Climate Impacts on South and Southeast Asian Hydropower

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Abstract

Hydropower accounts for 14.5% of total electricity generation in South and Southeast Asia, with a total hydropower installed capacity of 117 GW. The installed hydropower capacity is expected to grow further in order to meet the region's growing electricity demand and electricity export opportunities, and to maximise the merits of a cost-effective and flexible low-carbon power source. However, climate change poses an increasing challenge to South and Southeast Asian hydropower with rising temperatures, extreme rainfall patterns, melting glaciers, and increasing occurrence of extreme weather events. This report aims to support South and Southeast Asian hydropower in coping with the adverse impacts of climate change and in developing a tailored set of climate resilience measures based on a comprehensive assessment of climate risks and impacts. This report qualitatively assesses climate risks to South and Southeast Asian hydropower and quantitatively examines potential climate impacts, comparing three climate scenarios. Based on the assessment, it identifies measures to enhance climate resilience and provides policy recommendations.

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Executive summary

In South and Southeast Asia, hydropower accounts for 14.5% of total electricity generation with a total hydropower installed capacity of 117 GW. In some countries, such as Bhutan and Nepal, hydropower accounts for over 90% of total electricity generation. The installed hydropower capacity is expected to grow further in order to meet the region's growing electricity demand and electricity export opportunities, and to maximise the merits of a cost-effective and flexible low-carbon power source.

However, the rising temperatures, extreme rainfall patterns, melting glaciers and increasing occurrence of extreme weather events associated with climate change pose serious challenges to South and Southeast Asian hydropower. They can affect hydropower generation by increasing variability in streamflow, shifting seasonal flows and augmenting evaporation losses from reservoirs. Extreme weather events such as heavy rainfall and associated landslides can hinder development of hydropower projects as seen in the cases of Viet Nam's Thua Thien Hue hydropower project in 2020 and Lao People's Democratic Republic (Lao PDR)'s Xe-Pian Xe-Namnoy Dam in 2018. Glacier melt due to rising temperatures and the consequent glacial lake outburst floods caused severe damage to the Dhauliganga Hydropower Plant in India in 2021 and to the Golen Goal Hydropower Plant in Pakistan in 2019. Given that climate change could significantly affect the operation of hydropower plants, which usually operate for multiple decades, a comprehensive assessment of climate impacts is vital.

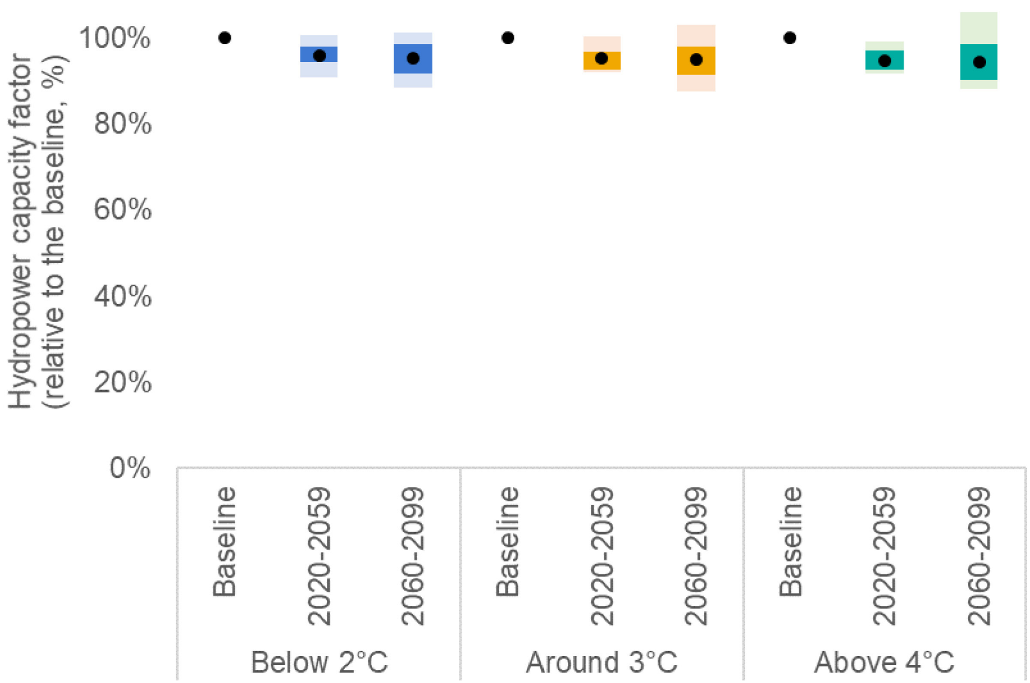
This report assesses potential climate impacts on about 86% of the total hydropower installed capacity in South and Southeast Asia, focusing on 13 countries with the largest hydropower installed capacity. It is based on three different scenarios: Below 2°C, Around 3°C and Above 4°C. Each represents a different level of greenhouse gas (GHG) concentration and its global average temperature outcome by 2100. The assessment shows changes in annual and monthly capacity factors from each country between 2020 and 2099, and compares the projected results against the values of the baseline period spanning 1970 to 2000.

From now until the end of the century, the regional mean hydropower capacity factor is projected to decrease due to changing climate conditions. The regional mean capacity factor from 2020 to 2059 is likely to decrease by around 4.6% on average (from 3.9% in the Below 2°C Scenario to 5.2% in the Above 4°C

Scenario), compared with the baseline level of 1970 to 2000. Between 2060 and 2099, the regional mean hydropower capacity factor is projected to be lower than the baseline by 5.1% on average (from 4.7% in the Below 2°C Scenario to 5.4% in the Above 4°C Scenario).

Comparison of the results from three different GHG concentration scenarios demonstrates that a higher GHG concentration will have stronger negative impacts on hydropower generation in South and Southeast Asia. Relative to the other scenarios, in the Above 4°C Scenario, which assumes a continuous increase in GHG emissions, there could be a stark decrease in the regional mean hydropower capacity factor over the remainder of 21st century.

Regional mean hydropower capacity factor, 2020-2099 relative to the baseline 1970-2000, by scenario



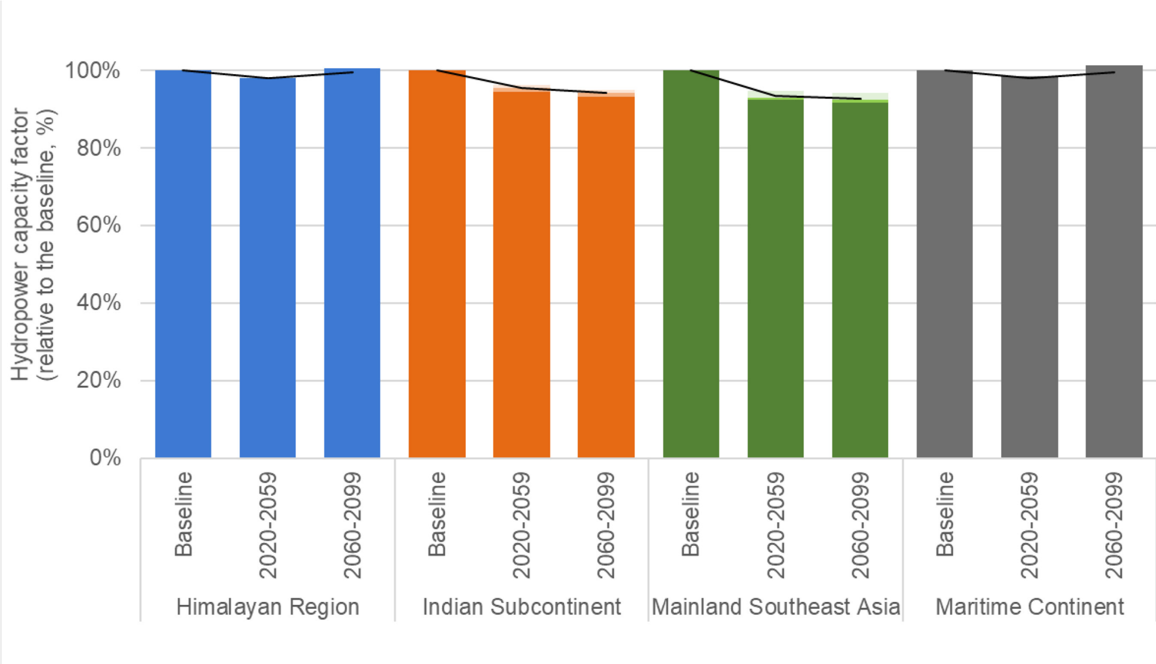
Note: The black dots indicate the average hydropower capacity factor of the selected South and Southeast Asian hydropower plants based on results from 20 combinations of GCMs and GHMs per scenario. The coloured bars indicate the range of the results; the darker colours in the bars show the range of 60% of the results.

Although all three scenarios estimate a decline in the regional mean hydropower capacity factor by 2100, this does not mean that climate change will have an equal impact on every hydropower plant. Rather, the impacts of climate change are likely to be spread unevenly across South and Southeast Asia, leaving some plants more exposed to climate change than others.

All three scenarios indicate that two sub-regions, the Indian Subcontinent (India, Pakistan, and Sri Lanka) and Mainland Southeast Asia (Cambodia, Lao PDR, Myanmar, Thailand, and Viet Nam) will see a continuous decline in hydropower capacity factor until the end of the century. Relative to the baseline, the hydropower plants in the Indian Subcontinent are projected to decrease by 5.1% in the Below 2°C Scenario and by 6.8% in the Above 4°C Scenario until the end of the century. Similarly, the hydropower capacity factor of Mainland Southeast Asia is expected to decrease by 5.9% in the Below 2°C Scenario and by 8.2% in the Above 4°C Scenario.

In contrast, the other two sub-regions, the Maritime Continent (Indonesia, Malaysia and the Philippines) and the Himalayan region (Bhutan and Nepal) show more complicated trends in hydropower capacity factors: a drop in 2020-2059 and a recovery in 2060-2099. In both sub-regions, a higher GHG concentration will lead to a more dramatic bounce in the hydropower capacity factor in the latter 40 years of the century.

Changes in hydropower capacity factor by Asian sub-region, 2020-2099 relative to the baseline 1970-2000



Notes: The lightly coloured areas indicate the gap between projections from different scenarios. The darkest colour indicates the projection in the Above 4°C Scenario; the lightest colour is the projection in the Below 2°C Scenario. The black lines indicate the average of the projections from the three scenarios.

Anticipating, absorbing, accommodating and recovering from adverse climate impacts, climate-resilient hydropower systems can bring multiple benefits: it can support the shift to low-carbon electricity technologies and provide power system flexibility for the rapid deployment of variable renewable energy sources such as wind and solar. It can also contribute to achieving universal access to affordable and reliable electricity services in countries such as Pakistan and Myanmar, where the rates of electricity access in 2019 were 73.9% and 68.4%, respectively.

To minimise the adverse impacts of climate change on South and Southeast Asian hydropower systems, governments and utilities need to scale up their efforts to address potential climate risks and impacts and identify effective measures to enhance resilience to climate change. The following policy recommendations can contribute to enhancing the climate resilience of South and Southeast Asian hydropower:

- Build robust climate databases and strengthen climate impact assessments.

Although various climate-related changes have critical implications for hydropower generation in the region, the climate data and projections for specific locations or events are still limited due to a lack of reliable data and the complexity of meteorological systems. In addition, the further development of frameworks, guidelines and tools could support and guide climate risk and impact assessments.

- Integrate climate resilience as a key element in hydropower planning and construction.

As the region seeks to expand hydropower generation to meet its growing economy and energy needs, integrating climate resilience in new project planning and construction will be crucial. Recent damage to India's Tapovan Vishnugad Hydropower Project and Lao PDR's Xe-Pian Xe-Namnoy Hydropower Project demonstrate the importance of factoring in climate resilience in the initial stages of hydropower projects. Governments can encourage developers and operators to integrate climate resilience in early stages of hydropower projects by adopting relevant regulations for climate resilience, such as climate-resilient construction codes and mandatory climate risk assessments and emergency response plans.

- Build climate resilience into hydropower operation and maintenance strategies.

As hydropower plants age, they tend to become more vulnerable to climate change. Given that extreme weather events are likely to occur more frequently and with greater intensity, the design of old hydropower plants may not suit the changed climate conditions. Governments can set guidelines or standards for project operators to integrate climate resilience monitoring and adaptation processes into operation and maintenance plans. These could include the regular collection of climate and hydrological information, the implementation of risk assessment updates, the effectiveness evaluation of adopted measures, and the clarification of responsibilities, thresholds and action plans for further adaptations. Leveraging public and private investment will be key to financing the modernisation of ageing hydropower plants.

- Enhance regional cooperation to coordinate sustainable resource development and achieve mutual benefits.

South and Southeast Asia have many transboundary rivers such as the Mekong River which runs through the People’s Republic of China (hereafter “China”), Myanmar, Lao PDR, Thailand, Cambodia and Viet Nam, and the Ganges-Brahmaputra-Meghna river basin that spreads across China, Bangladesh, Bhutan, Nepal and India. Regional cooperation is vital among countries with major shared water resources, in order to form mutually-beneficial strategies and to coordinate actions on water source development. The further institutionalisation of cooperation frameworks and strengthened implementation mechanisms would support better coordination and build the region’s adaptive capacity against the adverse impacts of climate change.

Chapter 1. Introduction

Hydropower will undergo massive growth in South and Southeast Asia to support both increasing electricity demand and clean energy transitions

The total hydropower installed capacity in South and Southeast Asia was 117 GW in 2020, accounting for 9% of the world total hydropower installed capacity. In the region, hydropower accounted for 14.5%[1] of total electricity generation – reaching over 90% in countries such as Bhutan and Nepal – and installed hydropower capacity is expected to grow further according to both IEA's Stated Policy Scenario (STEPS) and Sustainable Development Scenario (SDS). Even in 2020, despite the delay or halt in hydropower commissioning in the region due to the Covid-19 pandemic, a significant amount of hydropower capacity was still added, including 478 MW in India, 236 MW in Indonesia, 176 MW in Lao PDR, 102 MW in Pakistan and 101 MW in Malaysia.

According to IEA's Hydropower Special Market Report, growing electricity demand, electricity export opportunities and the merits of a cost-effective and flexible low-carbon power source, are driving hydropower expansion in South and Southeast Asia. For instance, with the announcement of the 728-MW Phou Ngoy Project, Lao PDR aims to export a total of 20 GW of electricity by 2030 to become the "battery of Southeast Asia". In India, work on a large number of stalled projects is expected to resume to meet rising power demand and facilitate the integration of rapidly expanding variable renewable energy (VRE) sources.

The IEA's STEPS estimates that hydropower generation in Southeast Asia will see a remarkable increase, from 164 TWh in 2020 to 347 TWh by 2050, and that hydropower generation in India could increase from 173 TWh to 386 TWh over the same period.

In reaching the Sustainable Development Goals (SDGs) and Paris Agreement goals, the role of sustainable and well-planned hydropower projects is critical in the region. According to the IEA's SDS, hydropower generation in Southeast Asia increases from 164 TWh in 2020 to 780 TWh by 2050 (+475%), increasing the

[1] The value considers South Asian countries (Afghanistan, Bangladesh, Bhutan, India, Pakistan, Nepal, and Sri Lanka) and Southeast Asian countries (Brunei, Cambodia, Indonesia, Lao PDR, Malaysia, Myanmar, the Philippines, Singapore, Thailand, Timor-Leste and Viet Nam).

share of hydropower in total electricity generation from 15% to 26%. In India, hydropower generation will more than double by 2050, though the share of hydro in total electricity generation may fall from 11% to 7%.

The growing importance of hydropower will require more attention to climate change

Climate change can affect the amount of water available to hydropower plants and poses challenges to hydropower generation, as it does for other types of power generation such as thermal power plants using cooling water. Increased variability in streamflow, shifting seasonal flows, augmented evaporation losses from reservoirs, melting glaciers and more frequent extreme weather events can all have strong impacts on hydropower. Although dams may help mitigate the negative impacts of climate change through drought management and flood control, their dependence on climatic and hydrological conditions for hydropower generation will mean they are susceptible to a changing climate.

Hydropower in South and Southeast Asia is also exposed to climate impacts. The region is very likely to experience a continuous warming in the 21st century and more frequent and intense rainfall and floods. These climate impacts could pose significant challenges to hydropower systems. Indeed, a series of landslides in October 2020 caused by heavy rainfall in Viet Nam suspended a hydropower project in Thua Thien Hue and killed workers. Similarly, the 420 MW Xe-pian Xe-Namnoy Dam in Lao PDR collapsed when it was 90% complete due to the summer monsoon and the passage of tropical cyclone Son-Tinh in July 2018.

Glaciers melting due to rising temperatures also bring challenges to hydropower systems. In February 2021, the Dhauliganga Hydropower Plant in India collapsed due to a massive flash flood probably triggered by a glacial burst. In July 2019, the 108 MW Golen Gol Power Station in Pakistan was severely damaged by a glacial lake outburst flood, leading to the closure of the station.

To minimise the adverse impacts of climate change on hydropower in South and Southeast Asia, governments and utilities need to scale up their efforts to address potential climate risks and impacts and identify effective measures to enhance resilience to climate change. Resilient hydropower generation fleets can accelerate clean energy transitions while providing adaptation benefits.

This report aims to help improve the resilience of hydropower in South and Southeast Asia by providing qualitative and quantitative analyses of climate risks and impacts and by introducing potential resilience measures. First, it presents a qualitative assessment of the climate risks to South and Southeast Asian hydropower based on three dimensions: hazard, exposure and vulnerability (Chapter 2). Second, it provides a quantitative examination of the potential climate impacts on South and Southeast Asian hydropower, comparing three climate scenarios (Chapter 3). Finally, it presents examples of measures to enhance climate resilience and suggests policies to enable such measures (Chapter 4).

Chapter 2. Climate risks to Asian hydropower

What is climate risk?

Climate risk indicates the factors associated with the potential consequences of climate change. According to the Intergovernmental Panel on Climate Change (IPCC), climate risk results from the interaction of hazard, exposure and vulnerability.

Hazard refers to the potential occurrence of physical impacts from changes in long-term climate trends or extreme weather events. For instance, if a country is projected to experience an increased frequency of intense climate-related events, the level of hazard will increase.

Exposure indicates the presence of assets, services, resources and infrastructure that could be adversely affected. For instance, if a hydropower plant is located in a drought-prone area, it is considered to be more exposed to climate risk than a plant located in an area with sufficient rainfall.

Vulnerability is the propensity or predisposition to be adversely affected. It includes sensitivity, which refers to the extent to which a system is impacted by a sector or a source that could be negatively affected by climate hazards. The concept of vulnerability also takes into account adaptive capacity, which refers to the ability of a system to anticipate, prepare and plan effectively for climate change. If there is competition for water resources, hydropower systems might be more vulnerable to impacts. If a hydropower system is equipped with a robust data system and capable human resources to anticipate and adapt to climate change impacts, it might be less vulnerable.

Identifying climate risks in terms of these three concepts creates a helpful framework. Governments and operators can address potentially hazardous events that could affect a power system, identify assets and resources exposed to the hazards, and pinpoint adaptive capacity needs to reduce vulnerability to these impacts. Based on the assessment of climate-related risks, effective measures that enhance resilience to these risks can be identified to mitigate the potential impacts of climate change.

Hazards

Concentrated rainfall over a short period becomes a growing concern to South and Southeast Asian hydropower, increasing the hazard of floods

South and Southeast Asia's climate concerns are particularly associated with concentrated rainfall and floods, which are closely related to monsoon systems and tropical cyclones. Intense rainfall and floods are likely to become more frequent in most parts of South and Southeast Asia, although each sub-region could follow different trends in long-term precipitation patterns.

In South and Southeast Asia, the regional monsoon brings a rainy season from June to August and a dry winter season. Climate projections show that summer monsoon precipitation will increase while offsetting the decrease in winter monsoon precipitation. This is projected to raise the regional mean precipitation by 14-36% under a high GHG emission scenario[2] and by 0.4-16% under a low GHG emissions scenario.[3] Given that summer monsoon precipitation is already providing about 80% of the annual rainfall in South Asia, these changes will make the region wetter in the wet seasons and drier in the dry seasons. The accentuated seasonal contrasts between summer and winter monsoons are expected to increase the seasonal variability of hydropower generation.

Climate projections show that heavy and concentrated rainfall during the summer monsoon period is likely to become more intense and frequent in South Asia. Both annual and summer monsoon precipitation will increase during the 21st century, with enhanced interannual variability. This could result in more frequent monsoon floods in the region, following the current trend of more frequent heavy precipitation and flood events in several areas in South Asia over the last few decades. For instance, it can be seen from the numbers of flood events between 1970 and 2019 in India that between 1970 and 2004, three extreme flood events occurred per year on average, but after 2005, the yearly average rose to 11. Extreme flood events have become more intense in recent decades due to the sharp surge in associated events. The frequency of associated flood events such as landslides, heavy rainfall, hailstorms, thunderstorms and cloudbursts surged by over 20 times between 1970 and 2019.

[2] SSP5-8.5.
[3] SSP1-2.6.

Southeast Asian countries are also likely to experience more intense and frequent heavy rainfall and floods, while the number of wet days are likely to decrease. The region has already experienced a significant increase in the number of record-breaking rainfall events. From 1981 to 2010, the number of daily rainfall events setting new local records nearly doubled in this region. This trend is likely to continue, increasing the hazard of floods. The compound impacts of climate change, human activities (e.g., urbanisation), and land subsidence will also exacerbate the damage from heavy rainfall and floods. For instance, inundation in the Mekong Delta is projected to be prolonged due to the compounded impacts.

In addition, the projected increase in the intensity of tropical cyclones in Southeast Asia may lead to more intense rainfall and floods.[4] Records show that the precipitation associated with tropical cyclones has increased since 1950. Global warming is likely to increase the rate of precipitation related to tropical cyclones by 11% in the 1.5°C scenario and 28% in the above 4°C scenario. The increased precipitation during tropical cyclones could result in flooding. The tropical-cyclone-induced floods already accounted for 24.6% of the occurrence of all floods between 1985 and 2018 and brought higher impacts than other types of floods in the Southeast Asian countries of Cambodia, Lao PDR, Myanmar, Thailand and Viet Nam.

More concentrated rainfall and floods due to the shifting monsoon system and intensified tropical cyclones will alter water availability, increase sediments or lead to the unplanned release of water from hydropower reservoirs, which could cause flooding in nearby settlements. Intense rainfall and floods can also cause physical damage to assets, as shown by the collapse of the 420 MW the Xe-Pian Xe-Namnoy Dam in Lao PDR due to the summer monsoon and the passage of tropical cyclone Son-Tinh in July 2018.

Glacial melt due to warming poses a threat to South and Southeast Asian hydropower

The annual mean surface temperature in Asia warmed over the 20th century, accelerating after the 1970s. In 2020, the mean temperature in Asia was 1.39 °C above the 1981–2010 average, making 2020 the warmest year on record in all data sets used for this assessment. The land surface temperature, sea-surface

[4] Although the number of tropical cyclones in Southeast Asia is projected to decrease, their intensity is expected to increase. There is no clarity in the trend of tropical cyclone intensity in South Asia.

temperature, and ocean heat content in the region show long-term warming trends larger than the global average.

In all of the scenarios, the warming is very likely to continue in South and Southeast Asia in the 21st century. If the world follows a low GHG emission pathway,[5] the temperature increase in South and Southeast Asia is expected to remain limited to 2°C in most areas. Under a high GHG emission scenario,[6] South and Southeast Asia could see a warming of around 4°C.

Extreme heat episodes have become more frequent in most parts of South and Southeast Asia. Climate projections show that heatwaves and humid heat stress will become more intense and frequent during the 21st century. In particular, under high GHG emissions scenarios,[7] dangerous heat stress thresholds will be crossed much more often. For instance, the number of days above the 41°C threshold of felt air temperature will increase by about 250 days in Southeast Asia and by 50 to 150 days in South Asia at the end of the century under a high GHG emissions scenario.[8] Even under a low GHG emissions scenario,[9] Southeast Asia, one of the world's most affected regions by heat extremes over the past few decades, will see an increase by about 100 days in some areas, while the increase could be limited to 30 or 40 days in South Asia.

The increasing temperature and extreme heat episodes in South and Southeast Asia are considered to be the main drivers of melting mountain glaciers. Over most of the Hindu Kush Himalayan region, which constitutes the world's largest glaciated region outside the poles and provides the headwaters for the ten largest rivers in Asia, the snow cover has decreased since the early 21st century, and glaciers have retreated and lost mass since the 1970s.

The Hindu Kush Himalayan region is projected to see a continuous decrease in snow-covered areas and glacier volumes during the 21st century in all scenarios, though this will be accelerated with higher GHG emissions. According to a study published by the International Centre for Integrated Mountain Development, two-thirds of the Himalayan glaciers could melt by 2100 if GHG emissions are not reduced. If the targets of the Paris Agreement are achieved, one third of the glaciers are projected to recede.

[5] SSP1-2.6.
[6] SSP5-8.5.
[7] RCP 6.0 and RCP 8.5.
[8] SSP5-8.5.
[9] RCP 2.6.

The decrease in glacier volumes in the Hindu Kush Himalayan region could have a dramatic impact on South and Southeast Asia's main rivers, given its role as "the freshwater tower" which feeds the largest rivers in the region, including the Mekong, Indus, Ganges and Irrawaddy. Given that glaciers in the region store water resources, the projected glacier recession will directly affect the streamflows of the major river basins. Some studies show that rising temperature around glaciated river basins would increase discharge and bring the benefit of additional water supply in the short term. The increasing temperature could create new glacier lakes and cause glacier lake outburst floods by bursting the banks of high-altitude lakes. Despite the short-term increase of discharge, river flows would decline in the long run and discharge would shift to rainfall-dominated regimes, becoming more sensitive to precipitation.

Hydropower projects around the Himalayas are directly affected by the consequences of melting glaciers, such as changing streamflow and glacier lake outburst floods. Up to two-thirds of the current and planned hydropower projects around the Himalayas are located in the path of potential glacier floods, and some of the projects have been already damaged by glacier melting. For instance, a glacial lake burst in the Rishiganga River of India damaged the 520 MW Tapovan Vishnugad Hydropower Project which was under construction, and destroyed the 13.2-MW Rashiganga Hydropower Project in February 2021. Glacier lake outburst floods were also responsible for significant damage to the 45-MW Upper Bhote Koshi Hydropower Plant of Nepal in July 2016 and the and th-MW Golen Gol Hydropower Station of Pakistan in July 2019, leading to its closure.

The massive damage caused by glacier lake outburst floods has raised public concern about hydropower dams, despite their potentially critical role in offsetting the intermittent power supply from other VRE sources. For instance, the 2013 and 2021 floods which killed over 5 200 people in India's Uttarakhand state sparked questions about the hydropower projects in the region. There have been some suggestions to address the concerns such as providing funding opportunities for flood defences, shifting the focus to pumped hydropower storage and adopting an ecologically-sensitive model of development.

Exposure

The significant growth of hydropower installed capacity in Asia could lead to a higher level of exposure to climate impacts

The hydropower installed capacity in South and Southeast Asia is expected to grow further to meet the soaring electricity demand in the region. The new addition of hydropower capacity is driven by growing electricity demand, power export opportunities, and merits of hydropower as cost-effective, low-carbon and flexible solutions. Southeast Asia's rising income and increasing demand for electricity access and air conditioning could double the region's electricity consumption by 2040, stimulating new hydropower projects. Power export opportunities can also motivate hydro development.

The increase of hydropower installed capacity is observed in countries such as Lao PDR, Nepal, Bhutan and Myanmar, which are already relying on hydropower for over half of annual generation. In Lao PDR, where hydropower accounts for more than 57% of electricity generation, 1.89 GW out of 7.38 GW of total installed hydropower capacity was added in 2019. The growth includes two major projects: the 1,295 MW Xayaburi run-of-river power station and 270 MW Nam Ngiep 1 project. Similarly, Bhutan, where hydropower accounts for more than 95% of electricity generation, commissioned the 720 MW Mangdechu project, the second largest project commissioned in 2019 after Lao PDR in South and Southeast Asia.

In addition to the newly commissioned projects, these countries have announced plans to expand their hydropower installed capacity. For instance, Nepal, where hydropower provides almost all (99%) of domestic electricity generation on the grid, announced an ambitious plan to reach 5 GW total hydropower capacity over the next five years. Bhutan also aims to build 10 000 MW of hydropower capacity in the coming years, with concessional finance from India which imports about 80% of the overall hydropower generation in Bhutan. Myanmar is planning to triple the installed hydropower capacity by 2030 reaching almost 9 000 MW, according to its 2015 Energy Master Plan. It will exploit Myanmar's untapped hydropower energy potential, which would be almost 108 GW according to the Masterplan on ASEAN Connectivity 2025.

The growth in hydropower installed capacity in the region is also driven by export revenue. Nepal which has become an energy surplus country ever since the 456 MW Upper Tamakoshi Hydropower Project came into full operation in August 2021, started discussions with India to export the surplus. Lao PDR, which is already a large exporter of hydroelectricity, has signed multilateral electricity trade agreement with Thailand, Malaysia, and Singapore. It plans to expand its markets from Thailand, which imported over 60% of Lao PDR's hydroelectricity export, to other countries.

A strong and increasing reliance on hydro for electricity generation in some Asian countries could raise concerns about their exposure to the adverse impacts of climate change. While hydropower plays a major role in mitigating climate change as the largest source of low-emissions electricity in these countries, it also needs to adapt to the potential impacts of climate change.

Vulnerability

Some hydropower plants need rehabilitation and upgrades to cope with concentrated rainfall and floods

Although a majority of the large hydropower plants in South and Southeast Asia are less than 20 years old, some of the older ones require modernisation efforts to withstand the changed rainfall patterns. Around half of the existing hydropower installed capacity in Asia (excluding China) will have undergone or be due for modernisation by 2030. The report of the International Hydropower Association (IHA) and the Asian Infrastructure Investment Bank (AIIB) identified 21 hydropower stations in high need of modernisation, and an additional 25 stations in medium need across South and Southeast Asia. Among the 46 stations in high and medium need of modernisation, 25 are in India.

Responding to the need for hydropower plant modernisation, the Government of India has made the renovation, uprating and life extension of old hydropower plants a high priority. The modernisation of hydropower plants and improving their operational reliability and efficiency is considered a faster and cheaper option for capacity addition than building new plants. India set up a National Committee in 1987, a Standing Committee in 1998 and later the Hydro Engineering Renovation & Modernisation Division under the Central Electricity Authority. The renovation and modernisation of 17 hydroelectric plants is planned for completion between 2017 and 2022 and another six are to be completed between 2022 and 2027. Nine plants with an aggregate installed capacity of about 1 354 MW have been completed as of June 2021.

The rehabilitation and upgrading of ageing hydropower plants in South and Southeast Asia can reduce their vulnerability to the projected increase in concentrated rainfall and floods. The modernisation of ageing hydropower facilities, such as upgrading spillway capacities, increasing dam safety, digitalising operations with installing new smart controls, and intelligent condition monitoring, will reduce their exposure to climate hazards and help them cope with unexpected disruptions.

Hydropower plants located in transboundary river basins can create tension among countries, demanding a regional approach

Transboundary river basins, such as Mekong river basin, shared by two or more countries, require extra efforts to build adaptive capacity since it demands a collaborative approach among relevant countries. Uncoordinated operation of hydropower dams located in upstream areas can have adverse impacts downstream by limiting water availability during droughts or by causing devastating flood damage.

The Mekong River, the longest river in Southeast Asia originating from the Himalayan Mountains, is an important water source for hydropower generation as well as agricultural, industrial, and domestic uses. Over 170 hydropower projects are either planned or operating along the river and the majority of them are large-scale reservoir dams. The Mekong River basin consists of two parts: the upper basin is in China and the lower basin that spans Myanmar, Thailand, Lao PDR, Cambodia and Viet Nam. Rapid development of hydropower projects has occurred in both basins over the past few decades. In the upper Mekong (also called the Lancang River) China has constructed hydropower dams since the early 1990s, and 11 dams are now in operation on the main stream with others on tributaries, with a total installed capacity of over 16 GW. Eleven more dams, each with a production capacity of over 100 MW, are under planning or construction as a part of “the Lancang Cascade”. In the lower basin, 89 hydropower plants with 12 GW total installed capacity are in operation (as of 2019). By 2040, the total installed capacity is estimated to grow to more than 30 GW.

There is potential for tension between the upper and lower Mekong basin countries given that the streamflow of the river could be critically affected by existing and planned dams. Some studies show that upstream dams may contribute to droughts downstream, and that decreasing the volume of streamflow could cause salt water intrusion in the Mekong Delta. The projected increase in the precipitation gap between the wet and dry seasons might cause the conflicts between upstream and downstream inhabitants.

To avoid tensions and promote regional cooperation, Lao PDR, Thailand, Cambodia and Viet Nam established the Mekong River Commission (MRC) in 1995 as an intergovernmental organisation to oversee the sustainable management and development of water and related resources in the Mekong River basin. The MRC and China have been exchanging hydrological data during the annual flood season since 2002 and have found that the upstream dams have narrowed the seasonal difference between the dry and wet season downstream water flow.

Countries around the Himalayas – Bangladesh, Bhutan, India, Nepal and Pakistan – have also experienced tensions over water management. The rivers that originate from and pass through the Himalayas play a critical role in electricity generation, agriculture and domestic water supply. Given that only one-third of the feasible hydropower potential has actually been tapped so far, the Himalayan region is considered as a land of opportunities for hydropower development. However, as climate change is altering the patterns and volume of streamflow around the Himalayas, the disputes over water have been exacerbated despite the relevant countries' efforts. For example, the waters of the Indus River, which begin in Tibet and the Himalayan mountains, have been regarded by India as a good location for hydropower generation, while Pakistan has perceived India's plan as a threat. The increasing aridity in most parts of Pakistan in recent decades and the projected growth in the frequency of droughts make it difficult to reach a resolution.

To resolve the disputes over water resources around the Himalayas, the countries have established bilateral agreements and taken collaborative actions. Nepal and Bhutan have signed bilateral agreements on hydropower development with India to increase the hydropower installed capacity, develop electricity transmission and irrigation networks and respond to the lack of financing and significant outages in both countries. India and Nepal also announced a new "energy banking" initiative aimed at addressing the seasonal variability in energy production, which includes hydropower generation. There are also ongoing discussions on multilateral cooperation and expanding the scope of collaboration. For instance, the establishment of the Bangladesh, Bhutan, India and Nepal (BBIN) Initiative in 1997 to accelerate the interconnection of power grids boosted hydropower development and brought revenue to Bhutan and Nepal from hydropower exports. In 2019, Nepal and Bangladesh agreed to trade power from the Karnali Hydropower Plant through India's transmission network within the next five years. The multilateral electricity trade among the BBIN countries based on hydropower generation can lead to efficient utilisation of the regional hydro potential, lower capital investments and reduced GHG emissions.

Chapter 3. Climate impacts on Asian hydropower

What are climate impacts?

Climate impacts are the actual consequences of climate change

Hydropower plants generally operate for multiple decades, sometimes even over 100 years, and as such are likely to be impacted by climate change during their lifespan.

The changes in long-term climate patterns directly affect hydropower generation. Rising temperatures will likely affect generation output and potential by increasing evaporation losses and by melting glaciers. Massive floods caused by a glacier breach in Uttarakhand, India, washed away the 13.2 MW Rishiganga hydropower project in February 2021 and caused severe damage to the 520 MW Tapovan Vishnugad hydropower project.

Changes in precipitation will also alter the potential generation output, peak level and seasonal variations of hydropower. Particularly in South and Southeast Asia, changes in the monsoon system with more concentrated rainfall are projected to add difficulties to water management for hydropower generation. The associated floods and landslides can also significantly damage hydropower plants.

The projected increase in the frequency and intensity of droughts in a large part of South Asia over the rest of the 21st century poses another challenge to the hydropower plants in the area. For instance, the hydropower generation from the 1 GW Tehri Hydropower Plant in northern India dropped significantly when a drought hit and left no usable water in its reservoir in May 2016.

Methodology

The assessment of climate impacts on hydropower requires a comprehensive analysis of various models

Despite tremendous efforts from the climate science community to provide more accurate projections of climate impacts, there is still a lack of agreement on the future climate and hydrological conditions in certain areas of South and Southeast Asia due to different assumptions and limited observations. This sometimes creates a gap between the results of various models. Given these embedded limitations, this report aims to examine as many combinations of climate and hydrological models as possible, aggregating various outcomes to present the trends that a majority of models could agree upon.

We compared 60 different ensembles of five General Circulation Models (GCM), four Global Hydrological Models (GHM) and three Representative Concentration Pathways (RCP),[10] with the aim to minimise the probability of misleading outcomes or distortion by outliers and to ensure diversity. Since outliers are often difficult to avoid due to the complexity of the climate system and the different assumptions within each model, this report compared and aggregated outcomes from various GCMs, GHMs and RCPs, and presented average annual and monthly capacity factors.[11]

Annual and monthly capacity factors per hydropower plant were mainly derived from a high-resolution global discharge map (15” × 15”) that combines low-resolution (0.5˚ x 0.5˚) monthly run-off data with high-resolution (15” × 15”) area accumulation and drainage direction maps available from HydroSHEDS. These discharge maps were used to extract the design discharge and to formulate load factors for each hydropower plant. By placing the discharge of a selected hydropower plant in sequence from the lowest to the highest month of discharge, a flow duration curve was generated. The value of the fourth-highest discharge month is called the design discharge and determines turbine capacity. The capacity factor is, by design, 100% for the four wettest months and less than 100% for the remaining eight drier months. Further information about the selected models and methodology is provided in the Annex.

This report assesses the climate impacts on hydropower generation as of the end of this century in 13 South and Southeast Asian countries

The assessment shows changes in annual and monthly capacity factors between 2020 and 2099, comparing the projected results with the values of the baseline

[10] Given the limited availability of updated GHM data for Shared Socioeconomic Pathways (SSP) as of October 2021, this report used RCPs.

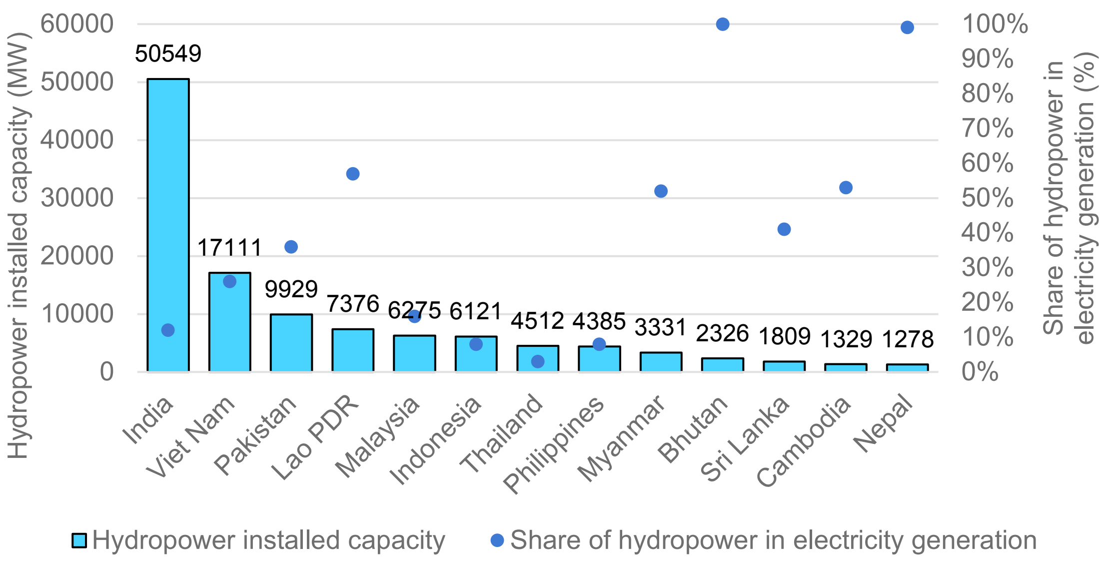
[11] Ratio of a power plant’s actual output over a period of time to its potential output if it were possible for it to operate continuously at full nameplate capacity over the same period of time.

period from 1970 to 2000. The baseline period was selected reflecting the maximum availability of historical climate records.

The assessment focuses on 13 South and Southeast Asian countries with the largest installed capacity of hydropower. The selected countries are arranged in four groups reflecting their climatic and geographic characteristics: Himalayan region (Bhutan and Nepal), Mainland Southeast Asia (Cambodia, Lao PDR, Myanmar, Thailand and Viet Nam), Maritime Continent (Indonesia, Malaysia and the Philippines) and Indian Subcontinent (India, Pakistan and Sri Lanka).

The total hydropower installed capacity in these 13 countries is over 116 000 MW, which accounts for 99% of the total installed capacity in South and Southeast Asia. The climate impacts on the regional mean hydropower capacity factor are heavily influenced by trends in the Indian Subcontinent and Mainland Southeast Asia. Indeed, India accounts for over 42% of the total hydropower installed capacity, followed by Viet Nam, Pakistan, Lao PDR and Malaysia. Given India's large share of total South and Southeast Asian hydropower installed capacity, the installed capacity from the 13 countries varies from 3% for the Himalayan region to 53% for the Indian Subcontinent.

Figure 3.1 Total hydropower installed capacity by country, 2020

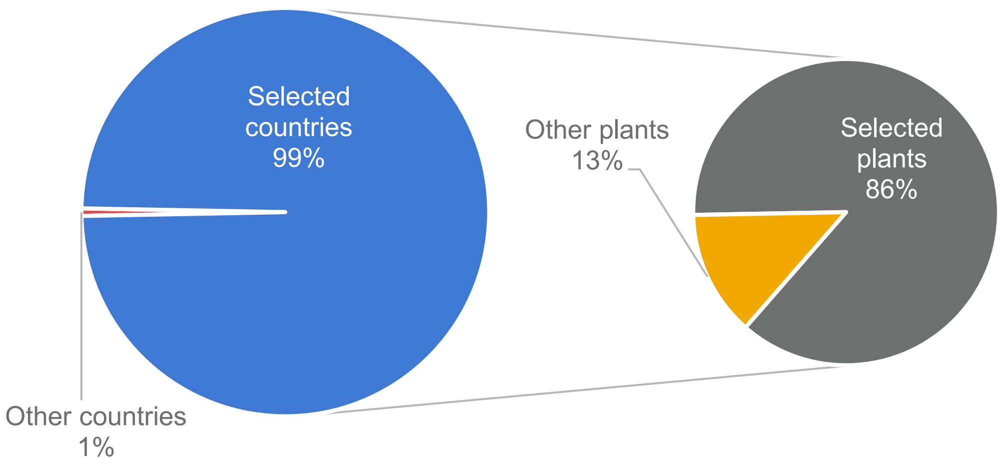


Note: Data on the share of hydropower in electricity generation refer to the most recent source available. Data for India, Indonesia, Myanmar, Nepal, the Philippines and Thailand are from the 2019 IEA database, while data for Cambodia, Malaysia, Pakistan, Sri Lanka and Viet Nam are from the 2018 IEA database. Lao PDR and Bhutan are not included in the IEA database. 2019 data are from the Our World in Data archive.

Sources: International Hydropower Association (2021), 2021 Hydropower Status Report; IEA, Countries and regions, https://www.iea.org/countries; Our World in Data, Share of electricity production from hydropower.

The analysis covers over 490 hydropower plants equivalent to 100 000 MW, covering 86% of the total installed hydropower capacity in South and Southeast Asia. The assessment calculates the climate impacts on each hydropower plant, using each station's specific geographic coordinates.

Figure 3.2 Shares of covered plants in terms of installed hydropower capacity in South and Southeast Asia



Note: "Other countries" refers to Afghanistan, Bangladesh, Brunei, Singapore and Timor Leste.

This report presents three scenarios with different levels of greenhouse gas concentrations

By comparing three scenarios, each with a different global average temperature – outcome Below 2°C, Around 3°C and Above 4°C, respectively by 2100 – this report aims to present how GHG concentrations are likely to affect hydropower generation in South and Southeast Asia.

These scenarios are based on the RCP of the Coupled Model Intercomparison Project Phase 5 (CMIP5) of the IPCC Fifth Assessment Report. The RCPs show various representative GHG concentration trajectories and their impacts on the future climate (see Annex).

The Below 2°C Scenario is based on the projections of the RCP 2.6 that assumes a radiative forcing value of around 2.6 W/m^2 in the year 2100. In the Below 2°C Scenario, the increase in the global annual mean temperature stays below 2 °C by 2100 compared to pre-industrial times (1850-1900). For the period 2080 to 2100, the global annual mean temperature increases by 1.6 (±0.4) °C above the level between 1850 and 1900. The Below 2°C Scenario assumes an early peak in global GHG emission trends followed by a drastic decline.

The Around 3°C Scenario follows the trajectory of the RCP 6.0 that assumes a radiative forcing value of around 6.0 W/m^2 in the year 2100. The Around 3°C Scenario is associated with a rise of 2.8 (±0.5) °C in the global annual mean temperature for the period 2080 to 2100 compared to the pre-industrial level. The Around 3°C Scenario is based on the assumption of stabilisation of total radiative forcing after 2100. Under this scenario, global GHG emissions would peak during the latter half of the century and then decline.

The Above 4°C Scenario is based on the high-emission trajectory, RCP 8.5, which assumes the absence of additional efforts to mitigate GHG emissions. The Above 4°C Scenario is associated with a radiative forcing value of around 8.5 W/m^2 in the year 2100 and a rise of 4.3 (±0.7) °C in the global annual mean temperature for the period 2080 to 2100 compared to the pre-industrial level. Under the Above 4°C Scenario, global GHG emissions do not reach their peak before 2100.

Table 3.1 Overview of the scenarios

Scenario	Below 2°C	Around 3 ° C	Above 4°C
Representative Concentration Pathway	RCP 2.6	RCP 6.0	RCP 8.5
Targeted radiative forcing in the year 2100	2.6 W/m^2	6.0 W/m^2	8.5 W/m^2
CO_2-equivalent concentrations (ppm)	430-480	720-1000	>1000
Global temperature change	1.6(±0.4)°C	2.8(±0.5)°C	4.3(±0.7)°C
Likelihood of staying below a specific temperature level over the 21st century	Likely to stay below 2°C	More unlikely than likely to stay below 3°C	More unlikely than likely to stay below 4°C

Source: IPCC (2014), Climate Change 2014 Synthesis Report.

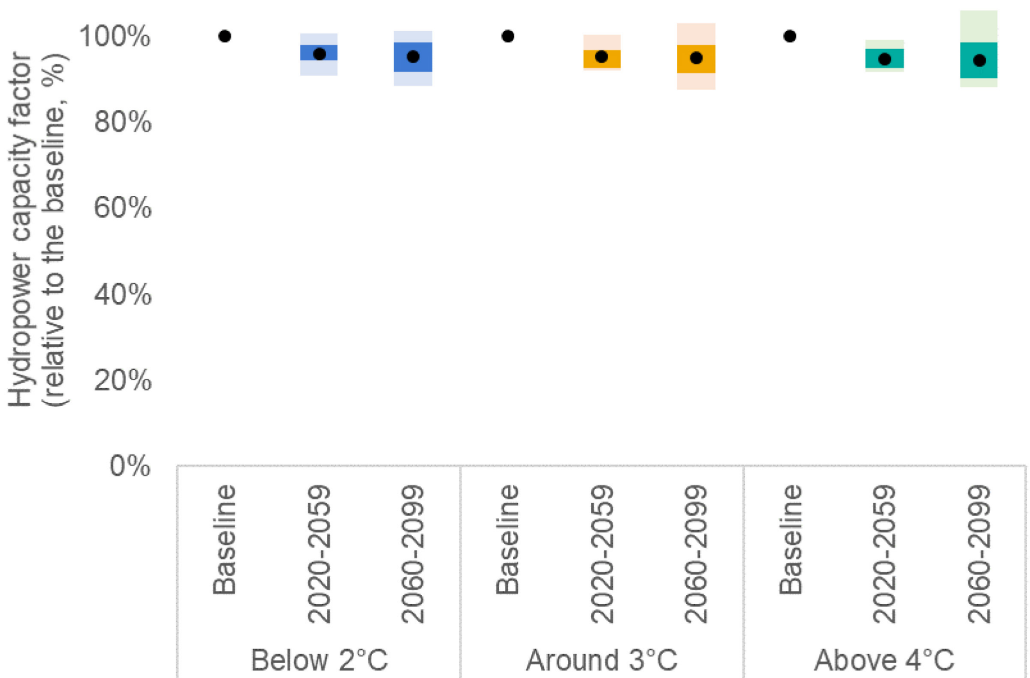
Key results

Climate change could cause a decrease in the regional mean hydropower capacity factor

By the end of this century, the mean hydropower capacity factor for South and Southeast Asian hydropower plants is projected to decrease in all three climate scenarios due to changing climate conditions. The regional mean capacity factor over the period from 2020 to 2059 is likely to decrease by 4.6% on average (from 3.9% in the Below 2°C Scenario to 5.2% in the Above 4°C Scenario), compared to the baseline level of 1970 to 2000. Between 2060 and 2099, the regional mean hydropower capacity factor is projected to be lower than the baseline by 5.1% on average (from 4.7% in the Below 2°C Scenario to 5.4% in the Above 4°C Scenario).

The results show that higher GHG concentration is likely to lead to a larger decline in the mean hydropower capacity factor in a majority of results.[12] This implies that reducing the overall GHG emissions could also limit the negative impacts of climate change on South and Southeast Asian hydropower.

Figure 3.3 Regional mean hydropower capacity factor, 2020-2099 relative to the baseline 1970-2000, by scenario



Notes: The black dots indicate the average hydropower capacity factor of the selected South and Southeast Asian hydropower plants based on results from 20 combinations of GCMs and GHMs per scenario. The coloured bars indicate the range of the results; the darker colours in the bars show the range of 60% of the results.

The projected decline in hydropower capacity factor could have negative implications on electricity supplies in South and Southeast Asia, given the growing importance of hydropower in the region to meet soaring electricity demand, earn export revenues and provide flexibility for other renewable energy sources. Currently, hydropower accounts for 15% of total electricity generation in the

[12] The results using Noresm Global Circulation Model project a different trend of regional mean hydropower capacity factor from the others, over the period of 2060-2099 in Around 3°C and Above 4°C Scenarios. The results of Noresm expect a slight reduction in 2020-2059 and a rebound in 2060-2099.

selected countries, with Bhutan, Nepal, Lao PDR, Myanmar and Cambodia relying on hydropower for more than 50% (as of 2018-2019) of their national electricity generation. The installed hydropower capacity is expanding rapidly in the region: over 1 GW of hydropower capacity was added in 2020 alone.

Change in mean capacity masks uneven climate impacts across the region

Although the regional mean hydropower capacity factor is projected to decrease by 2100, this does not mean that climate change will have an equal impact on every hydropower plant. Rather, the impacts of climate change are likely to be uneven across South and Southeast Asia.

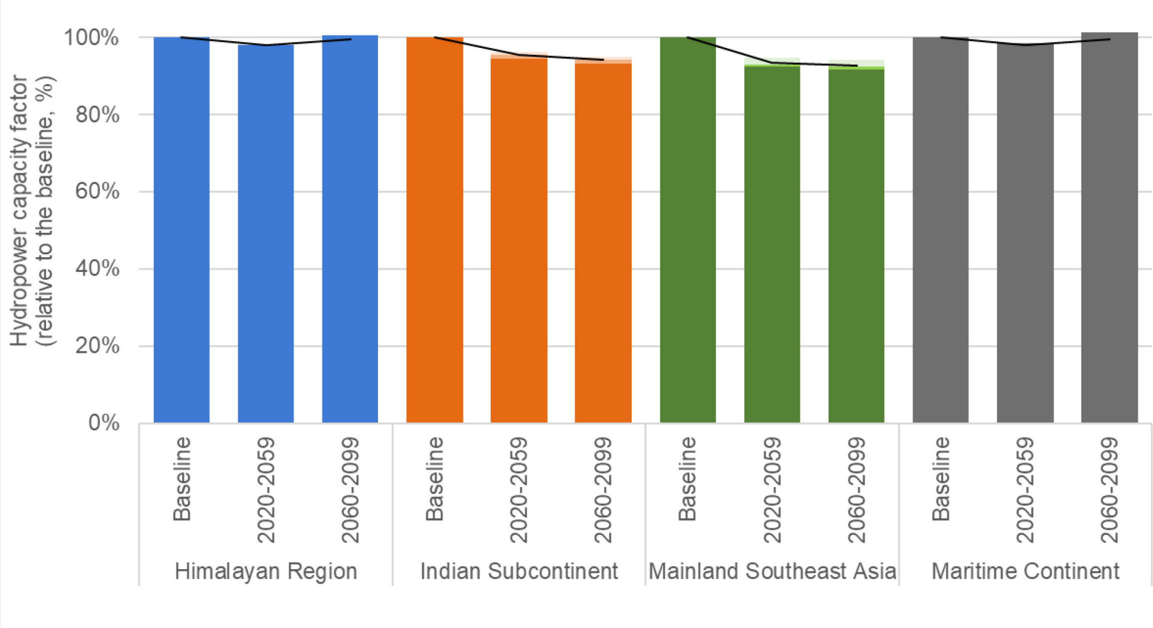
The results from the examined models show that two sub-regions, the Indian Subcontinent and Mainland Southeast Asia, will see a continuous decline in hydropower capacity factor until the end of the century in all three scenarios. The hydropower plants in the Indian Subcontinent are projected to experience a decline of 5.1% in the Below 2°C Scenario and of 6.8% in the Above 4°C Scenario until the end of the century, compared to the baseline. Similarly, the hydropower capacity factor of Mainland Southeast Asia is expected to decrease by 5.9% in the Below 2°C Scenario and by 8.2% in the Above 4°C Scenario.

In contrast, the other two sub-regions, the Maritime Continent and the Himalayan region will show more complicated trends in hydropower capacity factors: a drop between 2020 and 2059 and a recovery between 2060 and 2099. In both sub-regions, a higher GHG concentration will lead to a more dramatic bounce in the hydropower capacity factor in the latter 40 years of the century.

The hydropower capacity factor of the Himalayan region is projected to fall by 1.8% to 2.2% in 2020-2059 and then return to around the baseline level in 2060-2099. Under the Above 4°C Scenario, the recovery will be more significant, bringing the hydropower capacity factor slightly higher than the baseline.

The hydropower capacity factor of the Maritime Continent will follow a similar trend with a drop of 1.5% to 2.5% in the period of 2020-2059 and an increase between 2060 and 2099. The bounce in 2060-2099 will be particularly notable under the Above 4°C Scenario, which will eventually lead to an increase in the hydropower capacity factor of 1.4% in 2060-2099 compared to the baseline. In the Below 2°C Scenario, the hydropower capacity factor over the period of 2060-2099 will remain at the same level as 2020-2059, which is 2.5% lower than the baseline.

Figure 3.4 Changes in hydropower capacity factor by Asian sub-region, 2020-2099 relative to the baseline 1970-2000

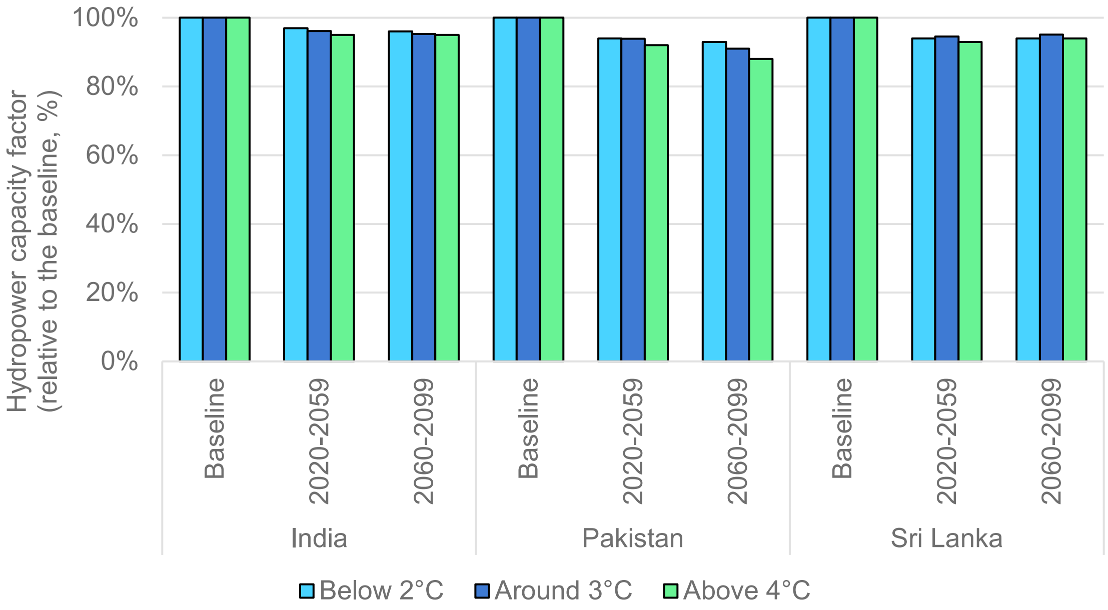


Notes: The lightly coloured areas indicate the gap between projections from different scenarios. The darkest colour indicates the projection in the Above 4°C Scenario; the lightest colour is the projection in the Below 2°C Scenario. The black lines indicate the average of the projections from the three scenarios.

The Indian Subcontinent is projected to see a decrease in the hydropower capacity factor due to a seasonal concentration of rainfall and increasing winter dryness

The hydropower capacity factor in the Indian Subcontinent, which includes India, Pakistan and Sri Lanka, is expected to decrease by 2100. The decline in the hydropower capacity factor is expected to be more marked with a higher GHG concentration. It is projected to fall by 5.1% under the Below 2°C Scenario but drop by 6.8% under the Above 4°C Scenario in 2060-2099 compared to the baseline period of 1970 to 2000.

Figure 3.5 Climate impacts on the hydropower capacity factor in the Indian Subcontinent by country, 2020-2099 compared to the baseline period, 1970-2000

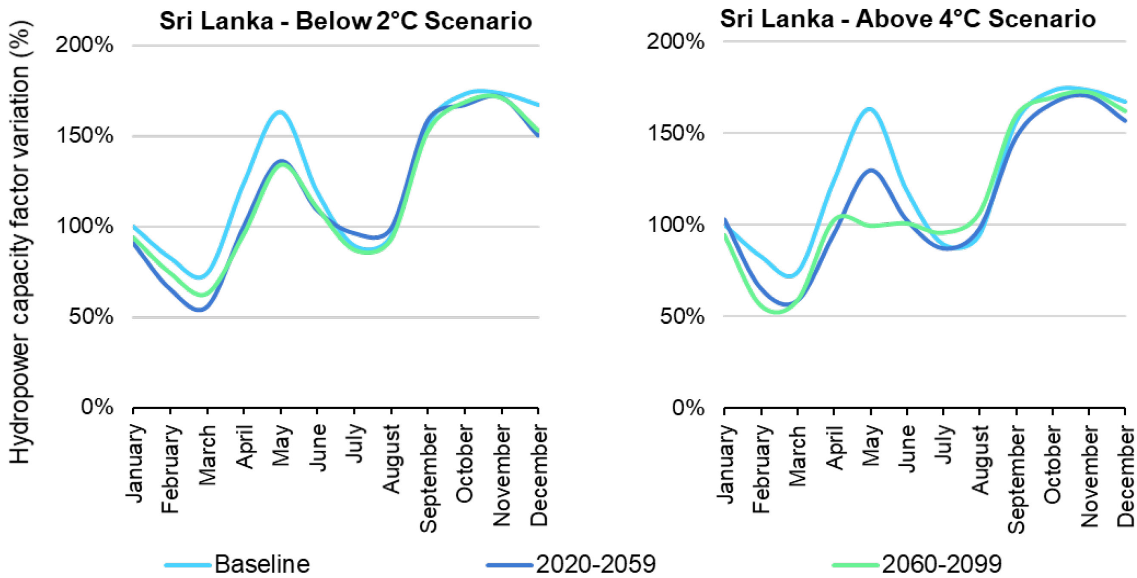


In India, which accounts for 81% of the total hydropower installed capacity of this sub-region, the decrease in hydropower capacity factors is mainly due to the rainfall being more concentrated during the summer monsoon period while winter precipitations decrease over the Indian Subcontinent. Although the annual precipitation in India is likely to increase, the winter monsoon precipitation is projected to fall, making the dry season drier. The reduced precipitation outside of the summer monsoon period will limit the water availability for hydropower and drag down the hydropower capacity factor.

Meanwhile, more intense rainfall during the summer monsoon period will not offset the reduction in the winter monsoon period. Excess water resulting from the concentrated rainfalls does not necessarily lead to increased hydropower generation since the hydropower capacity factor already reaches its peak during the summer monsoon when about 80% of the annual rainfall comes. The excess water flow can even have negative implications for hydropower generation. It can force hydropower plants to run at reduced capacity if turbines are not designed to cope with such increased water flow or the stronger flows pick up debris which can damage turbines or burst banks.

Sri Lanka's hydropower plants are also projected to be affected by changes in monsoon rainfalls. Sri Lanka has two seasonal monsoons: the Yala Monsoon brings rain to the west and southwest coasts from May to September, while the Maha Monsoon hits the east coasts from November to February. The historical trends of these two monsoons indicate that the Yala Monsoon is becoming more variable and is projected to bring less rainfall in May, while the Maha Monsoon is projected to stay strong and bring more rainfall around November. The concentration of rainfall during the Maha Monsoon period and less rainfall during the Yala Monsoon will lead to a reduction of hydropower capacity factors from March to July, while more rainfall around November is unlikely to fully offset the reduction.

Figure 3.6 The monthly hydropower capacity factors of Sri Lanka under the Below 2°C and Above 4°C Scenarios



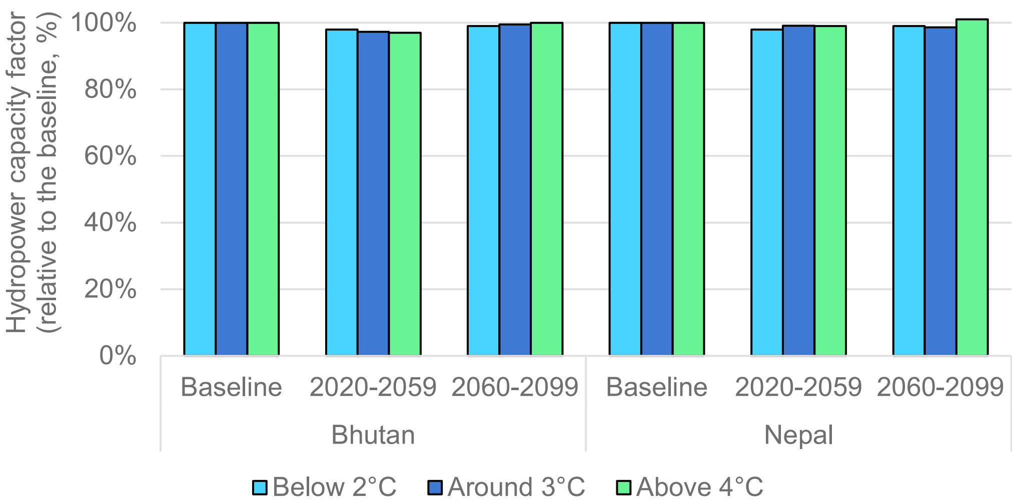
Among the three countries in the sub-region, the hydropower in Pakistan is likely to be the most affected by changing climate conditions. The capacity factor of Pakistan's hydropower is estimated to drop by 7% under the Below 2°C Scenario in the latter 40 years of the 21st century. It could show an even starker decrease, 12%, in the Above 4°C Scenario.

The projected decrease in the hydropower capacity factors of Pakistan is consistent with the trend of increasing dryness in the country. In recent decades, aridity has increased from March to June in most parts of Pakistan and some localised aridity trends are projected to continue over the rest of 21st century with less annual mean precipitation and less mean annual runoff.

The hydropower capacity factor in the Himalayan region could decline then recover, due to the combined effects of precipitation, warming and glacier melting

The hydropower capacity factors of Nepal and Bhutan, which are located in the Himalayan region in the northern part of South Asia, are projected to remain comparatively stable, showing a slight reduction in 2020-2059 and a recovery in 2060-2099. The sub-regional mean hydropower capacity factor of the Himalayan region is projected to fall by 1.8-2.2% in 2020-2059 and then return to around the baseline level between 2060 and 2099. In Bhutan, the largest hydropower capacity drop will be of 3% in 2020-2059 under the Above 4°C Scenario, which will be fully recovered between 2060 and 2099. In Nepal, the hydropower capacity factor will fall by 1% in 2020-2059 under the Above 4°C Scenario. It will then bounce back to above the baseline between 2060 and 2099.

Figure 3.7 Climate impacts on the hydropower capacity factors in the Himalayan region by country, 2020-2099 compared to the baseline period, 1970-2000



The slight fall in the hydropower capacity factors of Nepal and Bhutan in the period of 2020-2059 can be explained by the projected decrease in winter precipitation. Climate projections show that winter precipitation over the eastern Himalaya, where Nepal and Bhutan are located, would decrease over the 21st century.

In the latter 40 years of the 21st century, the combined impacts of warming and glacier melting are expected to offset the negative impact of the decreasing winter precipitation. The annual mean temperature over the Himalayan region is projected to increase by 5.23 °C ± 0.91 °C in the Above 4°C Scenario by the end of the 21st century relative to that of 1976-2005. The warming is projected to accelerate glacier mass loss and cause it to peak in the mid to late 21st century,[13] which would increase discharge in 2060-2099. An extended warm period with increased water flow from glacier melting is expected to help the hydropower capacity factor reach its maximum more often and for longer, although the trend may not remain consistent over the long run.

The melting of mountain glaciers in the Himalayan region may pose another challenge to hydropower, prompting more glacial lake outburst floods in the region. Nepal and Bhutan are already two of the countries with the highest risk of glacial lake outburst floods. Indeed, glacier lake outburst floods caused significant damage to Nepal's 45 MW Upper Bhote Koshi hydropower plant in 2016.

Box 3.1 Bhutan's policies for preventing glacial lake outburst floods

Bhutan, which relies almost entirely on hydropower for electricity supply, is well aware of the importance of monitoring its glacial lakes to prevent glacial lack outburst floods. Many hydropower plants in Bhutan are exposed to the risk of glacial lake outburst floods. For instance, two of the largest hydropower projects in Bhutan, the 1 200 MW Punatsangchu-I and 1 020 MW Punatsangchu-II, are being built downstream of the Thorthormi Lake – the largest glacial lake in the country. A powerful outburst flood could wreak havoc on these projects.

The Bhutan government has committed to preventing glacial lake outburst floods as one of the top priorities in its climate change adaptation policy. It began research to assess the risk in 2009 and identified 25 potentially dangerous glacial lakes. The government implemented a project funded by the Least Developed Countries Fund on Climate Change Adaptation entitled, "Reducing climate change induced risks and vulnerabilities from glacial lake outburst floods in the Punakha, Wangdue and Chamkhar Valleys". Bhutan has shared technical lessons with other countries prone to glacial lake outburst floods, presenting regional and international best practices and enhancing knowledge exchange.

[13] Due to projection uncertainties, simplicity of the models and limited observations, there is medium confidence in the magnitude and timing of glacier mass changes.

The output from these projects is integrated into national strategies, highlighting the importance of monitoring glacial lakes to prevent outburst floods. According to the National Centre for Hydrology and Meteorology, the recommendations and research output of these projects contributed to shaping the 11th Five Year Plan (FYP) 2013-2018 and the 12th FYP 2018-2023, which include a requirement for monitoring glacial lakes.

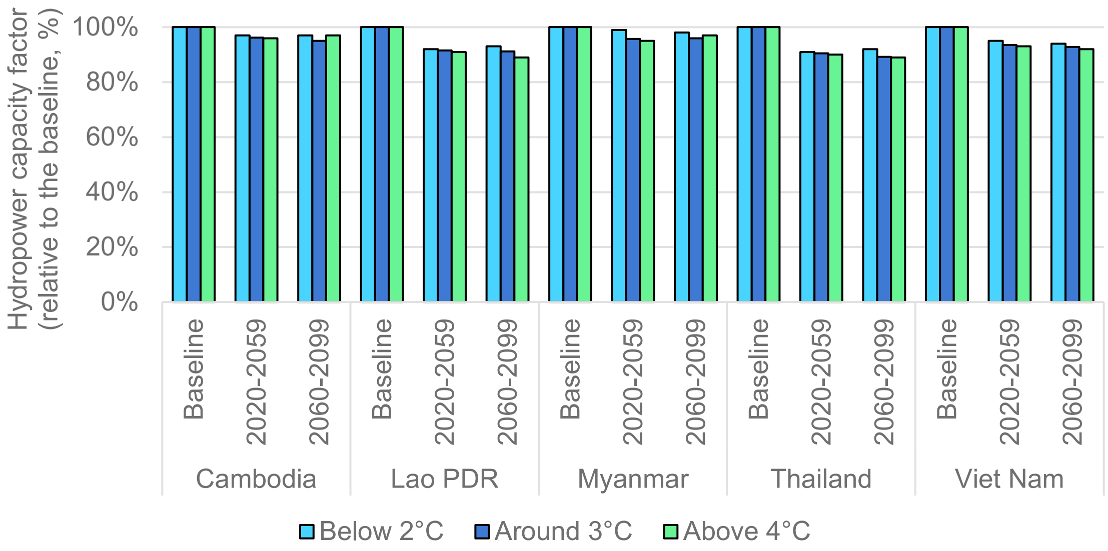
Source: Glacial Lake Outburst Flood (GLOF) - Reducing risks and ensuring preparedness, The Report on the International Conference, UNDP, 2013.

The hydropower capacity factor will decrease in Mainland Southeast Asia due to inconsistent water flow with more intense rainfall and droughts

Mainland Southeast Asia, which consists of Cambodia, Lao PDR, Myanmar, Thailand and Viet Nam, is projected to see a drop in its hydropower capacity factor. The decline is likely to be more significant with higher GHG emissions. Under the Above 4°C Scenario, the mean hydropower capacity factor of this sub-region in 2060-2099 is projected to be 8.2% lower than that of 1970-2000, while it would be 5.9% under the Below 2°C Scenario.

The hydropower capacity factors of Lao PDR and Thailand are expected to have the largest decreases under all climate scenarios. Over the period of 2060-2099, they will be 7% in Lao PDR and 8% in Thailand, lower than the baseline under the Below 2°C Scenario. The decreases could be more significant under the Above 4°C Scenario, which may reach 11% in both countries. The projected decline in the hydropower capacity factors can have negative implications for electricity security. This is especially the case in Lao PDR where hydropower accounts for more than 50% of the country’s total electricity generation, whereas hydropower accounts for less than 10% of Thailand’s total electricity generation.

Figure 3.8 Climate impacts on the hydropower capacity factor in Mainland Southeast Asia by country, 2020-2099 compared to the baseline period, 1970-2000



The declining hydropower capacity factor in Mainland Southeast Asia is closely connected to the changes in precipitation patterns. Although a stable and consistent water flow year round is ideal for hydropower generation, most parts of Mainland Southeast Asia have recorded a reduced number of wet days and more intense rainfall. In Thailand for instance, from 1955 to 2014, the average number of rain days decreased by 1.3 to 5.9 days per decade while the average daily rainfall intensity increased by 0.24–0.73 mm day per decade. The excess water due to intense rainfall does not necessarily contribute to hydropower generation, but increases sediments or leads to unplanned release of water from hydropower reservoirs. Furthermore, it can force hydropower plants to run at reduced capacity if the turbines are not designed to cope with such increased water flow or the stronger flow picks up debris which can damage hydropower dams.

Despite the increase in intense rainfall, more locations are projected to experience severe droughts with a decrease in the number of wet days. The area under the risk of severe droughts is likely to be extended to Cambodia and the southern part of Thailand from the north and south of Viet Nam, where droughts have been concentrated historically.

The projected expansion of drought areas could disrupt hydropower generation and eventually, electricity supply. Indeed, Cambodia faced a nation-wide power shortage in 2019 that was largely attributed to the drying up of the hydropower dams by a prolonged drought. After the experience of the 2019 droughts, Cambodia, where hydropower was providing almost half of the electricity generation, announced a number of long-term projects to ensure that a similar power crisis would not happen again. The Cambodia National Productivity Master Plan 2020-2039 calls for coal to generate 59% of the total power output, and solar PV to generate 27%, reducing the role of hydropower. Cambodia has withdrawn its plans to build two new hydropower plants on the Mekong River – Sambor (2.5 GW) and Stung Treng (1.2 GW) – and instead signed deals with two coal-fired power plants in 2020.

Changes in the hydropower capacity factors of the Maritime Continent vary depending on climate scenarios and locations

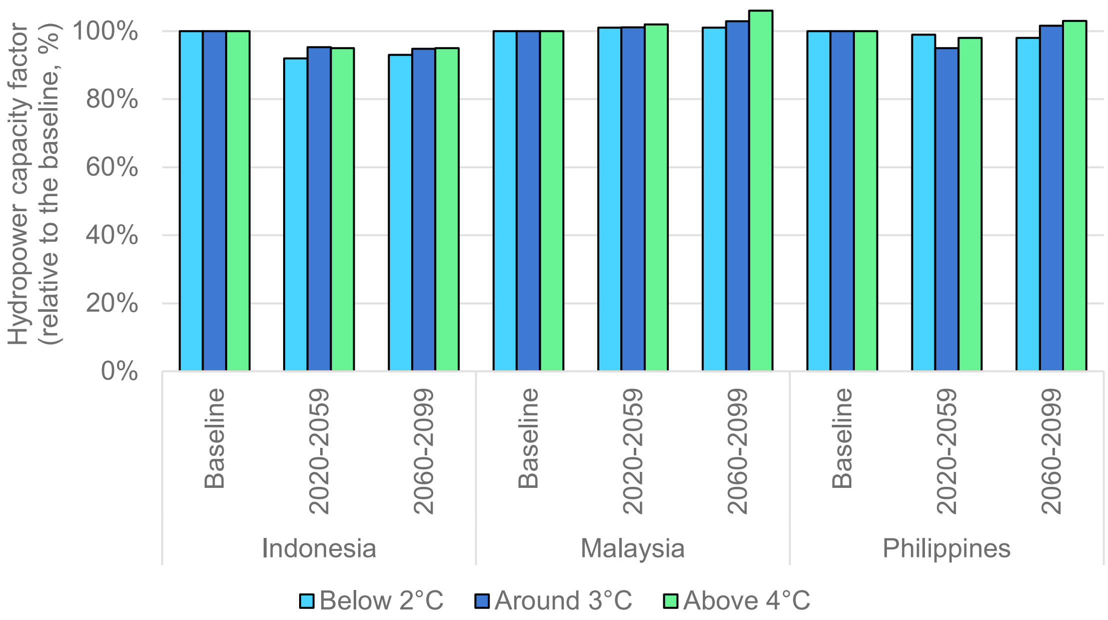
The mean hydropower capacity factor of the Maritime Continent, which consists of Indonesia, Malaysia and the Philippines, shows a different pathway depending on the climate scenarios. Under the Below 2°C Scenario, the hydropower capacity factor of the Maritime Continent is projected to fall by 2.5% in both periods (2020-2059 and 2060-2099) compared to the baseline. However, in the Above 4°C Scenario, it is projected to show a 1.4% increase for 2060-2099, despite a slight drop (1.5%) in 2020-2059.

The potential increase in the hydropower capacity factor in the Above 4°C Scenario is mainly attributed to the increases in Malaysia and the Philippines, where annual mean precipitation is projected to increase. Malaysia's hydropower capacity factor would be 6% higher in 2060-2099 compared with the baseline in the Above 4°C Scenario. The hydropower capacity factor of the Philippines is also projected to grow by 3% in 2060-2099 compared to the baseline. Even under the Below 2°C Scenario, the hydropower capacity factors of these two countries may remain relatively stable between +1% and -2%.

Both countries are planning to expand their installed hydropower capacity. In its National Renewable Energy Program, the Philippines envisions tripling renewable energy capacity by 2030, requiring an additional hydropower capacity of 8 700 MW. Malaysia is also expanding its hydropower projects, unlocking the untapped potential. Indeed, less than 20% of the technically feasible hydropower potential across the country has been utilised to date. Although the hydropower plants have been largely concentrated in Peninsular Malaysia, the state of Sarawak on the island of Borneo is also being considered for new developments.

In contrast to Malaysia and the Philippines, Indonesia is likely to experience a decrease in hydropower capacity factor due to reduced rainfall. The hydropower capacity factor of Indonesia over the period of 2060-2099 is projected to be lower than the baseline, by 7% in the Below 2°C Scenario and by 5% in the Above 4°C Scenario. The drop in the hydropower capacity factor could be explained by the projected decrease in the mean precipitation. By the end of the 21st century, Indonesia is forecasted to receive [20% to 30% less rainfall during the summer months.]

Figure 3.9 Climate impacts on the hydropower capacity factors in the Maritime Continent by country, 2020-2099 compared to the baseline period, 1970-2000



Chapter 4. Climate resilience

What is climate resilience?

Climate resilience is the ability to anticipate, absorb, accommodate and recover from adverse climate impacts

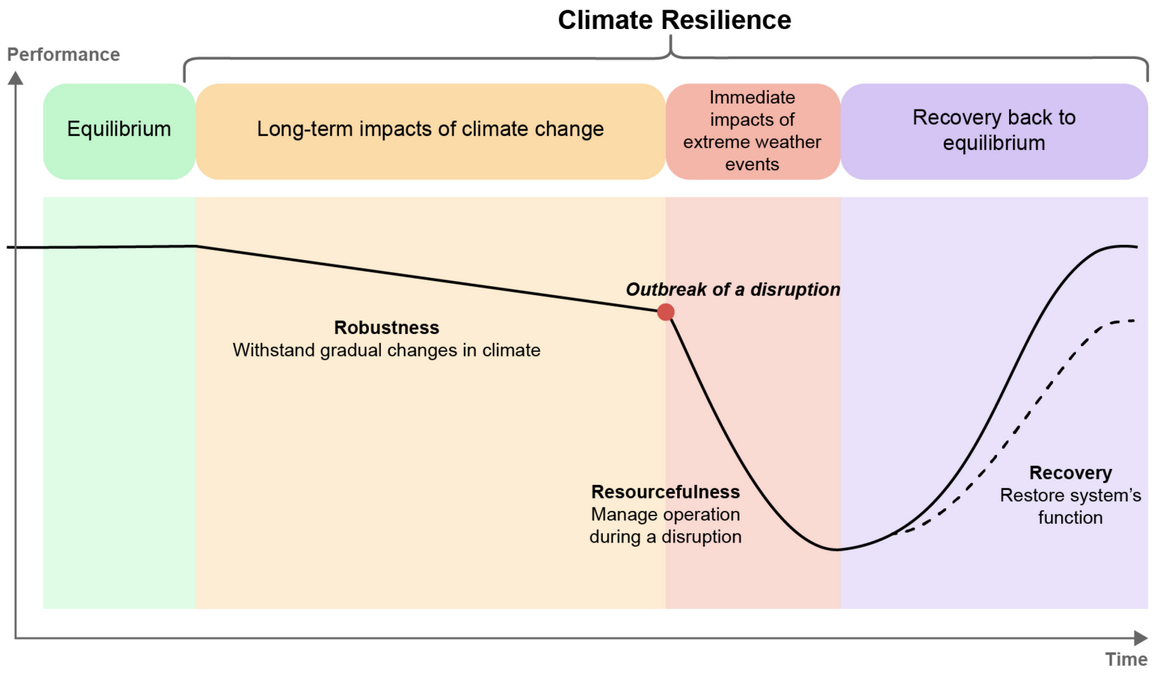
The climate resilience of energy systems is associated with three key dimensions: robustness, resourcefulness and recovery.

Robustness is the ability of an energy system to withstand gradual, long-term changes in climate patterns and to continue operation. For example, improved catchment management could make hydropower plants more resilient to a gradual increase in streamflow variability.

Resourcefulness is the ability to continue operations during immediate shocks such as extreme weather events. For example, a hydropower plant with a flood control reservoir is more likely to sustain a minimum acceptable level of operation in the face of floods, and thus likely to be more resilient to potential floods than one without a reservoir.

Recovery is the ability to restore the system's function after an interruption resulting from climate hazards. For example, a more resilient electricity system with a well-coordinated contingency plan for communications, temporary assets and the workforce will recover faster from the interruptions caused by climate impacts.

Figure 4.1 Conceptual framework for climate resilience and electricity systems



Source: Argonne National Laboratory (2012), Resilience: Theory and Applications (ANL/DIS-12-1), as modified by the International Energy Agency.

Benefits of climate-resilient hydropower

Climate-resilient hydropower systems support clean energy transitions in South and Southeast Asia

Renewable energy is expected to grow rapidly in the path towards clean energy transitions. The IEA World Energy Outlook's SDS estimates that the share of renewable forms of energy in Southeast Asia's total energy supply would increase from 17% in 2020 to 65% in 2050 and from 12% to 57% in India, leading future energy transitions. The rise of renewables is especially marked in the power sector where its share almost quadruples from 23% in 2020 to 86% in 2050 in Southeast Asia and from 22% to 90% in India, with a substantial increase in VRE. To meet the SDGs and deliver the Paris Agreement, over 400 GW of renewable capacity must be added every year from 2020 to 2030.

With the growing importance of renewables in the power sector, hydropower is expected to play a significant role in achieving sustainable energy for all and mitigating climate change. According to the IEA's Sustainable Development Scenario, the hydropower generation in Southeast Asia increases from 164 TWh in 2020 to 780 TWH by 2050, scaling up the share of hydropower in total electricity generation from 15% to 26%. In India, hydropower generation will more than double by 2050, although its share in total electricity generation may fall slightly from 11% to 7%.

Expanded hydropower capacity is likely to support further deployment of other low-carbon energy technologies, providing power system flexibility. Power system flexibility is the ability to effectively cope with variations in the supply or demand of electricity, balancing total load and generation at any time. In systems with a high share of VRE sources such as wind and solar, system flexibility is important to maintain system balance. Power systems will need to cope with increased flexibility requirements as the move towards low-carbon power systems accelerates.

Indeed, in most selected South and Southeast Asian countries, the share of VRE in total electricity generation has increased. For instance, the share of solar PV and wind has increased by 25 times in Southeast Asia and by over six times in India since 2010. The expansion of VRE and the decreasing capacity of conventional thermal power plants call for further flexibility solutions in the region.

Hydropower could offer a cost-effective flexibility solution to balance the variability of other renewables. Reservoir and pumped storage hydropower can be used to provide flexibility, energy storage and ancillary services. Although coal- and gas-fired power plants still provide the bulk of power system flexibility, hydropower already offers the largest portion of flexibility in some countries.

Climate resilience is essential for hydropower to continue delivering both electricity and flexibility on the path to clean energy transitions. Without enhancing climate resilience, the benefits of new capacity can quickly be disrupted by increasingly frequent extreme precipitation events and their associated hazards. Given that South and Southeast Asian countries, such as India, have ambitious plans to increase the share of solar and wind in power generation, the balancing role of hydropower will become more significant.

Climate-resilient hydropower systems contribute to achieving universal access to affordable and reliable electricity services

Ensuring universal access to affordable, reliable and modern energy services by 2030 is one of the objectives of the SDGs. Although the share of population with electricity access exceeds 90% in most of the South and Southeast Asian countries, several countries are lagging in this respect. In 2019, the electricity access rates of Pakistan and Myanmar were 73.9% and 68.4%, respectively.

Hydropower will play a critical role in achieving universal access to electricity in these two countries. Myanmar is planning to fulfil universal access to electricity by 2030 based on its National Electrification Plan. Hydropower, which currently accounts for over 50% of the country's total electricity generation is expected to play a critical role. Indeed, Myanmar set a target to triple the installed hydropower capacity by 2030 in its 2015 Energy Master Plan. Pakistan also aims to increase electricity access to over 90% by 2025 and provide uninterrupted and affordable electricity by doubling power generation to 42 000 MW. To fulfil its vision, Pakistan plans to increase the share of indigenous sources of electricity generation to over 50% with the completion of two major hydropower projects, the Diamer-Bhasha (4 800 MW) and Dasu (4 320 MW) dams.

As climate change is posing more challenges to hydropower generation in the region, climate resilience needs to be included within the plans to achieve universal electricity access. In Pakistan, the risks of diminishing run-off and more frequent glacial lake outburst floods may hinder hydropower generation and consequently impede reliable access to electricity. Factoring climate resilience in hydropower plant construction and management will therefore be essential.

Measures to enhance climate resilience

Enhancing climate resilience needs a tailored approach

There is no one-size-fits-all approach to enhancing the resilience of hydropower plants. Although climate change will have impacts across South and Southeast Asia, the wide range of patterns and magnitudes of potential climate impacts precludes a generic solution. A tailored combination of resilience measures based on a systematic assessment of climate risk and impact will help governments and plant operators increase system resilience.

Resilience measures can be categorised into "soft" and "hard" measures. Soft measures consist of strategies, policies and actions related to the planning, operational management and recovery of the hydropower system. Hard measures are associated with the physical enhancement of assets, such as technical and structural improvements, to hydropower plants.

Table 4.1 Examples of possible soft and hard measures to increase the resilience of hydropower plants

Soft measures	Hard measures
Strategies and regulations for resilience • Develop metrics and assessment approaches for assessing climate risks, impacts and resilience of hydropower projects • Incorporating assessment results into longer-term planning measures, when considering development of the future energy mix • Create a regulatory framework to develop and enforce rules to enhance climate resilience • Incentivise the implementation of climate resilience and risk mitigation measures (e.g. early warning systems, introduction of standards for climate resilience) • Introduce other relevant regulations (e.g. restriction of land development in vulnerable or critical areas such as catchments)	**Hardening and redesigning infrastructure** • Enhance reservoir capacity • Increase dam height • Modify canals or tunnels • Modify the type of turbines more suited to expected water flow rates • Build upstream sediment control facilities • Manage suspended solids and sediments • Increase flood fences to protect power stations • Strengthen banks • Relocate the powerhouses to higher ground • Modify the spillway capacities to flush silted reservoirs
Improving planning and operating rules • Consider possible climate impacts when designing hydropower plants • Revise operating regimes of a plant reflecting projected climate impacts	**Introduction of new technologies** • Digitalise data collection and monitoring • Adopt smart technologies in operation and maintenance
Emergency response and recovery • Establish plans for emergency response and recovery • Establish communication channels for better co-ordination among stakeholders in the event of emergency response (e.g. emergency release of water from dams) • Train human resources for emergency response and recovery	**Upstream management** • Manage a catchment (e.g. forestation) • Build smaller dams upstream

Source: IEA (2020), Climate Impacts on African Hydropower; IHA (2019), Hydropower Sector Climate Resilience Guide; WBCSD (2014), Building a Resilient Power Sector

Examples of soft measures

Soft measures can be adopted and implemented by both governments and operators. Based on a scientific and comprehensive assessment of climate risk and impact, governments and operators can take measures that would incorporate the assessment results into longer-term planning measures and the development of an energy mix which is more resilient and less vulnerable to climate change. The assessment of climate risk and impacts could also support decisions for the construction, operation, maintenance and modernisation of hydropower plants. International organisations such as the World Meteorological Organization, International Hydropower Association and World Bank provide tools for climate risk and impact assessments, along with guides for building and enhancing the climate resilience of hydropower.

Governments can also encourage power generators to pay more attention to climate resilience by creating a regulatory framework that incentivises the implementation of resilience measures. For example, governments can create criteria for "climate-resilient" hydropower projects and provide financial support for the inclusion of climate resilience in the planning and design of future assets and modernisation. India has come up with a budgetary support for flood moderation component for hydropower projects. This reduces the tariff that hydropower consumers pay by ensuring that they are charged on the basis of the power component only. Financial incentivisation can be implemented in collaboration with lending institutions (such as international financial institutions). Other relevant regulations, such as restricting land development around vulnerable catchment areas, can also reduce the probability of serious damage from climate hazards.

Power generators and project developers can better consider the potential impact of climate change when they design and plan hydropower plants. For existing hydropower plants, power generators could revise operating regimes in a manner that responds to projected climate impacts. For instance, integrating a climate resilience monitoring process into the operation and maintenance plans can provide regularly collected information relating to future climate risks and assign clear responsibilities for their control.

In addition, stronger and more co-ordinated emergency response measures with an early warning system can reduce recovery time, thereby limiting the impacts of climate change. For instance, regulators and commissions can develop emergency response plans with local authorities and operators to enhance resilience to extreme weather events. Governments can also support household and business emergency preparedness by improving institutional coordination and by disseminating information.

Examples of hard measures

Most hard measures are related to improving physical systems, introducing new technologies and upstream management. Enhancing reservoir capacity, increasing dam height, modifying turbines and redesigning spillways can also help manage erratic water flow patterns. Redesigning canals or tunnels can also contribute to better management of the variability of water levels by adapting to changed discharge patterns. In addition, an enlarged reservoir may help hydropower plants reduce their vulnerability to floods by limiting overflow, while reducing the adverse impacts of droughts by providing an augmented level of water storage.

In countries that are likely to experience more frequent, intense rainfalls in the forthcoming decades, hard measures to prevent overflowing will be particularly important. For instance, upstream sediment control facilities, flood fences for power stations, more robust banks and the relocation of powerhouses to raised areas can reduce the potential impact of floods.

The introduction of new technologies to hydropower operation and maintenance can enhance climate resilience. A digitalised system for data collection and monitoring can improve the quality of data and support better understanding of climate risks and impacts. Adopting smart technologies can support faster and more accurate detection of failure points; this could also enable automated and predictive maintenance, decreasing the possibility of unplanned outages.

Upstream management can help to enhance hydropower plant resilience. For example, building small dams upstream can help improve management of the increased water flow. Forestation around upstream catchments can also contribute to preventing landslides.

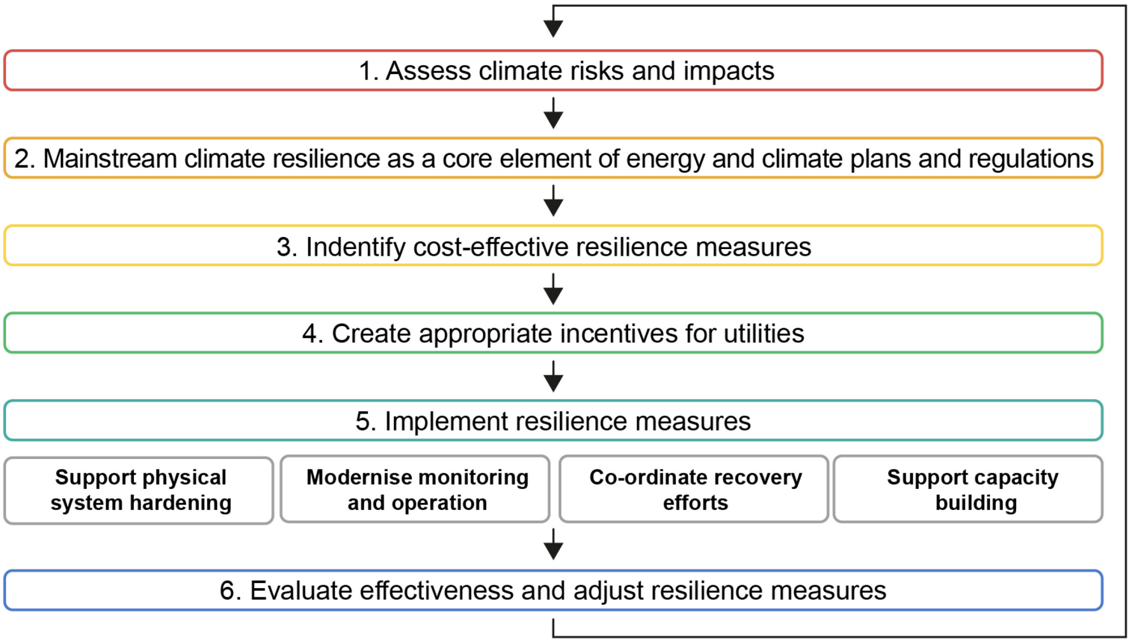
Policy recommendations

Policymakers have a critical role to play in building resilient hydropower systems by collaborating with businesses and adopting effective policy measures that can prevent potential market failure. The benefits of climate resilience and the costs of climate impacts tend to be distributed unevenly across the electricity value chain. This inevitably raises the question of who should be responsible for delivering resilience measures and paying for them.

Without government support and policy signals, multiple factors could limit utilities from aligning with adaptation needs. These include a lack of robust and available information on climate risks and impacts on hydropower, which limits the implementation of the most effective measures. There could also be lack of incentives to incorporate climate resilience in decision-making, as returns on investment occur in the medium- and long-term while the capital cost of implementation is incurred immediately. In addition, project developers and operators may not have the consideration for the overall social costs and benefits related to climate impacts, which tend to spread across the value chain and exceed gains or costs for generators and operators alone. Effective policy frameworks that capture the externalities of climate resilience and clarification of the roles and responsibilities are needed in order to promote actions and ensure sufficient investment in resilience.

It is therefore essential for governments and industries to collaborate and adopt effective measures to enhance climate resilience, including assessing climate risks and impacts, making climate resilience central to energy and climate plans, identifying cost-effective measures, creating appropriate incentives for utilities, implementing resilience measures efficiently, and conducting evaluation and measure adjustment for stronger effectiveness.

Figure 4.2 Sequential application of measures for climate resilience



Source: IEA (2021c), Climate Resilience.

Build robust climate data and strengthen climate impact assessments

Despite the increasing concern about the climate-related disruptions, information on climate data and projections for specific locations or events are still limited due to a lack of reliable data and the complexity of meteorological systems. For instance, there are still significant anomalies in observed glacier mass balances due to the lack of reliable data. The decline in the number of observation sites from 1991 after the Soviet Union collapsed, increased the uncertainty of the long-term climate estimates particularly at higher altitudes. There are also difficulties in making accurate climate projections for the South Asian summer monsoon due to their complex meteorological systems and sensitivity to variations.

Further development of robust data and comprehensive assessments of climate impacts are vital to building the necessary climate resilience of South and Southeast Asian hydropower plants. Several frameworks, guidelines and tools have been developed by governments, international organisations and academia to support and guide climate risk and impact assessment, such as the Hydropower Sector Climate Resilience Guide, developed by the International Hydropower Association. Collaborations among countries and international organisations have also supported assessments of climate impacts at the system and project levels. The MRC, for instance, released an assessment in 2018 on climate change impacts on hydropower production in the Mekong River basin in 2060 under nine climate scenarios, to inform sustainable hydropower development in the region.

Box 4.1 Power sector vulnerability assessment and resilience action plan of Lao People's Democratic Republic

In 2020, the United States Agency for International Development supported a power sector resilience planning process for Lao People's Democratic Republic, which relies on hydropower for 57% of its electricity generation. The process included a comprehensive vulnerability assessment and an action plan that proposes strategies to address the key vulnerabilities and increases the resilience of the country's power sector.

The analysis uses climate models to make climate projections and notes that despite variations among climate models, there is a clear trend and consensus on the climate change impacts for Lao PDR, mainly including "higher temperatures, longer dry seasons, severe and frequent rainfall, droughts, and floods (ADB 2017)". It underlines specifically that the hydropower sector "is vulnerable to existing extremes and variability in climate, and climate change modelling predicts that these extremes and variability may become more intense in the future under a range of greenhouse gas emission scenarios and pathways".

The vulnerability assessment identifies multiple natural hazards with medium-high likelihood for Lao PDR's power sector, including extreme precipitation, flooding, extreme temperatures and landslides. Taking into account also technological and human-caused hazards and the severity of potential impacts, the assessment highlights the 17 highest-risk vulnerabilities, including several strongly related to hydropower, such as dam construction not following design specifications, reservoir being too small for drought conditions, poor coordination between dam operators, but also heavy reliance on hydropower and lack of reliable or adequate meteorological, hydrological and climate change data for decision-making.

The vulnerability assessment supports prioritising actions to increase the resilience of the electricity system, many of which involve hydropower systems. These include developing climate projections and geospatial data for hydropower, strengthening data sharing and coordination across dam operations, improving the enforcement of dam design and construction codes, including planning for expected hazards, and measures facilitating better sedimentation management in hydropower watersheds.

Source: NREL (2020).

Box 4.2 India's Teesta-V Hydropower Station awarded 2021 IHA Blue Planet Prize

The IHA Blue Planet Prize for excellence in sustainable hydropower development was awarded in September 2021. During its assessment, NHPC Limited's 510 MW Teesta-V Project, located on the Teesta River in Sikkim, Northern India, met or exceeded international good practice standards across all 20 performance criteria using the Hydropower Sustainability Tools.

In 2019, the Teesta-V Hydropower Station was already rated as an example of international good practice in hydropower sustainability. It was reviewed by a team of accredited assessors using the Hydropower Sustainability Assessment Protocol (HSAP). Teesta-V was also the first hydropower project globally to publish results against new performance criteria covering its resilience to climate change and mitigation of carbon emissions, after the HSAP was expanded in scope in 2018.

Teesta-V exceeds basic good practice on "Climate Change Mitigation and Resilience". NHPC's 2018 Hydro-Meteorological Observation Manual provides methods for measuring climatic variables including precipitation, temperature, humidity, solar radiation and duration, wind and evaporation. A World Bank-funded project (National Hydrology Project) is currently installing a number of hydro-meteorological stations along the Teesta River which are likely to provide more data to the dam operators. That would give them the opportunity to change or update existing reservoir operational rules, taking climatic changes into consideration.

Regarding glacier lake outburst floods risk, except for the worst-case scenario when all glacial lakes in Sikkim burst at the same time, the Teesta-V dam is likely to survive all other scenarios. The study did not suggest that any lake outburst was imminent. The state government has access to an internationally run satellite-based glacier lake monitoring programme and an automated lake water level monitoring programme. Accessing this monitoring information would be helpful for Teesta-V in terms of taking emergency actions against any potential threats, as well as adopting long-term planning to enhance its resilience to climate change.

Integrate climate resilience as a key element in hydropower planning and construction as the region plans for considerable capacity expansion

As South and Southeast Asia seek to expand hydropower generation to meet their growing economic and energy needs, integrating climate resilience in new project planning and construction will be critical to ensuring project safety and sustainability, and to reducing potential damage, costs, and loss of life due to climate-related hydropower disruption. Recent incidents of damage to dams under construction (e.g., a glacial lake outburst flood in India's Tapovan Vishnugad Hydropower Project in 2021, heavy rainfall over Lao PDR's Xe-Pian Xe-Namnoy dam in 2018) demonstrate the importance of considering climate resilience from the initial stage of hydropower projects.

Governments can encourage developers and operators to integrate climate resilience in the early stages of hydropower project development. They can consider incorporating resilience standards into construction codes, and requiring developers to conduct project climate risk assessments, adaptation and emergency response plans. Project owners should also be encouraged to incorporate adaptability in project design, adopting resilience measures that allow for future adaptation if climate evolutions differ from expectations. For instance, Bhutan's Sustainable Hydropower Development Policy 2021 demands pre-feasibility studies and detailed project reports for hydropower projects to conform to international standards and best practices. In addition, the Bhutan Hydropower Guidelines 2018 stipulate that the potential impacts of climate change should be taken into account when estimating long-term water availability, with at least a sensitivity analysis based on previous studies in Bhutan and in the region, advising the use of several future scenarios to demonstrate sensitivity to various outcomes in terms of climate change.

Build climate resilience into hydropower operation and maintenance strategies

Hydropower plants typically have a long lifespan ranging from 30 to 80 years. As hydropower plants age, they are likely to become more vulnerable to risk triggers such as structural flaws, extreme floods and overtopping, landslides, internal erosion, and maloperation. Ageing could also increase the vulnerability of hydropower assets to climate change, as extreme weather events are likely to become more frequent and severe. Older assets could be particularly at risk if the designs were developed using historical and stationary climatic and hydrological data. Building climate resilience into hydropower operation and maintenance practices, in addition to plant design, is therefore crucial for the longevity of hydropower projects and securing the services they provide to the power system and society.

Governments can set guidelines or standards for project operators to establish climate resilience monitoring and adaptation processes into operation and maintenance plans, such as conducting regular collection of climate and hydrological information, risk assessment updates, evaluation of the effectiveness of adopted measures and clarification of responsibilities, thresholds and action plans for further adaptations. Operators could be encouraged to adopt more flexible operating regimes in response to variabilities, and to perform infrastructure hardenings such as enhancing reservoir and spillway capacity, landslide protection and sediment management.

India, one of the countries with the largest share of ageing hydropower plants in the region, has proactively responded to the need of hydropower modernisation. The Government of India has put a high priority on the renovation, uprating and life extension of old hydropower plants and announced that 17 hydroelectric plants would be modernised in 2017-2022 and other six during 2022-2027 under the Renovation & Modernisation of Hydro Power Stations programme. These efforts to build climate resilience into hydropower operation and maintenance will help Indian hydropower cope with the projected increase in the concentrated rainfalls and minimise the reduction in hydropower capacity factors.

Leveraging public and private investment will be important to finance the modernisation of ageing hydropower plants. As private investors may be reluctant to invest in plant upgrades due to uncertainties or lack of information on climate projections, or public ownership of certain hydropower assets, public financing can play a catalyst role by reducing project risk and sharing profit, such as by providing catalytic first loss capital through grants or other instruments, or adopting a Public Private Partnership (PPP) approach. For instance, the World Bank's Dam Rehabilitation and Improvement Project (DRIP-1) in 2012 supported Indian hydropower plants in improving the safety and sustainable performance of 223 existing dams in six states and one central agency. The Bank has recently approved a USD 250 million DRIP-2 which is envisaged to be implemented in around 120 dams so as to strengthen overall management, including by building dam safety guidelines and introducing a risk-based approach to dam asset management. This type of grant significantly increases the resilience of ageing hydropower plants while encouraging further investments from the private sector.

Box 4.3 The Malaysia Dam Safety Management Guidelines

Malaysia released the Malaysia Dam Safety Management Guidelines (MyDAMS) in 2017. They aim to provide detailed guidance for safety management over the lifecycle of dams (including for water supply, irrigation, hydropower, flood mitigation, water quality control, sediment retention and recreation) and bring them in line with internationally recognised practices.

MyDAMS sets out a hazard rating system taking into account the potential consequences of dam failure or mis-operation in terms of populations at risk, economic and infrastructure damage, and environmental and culture losses (such as damage to critical flora and fauna habitats or sites of cultural and historic value). It outlines the recommended dam management practices for dam design, construction, commissioning, maintenance, operation, safety surveillance, safety reviews, emergency preparedness, rehabilitation and decommissioning, as well as the roles and responsibilities of the key stakeholders such as dam owners, technical personnel, contractors and regulators.

MyDAMS recommends scenario and sensitivity analyses for establishing dam hazard rating and periodic re-evaluation each time the project is scheduled for inspection, or at least once every five years, so that hazard rating can be updated on the basis of factors such as changed reservoir or downstream development. The guideline notes that dam owners should understand the parameters within which the reservoir is to be operated for normal, unusual (e.g. floods) and extreme loading and operating conditions. Specific operation procedures for unusual, extreme and emergency conditions should be developed for dams with significant and higher hazard rating dams. MyDams states that dam upgrading is usually required following changes such as to upstream catchment, reservoir or standards that impact dam safety. Dam rehabilitation is required when the asset no longer meets an appropriate safety level. In parallel to releasing the guidelines, the Malaysian government also established a special committee to inspect existing dam infrastructure and stipulate maintenance works for high-risk dams.

Enhance regional cooperation to coordinate sustainable resource development and achieve mutual benefits

The South and Southeast Asia regions have many shared rivers and water systems across national borders, such as the Mekong River which runs through China, Myanmar, Lao PDR, Thailand, Cambodia and Viet Nam, and the Ganges-Brahmaputra-Meghna river basin that spreads across China, Bangladesh, Bhutan, Nepal and India. Therefore, one country's decision to build new hydropower projects can have impacts on the neighbouring countries, altering downstream water availability and the overall ecosystems. Meanwhile, sustainable and resilient development of hydropower could help to foster regional socioeconomic development, contribute to water, flood and drought management, and deliver co-benefits to sectors such as agriculture.

Regional cooperation is vital among countries with major shared water resources, in order to form strategies that are beneficial for all and to coordinate actions on water source development. South and Southeast Asia have prominent examples of regional cooperation on water resources such as the MRC and the Lancang-Mekong Cooperation Mechanism (LCM). The MRC has been contributing to climate resilience development in the region by providing technical support on data and climate impacts assessment, and helping mainstream climate adaptation in regional strategies. The LCM, which was established in 2016 based on the agreement among six countries (China, Cambodia, Lao PDR, Myanmar, Thailand and Viet Nam), has also bolstered the regional cooperation for water resource management. It announced a Joint Statement on Enhancing Sustainable Development Cooperation of the Lancang-Mekong Countries in June 2021, which demands extensive practical cooperation on basin planning, dam safety, emergency management and water-related risk and impact assessment, recognising the uncertainties brought by climate change. Further institutionalised cooperation and strengthening implementation mechanisms in South and Southeast Asia would support better coordination in the use of hydropower and water resources, addressing the growing concerns about climate change.

Box 4.4 The Mekong River Commission and sustainable hydropower development in the Lower Mekong River basin

The Mekong River Commission (MRC) is an intergovernmental organisation established in 1995 based on the Mekong Agreement between Cambodia, Lao PDR, Thailand and Viet Nam. It serves as a platform for regional dialogue and cooperation on sustainable development and management of water and related resources of the Lower Mekong River basin. The MRC works across water-related sectors and topics, such as fisheries, irrigation and agriculture, hydropower, navigation, flood and drought control and ecosystem conservation. China and Myanmar are Dialogue Partners of the MRC and participate in dialogue meeting, data and information sharing, joint studies and technical exchanges.

The MRC has developed various strategies, guidelines and studies to inform and facilitate decision-making and planning in the region, including several knowledge products on sustainable hydropower development. In recent years, the Commission released in 2018 a Basin-Wide Assessment of Climate Change Impacts on Hydropower Production to inform development of the Mekong Climate Change Adaptation Strategy and Action Plan, with recommendations on enhancing climate resilience of future dams and ancillary structures, and further studies on sedimentation effects and use of hydropower projects for adaptation purposes.

The Basin Development Strategy (BDS) 2020-2030, approved by the Council of Ministers from Cambodia, Lao PDR, Thailand and Viet Nam and released by the MRC in April 2020, identifies climate resilience as one of the five priority areas. The BDS plans for actions in strengthening network and systems for river monitoring, data management and sharing, flood and drought forecasting, supporting member countries to mainstream climate change adaptation in regional and national strategies and projects, and strengthening disaster management and resilience of water infrastructure operations (including by reviewing existing operating rules). Meanwhile, the BDS also notes that the overarching risk for the cooperation could lie in insufficient trust and a lack of capacity or implementation mechanisms, and stresses the importance of further strengthening cooperation among all basin countries and stakeholders, including with upstream countries such as China and Myanmar, as well as other regional cooperation mechanisms.

Annex: Methodology of the climate impact assessment

Scope

The assessment focuses on 13 South and Southeast Asian countries with the largest installed capacity of hydropower. The selected countries are arranged in four groups reflecting their climatic and geographic characteristics: Himalayan region (Bhutan and Nepal), Mainland Southeast Asia (Cambodia, Lao PDR, Myanmar, Thailand and Viet Nam), Maritime Continent (Indonesia, Malaysia and the Philippines) and Indian Subcontinent (India, Pakistan and Sri Lanka).

The total hydropower installed capacity in these 13 countries is over 116 000 MW, which accounts for 99% of the total installed capacity in South and Southeast Asia. India accounts for over 42% of the total hydropower installed capacity, followed by Viet Nam, Pakistan, Lao PDR and Malaysia.

The analysis covers over 490 hydropower plants equivalent to 100 000 MW, covering 86% of the total installed hydropower capacity in South and Southeast Asia. The assessment calculates the climate impacts on each hydropower plant, using each station's specific geographic coordinates. Each hydropower plant assessed in the study has a different level of capacity factors during the baseline period, depending on its location, size, type and other conditions. To present an integrated analysis of climate impacts on different hydropower plants, the study uses only relative values (% of changes compared to the baseline).

Share of selected hydropower plants in terms of hydropower installed capacity, by country

Countries	Number of selected plants	Installed capacity of selected plants [MW]	Total installed capacity [MW]*	Coverage
Bhutan	6	2326	2326	**100%**
Cambodia	8	1329	1329	**100%**
India	153	42049	50549	**83%**
Indonesia	41	5127	6121	**84%**
Lao PDR	19	6122	6275	**98%**
Malaysia	16	5990	7376	**81%**
Myanmar	22	3037	3331	**91%**
Nepal	71	1174	1278	**92%**

Pakistan	28	9808	9929	**99%**
Philippines	21	3584	4385	**82%**
Sri Lanka	33	1590	1809	**88%**
Thailand	17	3940	4512	**87%**
Viet Nam	58	14817	17111	**87%**
Total	**493**	**100893**	**116331**	**87%**

* Source: International Hydropower Association (2021), 2021 Hydropower Status Report

Models and data

High-resolution (15''x15'') global monthly discharge maps are developed by combining low-resolution (0.5˚x 0.5˚) monthly run-off data from each ensemble of General Circulation Models (GCM), Global Hydrological Models (GHM) and Representative Concentration Pathways (RCP) with high-resolution (15''x 15'') area accumulation and drainage direction maps available from the HydroSHEDS project (ISIMIP, Database; Gernaat et al., 2017; Lehner et al., 2008), and a low-resolution (0.5˚ x 0.5 ˚) map of monthly run-off.

The discharge maps were used to extract the design discharge and design load factors per hydropower plant (Gernaat, 2019). By ordering the discharge of a selected hydropower plant from the lowest to the highest month of discharge, a flow duration curve was generated. The value of the fourth-highest discharge month is called the design discharge and determines turbine capacity. The capacity factor is, by design, 100% for the four wettest months and less than 100% for the remaining eight drier months.

To analyse climate impacts on South and Southeast Asian hydropower, this report examined as many combinations of models as possible to enhance the reliability of results. It compared 60 different ensembles of five GCMs, four GHMs, and three RCPs to minimise the probability of misleading outcome and distortion by outliers. Since the outliers are often difficult to avoid due to the complexity of the climate system and the different assumptions within each model, this report compared and aggregated outcomes from various GCMs, GHMs and RCPs, and presented average annual and monthly capacity factors.

Overview of the GCMs, GHMs and RCPs considered in the assessment

General Circulation Models (GCM)	Global Hydrological Models (GHM)	Representative Concentration Pathways (RCP)
GFDL-ESM2M	H08	RCP 2.6
HadGEM2	LPJmL	RCP 6.0
IPSL-CM5	MPI-HM	RCP 8.5
MIROC-ESM	PCR-GLOBWB	
NorESM1		

General Circulation Models (GCM)

GFDL-ESM2M was developed by scientists at the Geophysical Fluid Dynamics Laboratory to make projections of the behaviour of the atmosphere, oceans and climate, using super-computer and data storage resources. The Laboratory has contributed to each assessment of the IPCC since 1990.

HadGEM2 stands for the Hadley Centre Global Environment Model version 2. The HadGEM2 family of models includes a coupled atmosphere-ocean configuration, with or without a vertical extension in the atmosphere to include a well-resolved stratosphere, and an Earth-System configuration which includes dynamic vegetation, ocean biology and atmospheric chemistry. Members of the HadGEM2 family were used in the IPCC Fifth Assessment Report.

IPSL-CM5 model is a full earth system model and the last version of the Institut Pierre Simon Laplace (IPSL) that is a consortium of nine research laboratories on climate and the global environment. Based on a physical atmosphere-land-ocean-sea ice model, it also includes a representation of the carbon cycle, the stratospheric chemistry and the tropospheric chemistry with aerosols. The IPSL-CM5 model contributed to the modelling for the IPCC Fifth Assessment Report.

MIROC-ESM was developed by the Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies.

NorESM1 is the first version of the Norwegian earth system model. It has been applied with medium spatial resolution to provide results for the modelling for IPCC Fifth Assessment Report. It provides complementary results to the evaluation of possible anthropogenic climate change.

Global Hydrological Models (GHM)

H08 is a grid-cell based global hydrological model developed by the National Institute for Environmental Studies of Japan. It consists of six sub-models, namely land surface hydrology, river routing, reservoir operation, crop growth, environmental flow and water abstraction.

LPJmL is a dynamic global vegetation model with managed land use and river routing. It is managed by the Potsdam Institute for Climate Impact Research. It is designed to simulate vegetation composition and distribution as well as stocks and land-atmosphere exchange flows of carbon and water, for both natural and agricultural ecosystems.

MPI-HM is a global hydrological model developed by the Max Planck Institute to investigate hydrological research questions mostly related to high-resolution river routing. While hydrological processes are implemented in similar complexity as in full land surface models, the MPI-HM does not compute any energy-related fluxes.

PCR-GLOBWB is a grid-based global hydrology and water resources model developed at Utrecht University. The computational grid covers all continents except Greenland and Antarctica. It simulates moisture storage in two vertically stacked upper soil layers, as well as the water exchange between the soil, the atmosphere and the underlying groundwater reservoir. The exchange with the atmosphere comprises precipitation, evaporation from soils, open water, snow and soils and plant transpiration, while the model also simulates snow accumulation, snowmelt and glacier melt.

Representative Concentration Pathways (RCP)

The IPCC Fifth Assessment Report defines RCPs as scenarios that include time series of emissions and concentrations of the full suite of GHGs and aerosols and chemically active gases, as well as land use/land cover (Moss et al., 2008). The word *representative* signifies that each RCP provides only one of many possible scenarios that leads to the specific radiative forcing characteristics. In the IPCC Fifth Assessment Report, four RCPs are presented: RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5. The RCPs show various representative GHG concentration trajectories and the impact of each level of GHG concentration on the future climate.

The IPCC Sixth Assessment Report use Shared Socioeconomic Pathways (SSPs), which show how societal choices will affect GHG emissions and how the climate goals of the Paris Agreement could be met. SSPs are expected to fill the missing pieces of socioeconomic narratives in RCPs, looking at five different ways in which the world might evolve in the absence of climate policy and how different levels of climate change mitigation could be achieved when the mitigation targets of RCPs are combined with the SSPs. However, this report decided to use RCPs instead of SSPs, given that more data resources are available for RCPs rather than SSPs across various GCMs and GHMs. This impact assessment could be updated in the near future reflecting the new trajectories of SSPs.

This report developed three scenarios based on three different RCPs. Each of them leads to a different global average temperature outcome: Below 2°C, Below 3°C and Above 4°C, respectively. By comparing these three scenarios, the report aims to present how greenhouse gas (GHG) concentrations are likely to affect hydropower generation in South and Southeast Asia.

The **Below 2°C** scenario is based on the projections of the RCP 2.6 that assumes a radiative forcing value of around 2.6 W/m2 in the year 2100. Under the Below 2°C scenario the rise in global annual mean temperature stays below 2°C by 2100 compared to pre-industrial times (1850-1900). For the period 2080 to 2100, the global annual mean temperature increases by 1.6(±0.4) °C above the level of 1850-1900. The Below 2°C scenario assumes an early peak in global GHG emission trends followed by a drastic decline.

The **Around 3°C** Scenario follows the trajectory of the RCP 6.0 that assumes a radiative forcing value of around 6.0 W/m2 in the year 2100. The Around 3°C Scenario is associated with a rise of 2.8 (±0.5) °C in the global annual mean temperature for the period 2080 to 2100 compared to the pre-industrial level. The Around 3°C Scenario is based on the assumption of stabilisation of total radiative forcing after 2100. Under this scenario, global GHG emissions would peak during the latter half of the century and then decline.

The **Above 4 °C** scenario is based on the high-emission trajectory, RCP 8.5, which assumes the absence of additional effort to mitigate GHG emissions. The Above 4°C scenario is associated with a radiative forcing value of around 8.5 W/m2 in the year 2100 and a rise by 4.3(±0.7) °C in global annual mean temperature for the period 2080 to 2100 compared to the pre-industrial level. Under the Above 4°C scenario, global GHG emission does not reach its peak before 2100.

Overview of the scenarios

Scenario	Below 2°C	Around 3 ° C	Above 4°C
Representative Concentration Pathway	RCP 2.6	RCP 6.0	RCP 8.5
Targeted radiative forcing in the year 2100	2.6 W/m^2	6.0 W/m^2	8.5 W/m^2
CO_2-equivalent concentrations (ppm)	430-480	720-1000	>1000
Global temperature change	1.6(±0.4)°C	2.8(±0.5)°C	4.3(±0.7)°C
Likelihood of staying below a specific temperature level over the 21st century	Likely to stay below 2°C	More unlikely than likely to stay below 3°C	More unlikely than likely to stay below 4°C

Source: IPCC (2014), Climate Change 2014 Synthesis Report.

Abbreviations and acronyms

AIIB	Asian Infrastructure Investment Bank
ASEAN	Association of Southeast Asian Nations
BBIN	Bangladesh, Bhutan, India and Nepal
BDS	Basin Development Strategy
CMIP5	Coupled Model Intercomparison Project Phase 5
CO_2	carbon dioxide
GCM	General Circulation Models
GHG	greenhouse gas
GHM	Global Hydrological Models
GLOF	Glacial Lake Outburst Flood
IHA	International Hydropower Association
IPCC	Intergovernmental Panel on Climate Change
Lao PDR	Lao People's Democratic Republic
LCM	Lancang-Mekong Cooperation Mechanism
MRC	Mekong River Commission
PPP	Public Private Partnership
RCP	Representative Concentration Pathways
SDG	Sustainable Development Goal
SDS	Sustainable Development Scenario
SSP	Shared Socioeconomic Pathways
STEPS	Stated Policies Scenario

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