hydropower reservoirs, as piloted in Thailand and Vietnam, offer promising solutions to offset seasonal variability and increase resilience to climate impacts (Sanchez et al., 2021; Smith & Rahman, 2022).

The adoption of machine learning techniques for inflow forecasting also stands out as an innovative approach to enhance the predictive accuracy of water availability. The use of neural networks and other machine learning algorithms has proven to improve the precision of hydropower forecasts, which is critical for optimizing operations during both drought and flood conditions (Kumar et al. (2022); Sapitang et al., 2020). However, despite these advancements, uncertainties in climate models persist, particularly regarding intra-annual variability, as highlighted by Ahmadianfar et al. (2021) and Turner et al. (2021). These uncertainties call for ongoing research to refine climate projections and improve the reliability of hydropower forecasting models.

One of the most promising findings of this study is the potential for hybrid energy systems, particularly the integration of solar and hydropower. As shown in China, hydro-photovoltaic plants demonstrate enhanced reliability by mitigating seasonal hydropower deficits with solar power, a solution that could be particularly beneficial in regions like India and Southeast Asia, where seasonal fluctuations in water availability are a concern (Yang et al., 2022; Tan et al., 2021). However, the integration of solar with hydropower requires advanced grid infrastructure and regulatory frameworks, which remain a challenge in many developing countries (Arango-Aramburo et al., 2019; Sanchez et al., 2021). Moreover, while decentralized micro-hydropower systems in rural areas like Nepal and Indonesia offer localized resilience, they struggle with financing and maintenance, as noted by Aryal et al. (2020) and Nguyen et al. (2023). This indicates that hybrid systems and decentralized solutions must be carefully considered, with attention to the economic and technical challenges specific to each region.

Despite the advances in technology and policy, this study also identifies critical

gaps in research. Most climate models focus on annual trends, neglecting the seasonal and intra-annual variations that significantly affect hydropower production. Furthermore, transboundary water governance frameworks, particularly in shared river basins like the Indus and Brahmaputra, are underexplored. As climate change exacerbates water scarcity and alters seasonal flows, effective transboundary cooperation is essential to prevent conflicts and ensure sustainable hydropower development (Rasul et al., 2021; Turner et al., 2021). Additionally, the socio-economic impacts of climate-induced hydropower changes, such as displacement due to reservoir projects and the effects on local communities, are often overlooked in techno-economic analyses. This study emphasizes the need for a more integrated approach that combines climate, engineering, and socio-economic considerations to develop comprehensive adaptation strategies.

In conclusion, the findings of this study highlight the intricate relationship between climate change and hydropower capacity in South and Southeast Asia. The region's dependence on hydropower for energy generation makes it particularly vulnerable to climate change impacts, which are expected to lead to a decline in hydropower capacity in many areas. However, through strategic adaptation measures, such as improved reservoir management, the integration of hybrid energy systems, and enhanced transboundary cooperation, the region can enhance the resilience of its hydropower infrastructure. Moving forward, further research is needed to refine climate models, explore innovative technologies, and assess the socio-economic implications of changing hydropower capacity. By addressing these gaps, the region can build a more sustainable and resilient energy future that balances environmental, economic, and social needs.

6. Conclusion

In conclusion, the analysis reveals the intricate relationship between climate change and hydropower capacity in South and Southeast Asia. As the region's reliance on hydropower for energy production grows, it becomes increasingly vulnerable to the impacts of climate change, including shifting precipitation patterns, glacier melt, and extreme weather events. The study indicates that while hydropower capacity may initially increase in some areas due to higher water availability resulting from increased precipitation, the long-term trend shows a decline in capacity factors. This decline is particularly evident in regions such as the Indian Subcontinent and Mainland Southeast Asia, where seasonal precipitation patterns and winter dryness significantly affect hydropower production. Furthermore, the analysis highlights the unique challenges faced by countries in the Himalayan region, where glacier melt and changes in precipitation pose both risks and opportunities for hydropower generation. While winter precipitation is expected to decline, leading to a temporary reduction in hydropower capacity factors, increased glacier melt could result in higher water flow, potentially offsetting these losses in the long term. Overall, the findings underscore the need for proactive measures to enhance the resilience of hydropower infrastructure in the face of climate

change. This includes investments in adaptive water management techniques, the development of robust hydropower plants, and the integration of hydropower with other renewable energy sources to create a more diversified and resilient energy mix. Moreover, collaboration among stakeholders, including governments, policymakers, and the private sector, is essential to address the multifaceted challenges posed by climate change to the hydropower sector. By implementing strategic adaptation measures and fostering regional cooperation, South and South-east Asia can better navigate the impacts of climate change on hydropower production and ensure the continued sustainability of its energy infrastructure.

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Conflicts of Interest

There are no conflicts of interest.

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