

Climate Impacts on Latin American Hydropower



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Abstract

Hydropower is the main source for electricity generation in Latin America, accounting for 45% of the total electricity supply from the region. By 2040, it is likely to remain significant or potentially increase, supporting the achievement of Sustainable Development Goals and carbon emissions reduction in the energy sector. However, climate change poses an increasing challenge to Latin American hydropower with rising temperatures, fluctuating rainfall patterns, melting glaciers, and increasing occurrence of extreme weather events. This report aims to support Latin American hydropower in coping with the adverse impacts of climate change and 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 Latin American hydropower and examines potential climate impacts quantitatively, 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 Latin America, hydropower is the main source for electricity generation in most countries, accounting for 45% of the total electricity supply from the region. By 2040, it is likely to remain significant or potentially increase, supporting the achievement of Sustainable Development Goals and carbon emissions reduction in the energy sector.

However, climate change poses an increasing challenge to Latin American hydropower with rising temperatures, fluctuating rainfall patterns, melting glaciers, and increasing occurrence of extreme weather events. These changes consequently affect hydropower generation by increasing variability in streamflow, shifting seasonal flows, and augmenting evaporation losses from reservoirs. Given that hydropower plants, which usually operate for multiple decades, are likely to be affected by climate change during their lifespan, a comprehensive assessment of climate impacts is needed.

This report assessed climate impacts on over 86% of the hydropower installed capacity of Latin America, focusing on 13 countries with the largest hydropower installed capacity. The assessment is based on three different scenarios: Below 2°C, Below 3°C and Above 4°C. Each of these scenarios represent 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, comparing the projected results against the values of the baseline period from 1970 to 2000.

The assessment shows that, 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 over the period from 2020 to 2059 is likely to decrease by around 8% on average (from 7.5% in the Below 2°C scenario to 9.6% in the Above 4°C scenario), compared to the baseline level of 1970-2000. Between 2060 and 2099, the regional mean hydropower capacity factor is projected to be lower than the baseline by over 11% on average (from 7.5% in the Below 2°C scenario to 17.4% 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 Latin America. In the Above 4°C scenario, which assumes a continuous increase in GHG emissions, there could be a starker decrease in the regional mean hydropower capacity factor for the rest of 21st century than the

other scenarios. In addition, a higher GHG concentration is likely to exacerbate the inter-annual variability in hydropower capacity factors in some sub-regions such as Central America and Mexico, and Southern South America.





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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 Latin America, exposing some plants to climate change more than others.

The climate projections included in this analysis show that two sub-regions, Central America and Mexico (Mexico, Costa Rica, Panama and Guatemala) and Southern South America (Argentina and Chile), would see a consistent decrease in mean hydropower capacity factors due to the decline in mean precipitation and runoff. However, the Andean region along the northwest coast of South America (Colombia, Ecuador and Peru) is projected to see a slight increase in hydropower capacity factor with increasing precipitation and runoff volume on average. For the rest of South America (Brazil, Venezuela, Paraguay and Uruguay), a comparatively mild decrease

in hydropower capacity factor is expected, although further studies are needed given the lack of agreement among climate models for future conditions in this sub-region.



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



To anticipate, absorb, accommodate and recover from adverse climate impacts, Latin American hydropower needs to enhance its climate resilience. Climate-resilient hydropower systems can bring multiple benefits not only to clean energy transition but also to sustainable water management. Hydropower can support the shift to lowcarbon electricity technology in Latin America, providing power system flexibility for further deployment of variable renewable energy sources, such as wind and solar. In addition, climate-resilient hydropower with a multipurpose water storage capacity can bring benefits to water management, acting as a storage buffer against increasing water variability due to climate change, and providing reliable water supply for irrigation and drinking.

To minimise the adverse impacts of climate change on Latin American hydropower, 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.

Executive summary

The following **policy recommendations** show how governments can contribute to enhancing the climate resilience of Latin American hydropower:

• Mainstream climate resilience as a core element of energy and climate policies.

Governments can send a strong signal to service providers and developers by mainstreaming climate resilience in their national policies and adopting supportive regulations. Although significant progress has been made in incorporating the climate resilience of hydropower in some countries, this varies considerably across Latin America. Among the selected 13 countries, only 6 countries have included climate impacts on hydropower and suggested actions in their national adaptation plans. Countries that are relying heavily on hydropower are recommended to consider climate impacts on hydropower in their national adaptation plane.

• Mobilise investment in modernisation of ageing hydropower plants.

Over 50% of the installed capacity in Latin America is over 30 years old. Ageing hydropower plants are expected to require modernisation to cope with the projected increase in extreme precipitation events, in addition to general rehabilitation. However, access to financing for modernisation of hydropower plants is often considered a substantial barrier. Public investment and the provision of financial risk coverage instruments by public financing institutions can catalyse private financing.

• Build and strengthen climate risk insurance.

Although utilities have a direct interest in insuring their assets against the adverse effects of climate change, they may be reluctant to pay a high cost for insurance. Moreover, their insurance could be limited to cover the damage to physical assets and lost revenue, rather than cover the broader damage to society and economy. An accessible and affordable climate risk insurance for hydropower infrastructure supported by governments or public institutions will significantly improve preparedness against climate hazards while helping to avoid excessive financial burdens on utilities.

• Support scientific research to increase the accuracy of climate projections.

Comprehensive and scientific projections of climate risks and the impacts on hydropower generation are essential to identifying the most effective set of resilience measures for hydropower plants. However, climate models often present a low agreement about future precipitation and runoff in certain parts of Latin America. To minimise these disparities and improve the accuracy of climate projections, governments are encouraged to support scientific research on future climate patterns and their impacts, increase access to national climate data sources, consistently update information systems, develop guidelines and provide financial support for climate research.

Chapter 1. Introduction

Hydropower is the largest source of electricity generation in Latin America.

Hydropower is the largest source of low-emissions electricity worldwide today. According to the <u>IEA Stated Policies Scenario (STEPS</u>), it is expected to maintain this status until 2030, while providing flexibility and other power system services, integrating and balancing variable renewable energy sources.

In Latin America, hydropower is the main source for electricity generation in most countries, accounting for 45% of the total electricity supply from the region. The total hydropower installed capacity in Latin America was 196 GW in 2019, of which 176 GW was from South America and the rest from Central America and Mexico. Because of this significant contribution of hydropower, Latin America has been the region with the largest share of electricity generation renewables. In Latin American countries where over 70% total electricity generation is from renewables (Paraguay, Costa Rica, Uruguay, Brazil, Panama, Ecuador and Colombia), hydropower provides the biggest share, ranging from 50% in Uruguay to 100% in Paraguay.

The role of hydropower in Latin America is likely to remain significant or potentially increase. <u>The IEA World Energy Outlook</u> projects that under a continuation of stated policies, the share of hydropower in the power sector would stay at its current level (Stated Policies Scenario) or increase to achieve sustainable energy objectives in full (Sustainable Development Scenario) by 2040.

Climate change will have increasing impacts on hydropower generation in Latin America

Climate change impacts on temperature and precipitation patterns could pose a challenge to hydropower generation in Latin America by increasing the variability in streamflow, shifting seasonal flows and augmenting evaporation losses from reservoirs. Rising temperatures, fluctuating rainfall patterns and the increase in extreme weather events have major impacts on streamflow and water availability, consequently affecting hydropower generation.

<u>Climate projections</u> show an increasing variability and probability of extreme precipitation events, which can result in heavy rainfall, floods and droughts by the

end of this century. <u>An increase in heavy precipitation</u> is projected for many areas of Latin America, although there are projected negative trends in some locations as well. <u>Some studies</u> project intense droughts during the 21st century in regions like Amazonia and northeast Brazil. El Niño-Southern Oscillations (ENSO) could exacerbate these extreme regional precipitation events. The increased probability of extreme precipitation events will consequently <u>increase risks to hydropower</u> <u>generation</u> by altering water availability, increasing sediments or causing physical damages to assets.

To minimise the adverse impacts of climate change on Latin American hydropower, 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. A resilient hydropower system can accelerate clean energy transitions while providing adaptation benefits.

This report aims to help improve the resilience of hydropower in Latin America by providing qualitative and quantitative analyses of climate risks and impacts and by introducing potential resilience measures. First, it qualitatively assesses the climate risks to Latin American hydropower based on three dimensions: hazard, exposure and vulnerability (Chapter 2). Second, it examines the potential climate impacts on Latin American hydropower quantitatively, comparing three climate scenarios (Chapter 3). Finally, Chapter 4 presents examples of measures to enhance climate resilience and suggests policy recommendations.

Chapter 2. Climate risks to Latin American 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 <u>hazard, exposure and vulnerability</u>.

- Hazard refers to the potential occurrence of physical impact 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 framework to effectively describe the issues resulting from climate change. 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

Spatial variations in the trends of temperature and precipitation will pose different levels of risks to Latin American hydropower

Climate change in the trends of temperature and precipitation could increase the level of hazard for Latin America hydropower. Rising temperatures, fluctuating rainfall patterns, melting glaciers, and increasing occurrence of extreme weather events such as floods and droughts have major impacts on the streamflow and water availability, which will consequently affect hydropower generation.

Observations and projections show that climate hazards are expected to be unequally distributed across Latin America. For instance, some regions might be more affected by increased aridity at the end of the 21st century, while others might experience a significant increase in heavy precipitation. Spatial variations in temperature and precipitation trends will lead to differing climate hazards for hydropower generation in Latin America.

Although there is broad consensus that temperature will increase across Latin America, the magnitude of warming is likely to vary depending upon location. According to the <u>IPCC Fifth Assessment Report</u>, a temperature rise in Central America and Mexico, compared to the mean of 1986-2005, could reach approximately 4.0 °C by the late 21st century under a high greenhouse gas (GHG) concentration scenario, while it may exceed 5.0 °C in inland South America.

Spatial variation is also observed in precipitation patterns. Some regional trends have been identified although in some cases the variance between the models of future precipitation patterns still exists due to underlying climate uncertainties and inconsistent observation trends in certain parts of Latin America.

Central America and Mexico, and a large part of Chile and Argentina (from the Central Andes and Patagonia) are projected to see <u>a consistent reduction in precipitation and runoff</u> over the coming century, which would consequently have negative implications to hydropower generation. Similarly, <u>overall reductions to hydropower</u> <u>generation</u> are also expected from Chile for the main hydropower generation river basins and from the Argentinean Limay River basin due to a decrease in precipitation and runoff.

Conversely, coastal regions of Andean countries, such as <u>Peru, Ecuador and</u> <u>Colombia</u>, are projected to have <u>more rainfall</u>. For example, in Colombia the annual average rainfall is <u>projected to increase</u> from 0.8% to 1.6% overall, although some areas of Colombia could suffer from <u>decreasing precipitation</u>. An increment in precipitation in the <u>Paute River basin of Ecuador</u> would lead to an increase in hydropower generation capacity.

In the rest of South America, climate models present marked disparity in climate and hydrological projections. For instance, future climate patterns in Brazil are still highly uncertain. An assessment of various climate models shows that climate change projections have a wide spread and <u>data from several models</u> provides a disparate rainfall variance ranging from between +40 mm to -38 mm across the country. For southeast Brazil, different models calculated a vague <u>precipitation pattern</u> between -30% to +30%. And for the <u>Amazon in Brazil</u>, the latest results from CMIP6 models anticipate less precipitation and decreasing runoffs under a high GHG concentration scenario (RCP 8.5), while previous CMIP5 models forecast a wetter climate. This spatial variation in precipitation patterns could add complexity to climate projections. <u>A study</u> compared four scenarios based on two General Circulation Models (Eta-HadGEM2-ES and Eta-MIROC5) and two GHG concentration scenarios (RCP 4.5 and 8.5) point to a reduction in rainfall volume and inflows in the north-central portion of Brazil and a slight increase in southern region of the country.

More frequent extreme precipitation events may add risks to hydropower generation in Latin America

Climate projections show an increased probability of extreme precipitation events such as heavy rainfall, floods and droughts across the world, which will consequently increase risks to hydropower generation by altering water availability, increasing sediments, or making physical damages to assets. Some areas of Latin America are likely to experience more frequent extreme precipitation events, although there will be a significant spatial variation.

In many areas of Latin America, an increase in extreme precipitation events has been observed. According to the IPCC's Fifth Assessment Report, Latin America has observed positive trends in the intensity of heavy rainfall in many areas, while some locations have seen negative trends. Historical records between 1961 and 2003 show that the maximum amount of 1-day-rainfall in Central America and northern South America significantly increased. In Colombia, the number of climate disasters and the intensity of extreme weather events have <u>increased</u>, with 90% of disasters associated with hydrometeorological phenomena in the last 50 years. In Peru, 72% of total national emergencies were related to hydrometeorological threats such as droughts, heavy rainfall and floods.

<u>Climate models</u> project that many parts of the region are likely to experience more extreme precipitation events, although their types and intensities may significantly

vary between locations. By the end of 21st century, the number of heavy precipitation events are projected to increase in some places such as the Amazon, south-eastern South America and the west coast of South America, while a higher level of dryness is expected in other places, including Central America, Mexico, northeast Brazil and south-western South America. Some country case studies also forecast more frequent extreme precipitation events. Colombia is expected to experience more frequent extreme rainfall days by 26-36% by 2050 compared to 1986-2015, while Chile is projected to experience more extreme events by over 10 times in the next 30 years.

<u>El Niño-Southern Oscillations (ENSO)</u> could exacerbate these extreme precipitation events, although there are <u>ongoing debates</u> on how anthropogenic climate change and ENSO interact. ENSO is a large-scale natural fluctuation of ocean surface temperatures in the equatorial Pacific, coupled with changes in the overlying atmospheric circulation. The warm phase, which is known as El Niño, and the cold phase, La Niña, significantly affect temperature and precipitation in Latin America. <u>The 2015-16 El Niño phenomenon</u>, <u>one of the three strongest</u> El Niño events since 1950, led to <u>one of the worst droughts</u> in Mexico and Central America, where precipitation and runoff were already declining due to climate change. At the same time, the El Niño phenomenon prompted widespread flooding in Peru and Ecuador, where climate change had created a wetter climate.

Since the effects of ENSO vary every year, it is often considered as <u>one of the</u> <u>main causes</u> of marked inconsistency in precipitation projections in South America. As modelling improves, biases in ENSO would be reduced while <u>increasing the</u> <u>accuracy</u> of future streamflow and hydropower generation projections.

Exposure

A heavy reliance on hydropower in Latin America could raise a concern about its exposure to climate change

In Latin America, hydropower is the main source for electricity generation in most countries. Hydropower accounts for over 45% of total electricity generation of Latin America and generated 745 000 GWh in 2018. <u>The total installed capacity</u> in Latin America was 196 GW in 2019, of which 176 GW was from South America and the rest from Central America and Mexico. In countries such as Panama, Ecuador and Paraguay, <u>hydropower's share</u> of electricity generation exceeds 70%.

The role of hydropower in Latin America is likely to remain significant or potentially increase. According to the IEA's <u>Renewables 2020</u>, hydropower additions in Latin

America are expected to be stable during the next five years (2021-25) at 2 GW per year. More than half of the growth in 2021-25 will result from large reservoir projects in Colombia and Argentina, with small-scale hydropower projects in Brazil. The IEA's <u>World Energy Outlook</u> projects that under a continuation of stated policies, the share of hydropower in the power sector would stay at the current level (Stated Policies Scenario) or increase to achieve sustainable energy objectives in full (Sustainable Development Scenario) by 2040.

Already in 2019 significant hydropower capacity was added in Latin America. South America saw <u>the fastest hydropower growth rate</u> and became the region with <u>the second highest capacity</u> added in the world. Brazil alone added <u>4 919 MW hydropower capacity</u>, which was mainly attributed to the completion of the 11 233 MW Belo Monte hydropower plant.

A strong reliance on hydro for electricity generation in Latin America often raises a concern about its exposure to the adverse impacts of climate change. Hydropower is expected to remain significant in mitigating climate change as the largest source of low-emissions electricity by 2030. However, the impacts of climate change could disturb the <u>operation of hydropower</u> by increasing variability in streamflow, shifting seasonal flows and augmenting evaporation losses from reservoirs. Given the presence of a large hydropower capacity in the region and its exposure to climate change, proper measures to enhance resilience to the adverse impacts of climate change are needed.

Vulnerability

Ageing hydropower plants can be more vulnerable and require further efforts to reduce climate risks

Over 50% of the installed capacity in Latin America is <u>over 30 years old</u>. In Mexico, most hydropower plants are <u>older than 50 years</u>. Given the <u>limited availability of</u> <u>capital</u> and <u>increasing environmental constraints</u> for new hydropower projects across the region, an extended lifetime of existing hydropower plants is likely to become common practice in Latin America. For instance, the typical average technical lifetime of a hydropower facility in Peru is estimated to be <u>between 81 and</u> <u>104 years</u>, which is longer than <u>a usual lifespan of hydropower</u>, 30 to 80 years.

<u>Ageing of hydropower assets</u> in Latin America drives the trend to modernise the hydropower fleet. According to <u>a recent study</u> by the Inter-American Development Bank (IDB) and International Hydropower Association (IHA), 20 stations with an

installed capacity of 15 GW out of 127 GW are older than 20 years in Latin America and the Caribbean and are in high, urgent need of modernisation.

Ageing hydropower plants need rehabilitation and upgrades to cope with the projected increase in the frequency of extreme precipitation events, in addition to their general rehabilitation needs. Larger flows of debris, suspended solids and sediments <u>due to extreme precipitation events</u> can accelerate equipment ageing. Hydropower plants that cannot withstand increasing extreme precipitation events could make the entire electricity system fragile, augmenting possibilities of disruptions in electricity supply. The modernisation of ageing hydropower facilities, such as upgrading spillway capacities, replacing equipment and increasing dam safety, will reduce their exposure to future climate hazards and help these facilities adapt to new climate conditions.

Box 2.1 Modernisation and upgrades of Callahuanca hydropower plant

The 82 MW <u>Callahuanca hydroelectric power plant</u> in Peru was commissioned in 1938. When multiple landslides and flooding hit Callahuanca hydropower plant at the beginning of 2017, it was almost 80 years old. Landslides caused by torrential rains severely damaged 95% of the total infrastructure and equipment, including a severe impairment of the powerhouse and breakdown of protection systems. Callahuanca hydropower plant shut down <u>causing blackouts</u> in some areas of Peru.

The modernisation of Callahuanca hydropower consisted of <u>rehabilitation and</u> <u>upgrading activities</u> to address heavy rainfall and floods. It included reconditioning three generators and turbines and the installation of a new generator. A new automation and control system was installed. In addition, a new contention wall was constructed next to the river to protect the station from similar events. In 2019, Callahuanca hydropower plant restarted operations after two years of rehabilitation.

Source: Andritz Hydro GmbH, Bring Back to Life; CONELSUR (2018), Reconstrucción de la subestación Callahuanca 220/60 kV fortalecerá el sistema de transmisión eléctrico del país.

Increasing competition over water use and deforestation makes Latin American hydropower more vulnerable to climate change

Increasing competition over water resources will likely increase the vulnerability of Latin American hydropower by making it more sensitive to water availability. By 2050, it is estimated that global water demand in terms of water withdrawals for energy

generation, manufacturing and domestic use will <u>increase up to 55%</u> on average. In fact, when a drought hit southeast Brazil in 2014, the shortage of water created conflicts between different users. The <u>drought</u> affected hydropower generation, urban supply and wastewater treatment until it was finally settled by an agreement among sectors.

In addition, a rapid increase in deforestation in Latin America could augment hydropower's vulnerability to climate change by lowering the level of adaptive capacity. Healthy forests anchor soil against erosion and prevent sediment from flowing into streams. The role of forests is particularly important for countries where a significant increase in precipitation is expected. For instance, the recent trends of deforestation for agriculture and urbanisation in Colombia, Peru and Ecuador could increase hydropower plants' vulnerability to climate change, exacerbating soil erosion and runoff, and affecting sedimentation. According to the OLADE's simulation in the pilot basins of these countries, adaptation measures such as reforestation and agroforestry can significantly reduce the volume of sediment in cases of extreme weather events while having a minimal or no impact on the volume of electricity generation. Overall, climate change could decrease dry season hydropower potential by 430-312 GWh per month (-7.4 to -5.4%), while the combined effects of deforestation could increase interannual variability from 548 to 713-926 GWh per month (+50% to +69%). To avoid further deforestation, some Latin American countries including Mexico, Costa Rica, Ecuador, Brazil and Colombia have implemented Payment for Ecosystem Services (PES) programmes.

Chapter 3. Climate impacts on Latin American hydropower

What is climate impact?

Climate impacts are the actual consequences of climate change

Hydropower plants operate <u>for multiple decades</u>, sometimes even beyond 100 years, and as such are likely to be <u>impacted by climate change</u> 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. Projected water shortage <u>due to melting glaciers</u> along with droughts could affect hydropower generation in regions where hydropower plants rely heavily on glacier water. Changes in precipitation will also alter potential, generation output, peak level and seasonal variations of hydropower. Erratic precipitation patterns could lead to water scarcity and concerns over interrupted hydropower generation. For instance, the electricity supply in Venezuela was interrupted <u>in 2016 and 2018</u>, due to a low water level in hydroelectric dams triggered by a severe droughts. Similarly, Brazil almost entered into <u>electricity rationing</u> when the inflows into the hydropower reservoirs in the Southeast and Northeast regions reached their lowest levels in February 2014 and January 2015 since the records began in 1931.

More frequent extreme weather events such as cyclones or floods and their consequences, such as landslides, can also damage hydropower assets and disrupt electricity supply. For instance, large landslides after heavy precipitation events in 2017 prompted a shutdown of the Callahuanca hydropower plant in Peru.

Methodology

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

To analyse climate impacts on Latin American hydropower, this report examined as many combinations of models as possible to enhance the reliability of results. It compared 60 different ensembles of five General Circulation Models (GCM), four Global Hydrological Models (GHM), and three Representative Concentration Pathways (RCP), aiming 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.¹

Annual and monthly capacity factors per hydropower plant were mainly derived from a high-resolution global discharge map $(15" \times 15")$ that combines low-resolution $(0.5^{\circ} \times 0.5^{\circ})$ monthly run-off data with high resolution $(15" \times 15")$ area accumulation and drainage direction maps available from HydroSHEDS. These discharge maps were used to extract the design discharge and design load factors per 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 on the selected models and methodology is described in the <u>Annex</u>.

This report assesses climate impacts on hydropower generation by the end of this century in 13 Latin American 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 period from 1970 to 2000. The baseline period was selected reflecting the maximum availability of historical climate records.

The assessment focuses on 13 Latin American countries with the largest installed capacity of hydropower. The selected countries consist of four groups reflecting their climatic characteristics: Central America and Mexico (Mexico, Costa Rica, Panama and Guatemala), Andean region (Colombia, Ecuador and Peru), Southern South America (Argentina and Chile) and the rest of South America (Brazil, Venezuela, Paraguay, and Uruguay).

¹ Although the capacity factor of hydropower plants is a useful indicator to measure climate impacts on hydropower generation, it is not an exclusive attribute. Further studies on other factors (e.g., cascading impacts of climate change between neighbouring hydropower plants and river basins) and the impacts of various adaptation and mitigation measures would enable a more comprehensive assessment of climate impacts.

The total hydropower installed capacity in these 13 countries is over 193 000 MW, which accounts for 98% of total installed capacity in Latin America. Brazil provides over 55% of the total hydropower installed capacity, followed by Venezuela, Mexico, Colombia and Argentina. Given Brazil's large share of total Latin American hydropower installed capacity, the installed capacity from the 13 countries varies from 9% for Central America and Mexico to 70% for the rest of South America.



Figure 3.1 Total hydropower installed capacity by countries, 2019

This report assesses climate impacts on over 370 hydropower plants, which accounts for 87% of the installed hydropower capacity in 13 Latin American countries. It covers over 168 000 MW, accounting for 86% of the total installed hydropower capacity in Latin America. The selected hydropower plants have various sizes of installed capacity: 20% of them are small hydropower plants with an installed capacity of less than 20 MW, while 62% are 20-500 MW and 18% are over 500 MW. The assessment calculates climate impacts on each hydropower plant, using each station's specific geographic coordinates.



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

This report selected three scenarios and each of them leads to a different global average temperature outcome: Below 2°C, Below 3°C and Above 4°C, respectively by 2100. By comparing these three scenarios, the report aims to present how GHG concentrations are likely to affect hydropower generation in Latin America.

These scenarios are based on the RCP of the Coupled Model Intercomparison Project Phase 5 (CMIP5) of the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report.² 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/m2 in the year 2100. In the Below 2°C scenario, the increase 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 (\pm 0.4) °C above the

² The three scenarios were chosen from the existing four RCPs—RCP2.6, RCP4.5, RCP6.0, and RCP8.5. RCP2.6, RCP4.5 and RCP8.5 were selected because these three represent similar radiative forcing levels to the ones from the proposed scenarios for the IPCC Sixth Assessment Report. The Below 2°C scenario represents a pathway with a substantial effort for reducing GHG emissions, while the Below 3°C scenario describes a stabilisation scenario. The Above 4 °C scenario represents a high emission trajectory. This report uses these three scenarios to present distinctive pathways without assuming a certain scenario as default or baseline.

level of 1850-1900. The Below 2°C scenario assumes an early peak in global GHG emission trends followed by a drastic decline.

The **Below 3°C** scenario follows the trajectory of the RCP 4.5 that assumes a radiative forcing value of around 4.5 W/m² in the year 2100. The Below 3°C scenario is associated with a rise by 2.4 (\pm 0.5) °C in global annual mean temperature for the period 2080 to 2100 compared to the pre-industrial level. The Below 3°C scenario assumes a peak in global GHG emission trends by mid-century that subsequently declines.

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.

Table 3.1 Overview of the scenarios

Scenario	Below 2°C	Below 3°C	Above 4°C
Representative Concentration Pathway	RCP 2.6	RCP 4.5	RCP 8.5
Targeted radiative forcing in the year 2100	2.6 W/m ²	4.5 W/m ²	8.5 W/m ²
CO ₂ -equivalent concentrations (ppm)	430-480	580-720	>1000
Global temperature change	1.6 (±0.4) °C	2.4 (±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	Likely to stay below 3 °C	More unlikely than likely to stay below 4 °C

Source: IPCC (2014), Climate Change 2014 Synthesis Report, https://www.ipcc.ch/report/ar5/syr/.

Key results

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

A lack of agreement on future climate and hydrological conditions in certain areas of Latin America sometimes create a gap between the results from 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 trends on which a majority of models could agree.

The examined sets of models from all three scenarios show that, from now through the end of the century, mean hydropower capacity factor from the assessed plants is projected to decrease due to changing climate conditions. The regional mean capacity factor over the period from 2020 to 2059 is likely to decrease in most of the examined sets of models, by around 8% on average (from 7.5% in the Below 2°C scenario to 9.6% in the Above 4°C scenario), compared to the baseline level from 1970-2000. The regional mean hydropower capacity factor is projected to be lower than the baseline in the latter 40 years of the century in all examined model sets, although the size of decrease varies among scenarios. Between 2060 and 2099, the regional mean hydropower capacity factor is projected to be lower than the baseline by over 11% on average (from 7.5% in the Below 2°C scenario).

The projected decline in hydropower capacity factor could have negative implications to electricity security in Latin America, given the prominence of hydropower as a source for electricity generation. Currently, hydropower accounts for over 50% of electricity generation in Costa Rica, Peru, Brazil, Uruguay and Venezuela, and exceeds 70% in Panama, Ecuador and Paraguay.



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

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A comparison of results from three different GHG concentration scenarios shows that GHG emissions reduction is key to minimise the negative impacts of climate change on Latin American hydropower. The results show that a higher GHG concentration will have stronger negative impacts on hydropower generation in Latin America. In the Above 4°C scenario, which assumes a continuous increase in GHG emissions, there could be a starker decrease in the regional mean hydropower capacity factor for the rest of 21st century than the other scenarios. The hydropower capacity factor is expected to drop by 9% in 2020-2060 and 17% in 2060-2100 compared to the baseline level. Conversely, the Below 2°C scenario projects that the regional mean hydropower capacity factor would drop below the baseline level, but then remain stable for the rest of the century.





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Notes: Black dots indicate average hydropower capacity factor for selected Latin American hydropower plants based on the results from 20 combinations of GCMs and GHMs per scenario. Coloured bars indicate the range of the results; darker colours in the bars show the range of 80% of the results.

Climate impacts on Latin America hydropower will vary geographically

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 Latin America, exposing some plants to climate change more than others.

The climate projections included in this analysis show that two sub-regions,³ Central America and Mexico and Southern South America, would see a consistent decrease in mean hydropower capacity factors due to a decline in mean precipitation and runoff. However, the Andean region along the northwest coast of South America is projected to see a slight increase in hydropower capacity factor with increasing precipitation and runoff volume on average. For the rest of South America, a comparatively mild decrease in hydropower capacity factor is expected, although further studies are needed given the low agreement level between climate models for the future conditions of this sub-region.

Figure 3.5 Changes in hydropower capacity factor by Latin American sub region, 2020-2099 relative to the baseline 1970-2000



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Notes: Lightly coloured areas indicate the gap between projections from different scenarios. The darkest colour indicates the projection from the Above 4°C scenario; the lightest colour shows the projection from the Below 2°C scenario. Black lines indicate an average of the projections from three scenarios.

³ This report categorises the selected countries into four groups reflecting their climatic characteristics: Central America and Mexico (Mexico, Costa Rica, Panama and Guatemala), Southern South America (Argentina and Chile), Andean region (Colombia, Ecuador and Peru), and the rest of South America (Brazil, Venezuela, Paraguay, and Uruguay).

Box 3.1 Climate impacts on the variability of hydropower capacity factors by country from 2020-99

One of the challenges caused by climate change is the increased year-to-year variability in hydropower capacity factors. Increasing anomalies in climate patterns in some parts of Latin America could make hydropower capacity factors fluctuate more in some countries. For instance, most of the covered hydropower plants in Central America and Mexico are likely to experience an increase in inter-annual variability of hydropower capacity factors during the latter 40 years of this century, especially when the GHG emissions are not mitigated.

A higher GHG concentration is likely to exacerbate inter-annual variability in hydropower capacity factors in some sub-regions such as Central America and Mexico, and Southern South America. In these sub-regions, the year-to-year variability in hydropower capacity factors are greater in the Above 4°C scenario than in the Below 2°C. The results show how unmitigated global GHG emissions can have adverse impacts on electricity security in some Latin American countries and why they should be regulated.





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Note: Each dot represents the relative value of the projected average hydropower capacity factor from each country every five years between 2020 and 2100.

A notable decrease in hydropower capacity factor with a high GHG concentration could pose a challenge to Central America and Mexico

Hydropower capacity factor in Central America and Mexico is likely to fall by the end of this century in the Below 3°C and Above 4°C scenarios, mainly due to a consistent decrease in precipitation and runoff. Countries in the northern part of this sub-region, Mexico and Guatemala, are projected to see a starker decrease than Costa Rica and Panama in all scenarios.

Most of the modelling outcomes also show that hydropower capacity factor in Central America and Mexico will react the most sensitively to the increase in GHG emissions than other countries. In the Below 2°C scenario, hydropower capacity factor is estimated to decrease slightly by 5%. However, in the Above 4°C scenario, the mean hydropower capacity factor of Central America and Mexico could drastically fall up to 28%. In Guatemala, where hydropower currently takes up one third of electricity generation, hydropower capacity factor may decline by over 35% compared to the levels of 1970-2000 in the latter 40 years of this century in the Above 4°C scenario.

A high GHG concentration will raise concerns to Costa Rica and Panama as well. These two countries rely heavily on hydropower that generates over two thirds of their total electricity. Although both countries are expected to maintain a stable level of hydropower capacity factor in the Below 2°C scenario, they will be unable to do so in the Above 4°C scenario. With a high GHG concentration, hydropower capacity factors could fall by 26% and 17% in Costa Rica and Panama respectively. For the electricity security of Costa Rica and Panama, global GHG emissions reduction will be vital.

As climate change is likely to decrease hydropower capacity factors, countries in this sub-region are making efforts to make their hydropower plants more resilient and adapt to changing climate conditions. Mexico announced <u>a new national electricity program</u> in late 2018 to increase hydropower generation capacity by 26% through modernising and upgrading 60 existing hydropower plants. Costa Rica, where almost 100% of electricity is generated from renewable sources—a majority of which is from hydropower, is diversifying its electricity mix by increasing the role of other renewables such as biofuels, geothermal, wind and solar PV. As a result, the share of hydropower in the power mix of Costa Rica has dropped by over 7% during last decade despite the addition of new hydropower capacity such as Reventazón and Bijagua.

Figure 3.6 Climate impacts on hydropower capacity factor in Central America and Mexico by country, 2020-2099 compared to the baseline period, 1970-2000



Central America and Mexico

Southern South America could see a significant decrease in hydropower capacity factor due to reductions in precipitation and runoff

Southern South American countries, Chile and Argentina, are projected to experience notable reductions in hydropower generation between 2020 and 2100 in most models. This is largely due to a notable decrease in average precipitation around central Andes and Patagonia, and a reduction in streamflow of major river basins. Southern South America, together with Central America and Mexico, is the region that would show the sharpest drop in hydropower capacity factor.

A majority of modelling outcomes present that hydropower capacity factor of Southern South America is likely to decrease further with higher GHG concentrations. In the Below 2°C scenario, hydropower capacity factor is projected to remain at around 90% of the baseline level for 2020-2100. In contrast, the Above 4°C scenario projects that hydropower capacity factor is expected to fall by 15% and 28% on average in the periods of 2020-2060 and 2060-2100 respectively compared to the baseline; in Chile especially, this decrease is likely to be more

Notes: Lightly coloured areas indicate the gap between projections from different scenarios. The darkest colour indicates the projection from the Above 4°C scenario; the lightest colour shows the projection from the Below 2°C scenario. Black lines indicate an average of the projections from three scenarios.

marked. If GHG emissions are not mitigated from the level of the Above 4°C scenario, Chile's hydropower capacity factor could substantially decline by over 34%.

Despite the considerable magnitude of decrease, the projected drop in hydropower capacity factor could have a comparatively mild impact on electricity supply in southern South America. Chile and Argentina are less dependent on hydropower for electricity generation than most of the selected Latin American countries. The hydropower share in electricity generation of Chile was 27% in 2019. In Argentina, where the use of gas to generate electricity has consistently increased, the share of hydropower decreased to 20% in 2019 from 32% in 2000.

Figure 3.7 Climate impacts on hydropower capacity factor in southern South America by country, 2020-2099 compared to the baseline period, 1970-2000



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Notes: Lightly coloured areas indicate the gap between projections from different scenarios. The darkest colour indicates the projection from the Above 4°C scenario; the lightest colour shows the projection from the Below 2°C scenario. Black lines indicate an average of the projections from three scenarios.

Hydropower capacity factor could be slightly over the baseline level in the Andean region, but extreme precipitation events will add stress to operation

Hydropower generation in the Andean region, including Peru, Ecuador and Colombia, is expected to maintain the baseline level, or even slightly increase by 2100 in a majority of models. This could be due to a notable increase in rainfall along

their coastlines, although some locations may experience a mild decrease in precipitation and a decline in runoff with a continuing trend in <u>glacier loss</u>.

Different levels of GHG concentrations are unlikely to have a critical impact on total hydropower generation of the Andean region, where hydropower accounts for the biggest share in electricity generation. Hydropower capacity factors in the Andean region are projected to stay within a range of +3% to -3% from the baseline in all three scenarios. Only in Ecuador a higher GHG concentration may be associated with a mild increase in hydropower capacity factor between 2060-2100.

Although a changing climate would not have a critical impact on the total hydropower generation in the Andean region, a potential increase in extreme precipitation will likely add stress to hydropower operation. In some areas of the region, climate change is projected to <u>exacerbate seasonal variations</u>, with higher rainfall in the rainy season and less in the dry season with longer periods of drought. The frequency of extreme precipitation events and their consequences, such as floods and droughts, are projected to increase, <u>posing a greater challenge</u> to hydropower plants that do not have seasonal storage capacity. Colombia is expected to see more extreme precipitation events <u>by 26-37% by 2050</u>. An <u>ENSO phenomenon</u> could also affect hydropower operation, prompting heavy rainfalls and widespread flooding between April and October along the coasts of northern Peru and Ecuador. As that the Andean region relies significantly on hydropower for electricity generation, enhancing their resilience to future extreme precipitation events will be essential for reliable electricity supply and ensuring greater long-term opportunities.

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



Andean Region

Notes: Lightly coloured areas indicate the gap between projections from different scenarios. The darkest colour indicates the projection from the Above 4°C scenario; the lightest colour shows the projection from the Below 2°C scenario. Black lines indicate an average of the projections from three scenarios.

Current climate projections suggest a decrease in hydropower capacity factor in the rest of South America, although further studies might be required

There are still limitations in fully understanding the climate impacts on hydropower capacity factor in the rest of South America. Current climate models often present a marked disparity in forecasting precipitation patterns for this sub-region. For instance, the assessment of various climate models shows <u>a large spread</u> of climate change projections in Brazil. Further studies on future climate patterns across the sub-region would help to obtain more accurate projections.

Despite the limitations, a majority of modelling outcomes show that the mean hydropower capacity factor for the rest of South America (Brazil, Paraguay, Uruguay and Venezuela) for 2020-2100 would be lower than the level of 1970-2000. The projections for 2060-2100 imply a higher GHG concentration would bring a more drastic decline in hydropower capacity factor, although several models present conflicting results about some hydropower plants. A majority of climate models show that the hydropower capacity factor of the rest of South America would decrease by over 15% in 2060-2100 compared to the baseline (1970-2000) in the Above 4°C scenario, while it would fall by around 9% in the Below 2°C scenario.

These modelling outcomes also indicate that national-level trends could vary among countries in each sub-region. For instance, Venezuela is likely to maintain its baseline level of hydropower capacity factor by 2060 in all scenarios, while a majority of the examined models project a decrease for Brazil and Paraguay. Uruguay is projected to have the smallest changes in hydropower capacity factor across three scenarios over the period of 2020-2100.

Figure 3.9 Climate impacts on hydropower capacity factor in the rest of South America by country, 2020-2099 compared to the baseline period, 1970-2000



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Notes: Lightly coloured areas indicate the gap between projections from different scenarios. The darkest colour indicates the projection from the Above 4°C scenario; the lightest colour shows the projection from the Below 2°C scenario. Black lines indicate an average of the projections from three scenarios.

Box 3.2 Variations in projections about the climate impacts on hydropower in Brazil

The assessment of climate impacts on hydropower in Brazil requires a comparison of various models given a significant level of uncertainty in forecasting climate patterns and runoff. Some studies have already tried to compare various climate models and calculate their overall impact on hydropower generation in Brazil. They suggest that hydropower generation in Brazil could be <u>negatively affected</u> by <u>reduced streamflow</u> due to climate change for the rest of 21st century, although the magnitude of impacts may vary across river basins.

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This report assessed the climate impacts on 88 hydropower plants in Brazil using diverse GCMs, GHMs and RCPs. A majority of the examined models project a decrease in the hydropower capacity factor in Brazil during the rest of this century, compared to the level of baseline (1970-2000). However, the estimated levels of impacts vary among the model sets, and the difference tends to be larger in higher GHG concentration scenarios (Below 3°C and Above 4°C). For instance, the results based on IPSL-CM5, expect a rebound of hydropower capacity factor in 2060-2100 after a mild decrease in 2020-2060 in the Above 4°C scenario, while other model sets project a continuous decrease by the end of this century.

The results also show spatial variations in climate impacts on hydropower generation. Some hydropower plants located in southern Brazil, such as Barra Grande and Machadinho, would be less affected by climate change in all three scenarios, while others experience a notable change to their hydropower capacity factors.



Average hydropower capacity factor in Latin America by scenario, 2020-2099 relative to the baseline 1970-2000

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Notes: Black dots indicate the average hydropower capacity factor for the selected Brazilian hydropower plants based on results from 20 combinations of GCMs and GHMs for each scenario. Coloured bars indicate the range of the results; darker colours in the bars show the range of 80% of the results.

Chapter 4. Measures to enhance the resilience of Latin American hydropower

What is climate resilience?

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

Climate resilience is associated with <u>three key dimensions</u>: robustness, resourcefulness, and recovery.

- **Robustness** is the ability of an energy system to withstand the gradual, long-term changes in climate patterns and 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 operation 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 than one without a reservoir.
- **Recovery** is the ability to restore the system's function after an interruption resulting from climate hazards. A more resilient electricity system with a well-coordinated contingency plan for communications, alternative assets and workforce will recover faster from the interruptions caused by climate impacts.





Sources: IEA (2020c), Power Systems in Transition; Argonne National Laboratory (2012), <u>Resilience: Theory and</u> <u>Applications (ANL/DIS-12-1)</u>; as modified by International Energy Agency.

Benefits of climate resilience

Climate-resilient hydropower systems support clean energy transition in Latin America

Renewable energy is expected to grow rapidly in the path toward clean energy transitions. The IEA World Energy Outlook's <u>Sustainable Development Scenario (SDS)</u> estimates that the share of renewables in global total primary demand would increase from 14% in 2019 to 35% in 2040, leading future energy transitions. The rise of renewables is especially marked in the power sector where the share of renewables almost quadruples, from 16% in 2019 to 57% in 2040, with a substantial increase in variable renewable energy. To meet the Sustainable Development Goals and deliver the Paris Agreement, over 400 GW of renewable capacity needs to be added every year from 2020-2030.

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. In Latin America, where hydropower has been the biggest source of electricity for many years, <u>the share of hydropower</u> is projected to expand further. Aligned with the global vision toward clean energy transitions, the share of hydropower in total primary demand for power sector would <u>increase from 33% to</u> <u>39%</u> in Central and South America between 2019 and 2040.

The increasing share of hydropower is also 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 variable renewable energy sources such as wind and solar, system flexibility is important to maintain system balance. With the efforts for carbon emissions reduction and clean energy transition, power systems will need to cope with increased flexibility requirements.

Indeed, in most of selected Latin American countries, the share of variable renewables in total electricity generation has increased. For instance, the share of <u>solar PV and wind</u> has increased by over 30% in Uruguay, and by over 10% in Brazil, Costa Rica and Chile since 2000. The expansion of variable renewable energy 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 <u>the largest portion of flexibility</u> in some countries, including Brazil.

Climate resilience is essential for hydropower to continue delivering its function in the path of clean energy transitions. Without enhancing climate resilience, adding new capacity and flexibility services can quickly be disrupted by increasingly frequent extreme precipitation events and their associated hazards. For instance, in Colombia, large landslides after a heavy rainfall resulted in a blockage of the diversion tunnels at the Ituango hydropower project site in May 2018. The premature filling of the reservoir damaged infrastructure and equipment, and delayed commissioning of the hydropower plant. Similarly, landslides after torrential rains in Peru severely damaged the Callahuanca hydropower plant in early 2017; the damage was so devastating to the entire system that the power station had to be shut down for two years.
Climate resilient hydropower plays an important role in water management

Climate resilient hydropower with a multipurpose water storage capacity can bring benefits to water management. Hydropower's reservoir capacity can act as <u>a storage buffer</u> against increasing water variability due to climate change, providing reliable water supply for irrigation and drinking. The multipurpose water storage of hydropower can also contribute to food security by enhancing water security, and provide <u>better economic returns</u> than other reservoirs built for irrigation or domestic supply.

More frequent floods and droughts and their associated events, such as landslides and wildfires in some parts of Latin America, would also highlight the role of hydropower in water management. Improved water management with sufficient water storage for hydropower can prevent <u>large economic losses</u> from extreme precipitation events, particularly in vulnerable countries. Enhanced resilience for hydropower infrastructure ensures hydropower operation will bring benefits not only to electricity generation but also to water security.

Measures of climate resilience

Enhancing climate resilience needs a tailored solution

There is no one-size-fits-all solution to enhance hydropower plants' resilience. Although climate change will have impacts across Latin America, the wide range of patterns and the magnitude of potential climate impacts makes it difficult to develop a generic solution. A tailored combination of resilience measures based on a systematic assessment of climate risk and impact will help countries and operators increase their systems' resilience.

Resilience measures comprise strategic, operational and physical arrangements, and 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 4.1Examples of possible soft and hard measures for the resilience of Latin
American hydropower

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 station Strengthen banks Relocate the powerhouse to higher ground Modify 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 technology 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

Sources: IEA (2020), Climate Impacts on African Hydropower, <u>https://www.iea.org/reports/climate-impacts-on-african-hydropower</u>; IHA (2019), Hydropower Sector Climate Resilience Guide, <u>https://www.hydropower.org/publications/hydropower-sector-climate-resilience-guide</u>; WBCSD (2014), Building a Resilient Power Sector. <u>https://www.wbcsd.org/Programs/Climate-and-Energy/Climate/Resources/Building-a-Resilient-Power-Sector</u>; IEA (2016), "Energy, Climate Change and the Environment"; The Global Energy Challenge. <u>https://www.iea.org/reports/energy-climate-change-and-environment-2016-insights</u>.

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 could take measures that would incorporate the assessment results into longer-term planning measures and 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, the International Hydropower Association and the 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 <u>a regulatory framework</u> 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 for future assets and modernisation. The 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, power generators can adapt to climate change by revising operating regimes in a manner that responds to projected climate impacts. For instance, generators can integrate a climate resilience monitoring process into operation and maintenance plans to help them regularly collect information related to future climate risks and assign clear responsibilities.

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 disseminating information.

Examples of hard measures

Most hard measures are related to hardening 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 likely to experience more frequent, intense rainfalls in 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 relocation of powerhouses to raised areas can reduce the potential impact of floods.

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. Forestations around upstream catchments can also contribute to preventing landslides.

Policy recommendations

Mainstream climate resilience as a core element of energy and climate policies

Governments can send a strong signal to service providers and developers by mainstreaming climate resilience in their national policies. For instance, the National Adaptation Plan to Climate Change of Brazil, published in 2016, clearly shows the government's interest in resilient hydropower infrastructure with a dedicated chapter. This chapter broadly covers hydropower's resilience to climate impacts, suggesting actions to enhance the energy sector's climate resilience. Proposed actions include studies on climate impacts, a greater engagement of stakeholders and efforts to improve planning tools. The National Adaptation Plan to Climate Change of Guatemala published in 2018, also highlights the need for climate resilience of hydropower against extreme weather events and emphasises the importance of an emergency preparedness plan for each hydropower plant.

Although significant progress has been made to incorporate the climate resilience of hydropower in some countries, this still varies considerably across Latin America. Among the selected 13 countries, 6 countries have included climate impacts on hydropower and suggested actions in their national adaptation plans, while 7 countries are still developing their plans, or do not specifically mention hydropower. Countries that rely heavily on hydropower are recommended to consider the climate impacts on hydropower and include concrete actions that enhance the climate resilience of hydropower in their national adaptation policies.

Governments can also encourage developers and operators by adopting relevant regulations for climate resilience. For instance, incorporating resilience standards into construction codes requires developers to pay attention to climate resilience from an early stage of a hydropower project. Requirements for a regular climate risk assessment in operation and maintenance rules could raise awareness among operators of climate risks and impacts. Regulations for improved water management and protection of forestation would also reduce vulnerability and enhance climate resilience for Latin American hydropower.

Box 4.1 Case study: Brazil's policies to support climate resilience of hydropower

The National Adaptation Plan of Brazil, announced in 2016, proposes actions, strategies and guidelines for managing climate risk. With the aim of identifying measures that promote adaptation and reduce the level of climate risk, the Plan broadly covers potential climate impacts on hydropower plants and suggests some measures to enhance climate resilience.

The Plan projects climate impacts on hydropower using two climate models (HadGEM2-ES and MIROC5), comparing two greenhouse gas concentration pathways (RCP 4.5 and RCP 8.5). According to the projections, climate change accentuates differences in seasonal rainfall patterns between river basins of the Central-South and those of the North. As an example of an adaptation measure, the Plan suggests enhanced interconnection between different river basins to fill the gap. Projections also estimate that hydropower plants of different sizes are likely to be affected by climate change in different ways: hydropower plants with large reservoirs may be able to mitigate the effect of streamflow variation, while run-of-river plants and others with small reservoirs would be more subject to climate variability. To better cope with the various impacts of climate change, the Plan recommends assessing climate risk to energy sector infrastructure with a focus on contingency plans for extreme weather events and promoting a greater engagement of energy institutions.

Source: Ministry of Environment, Brazil (2016) National Adaptation Plan to Climate Change. https://www4.unfccc.int/sites/NAPC/Documents/Parties/Brazil%20NAP%20English.pdf.

Mobilise investment in modernisation of ageing hydropower plants

The wide presence of ageing hydropower plants in Latin America requires modernisation of hydropower infrastructure. Over 50% of the installed capacity in Latin America is <u>over 30 years old</u>. Ageing hydropower plants are expected to require modernisation to address the projected increase in extreme precipitation events in addition to general rehabilitation. Some efforts, such as upgrading spillway capacities and increasing dam safety, will protect ageing hydropower plants against future climate hazards and help them adapt to new climate conditions.

Modernisation of hydropower plants in Latin America needs further investment. Access to financing is considered <u>the main barrier for modernisation</u>. For instance, <u>a 30 year rehabilitation plan</u> for the Salto Grande hydropower facility in Argentina and Uruguay would need USD 960 million to extend the plant's lifespan and improve its efficiency. <u>The modernisation project</u> of Itaipu hydropower plants in Brazil and Paraguay will require an investment of USD 500 million.

Public investment has been playing a major role in financing modernisation of hydropower plants in some Latin American countries. For instance, <u>a USD 500 million project</u> for the upgrade and rehabilitation of Yacyretá hydropower plant was announced to be funded by the Yacyretá Binational Entity, a joint entity between the Governments of Paraguay and Argentina. This project will add 276 MW and will increase production by 9% with three new turbine generator units and extend the lifespan of 20 existing units. Similarly, the Inter-American Development Bank (IDB) offered <u>a USD 125 million loan</u> for modernisation of Acaray Hydropower plant.

Private investors are often reluctant to invest in rehabilitation and upgrade projects for some reasons: high uncertainties in climate projections and limited access to information on climate-related risks in some cases, could make private investment difficult; public ownership of many hydropower plants in Latin America can decrease the attractiveness of a rehabilitation project, as the renovated plant would become an integral part of a government owned asset.

Public financing institutions can play an important role in the modernisation projects for ageing hydropower plants by providing financial risk coverage instruments. Public investment could catalyse private financing by investing in a riskier tranche of the investment and providing <u>catalytic first loss capital</u>. <u>A Public Private Partnership</u> (<u>PPP</u>) approach with a pledge of sharing an appropriate portion of the profit with private investors in return for the investment could also attract more private investment. <u>Financial risk coverage instruments</u>, which are available from international financial institutions, can also mobilise further investment in rehabilitation projects by supporting utilities that lack adequate credit ratings to

satisfy investors or provide supplementary guarantees to some countries with high political risk. For instance, <u>Inter-American Development Bank (IDB)</u> provided a USD 128 million loan for the modernisation of two hydropower facilities in Brazil, Furnas and Luiz Carlos Barreto de Carvalho, and a USD 700 million loan for Guri hydropower plant in Venezuela.

Box 4.2 Case study: Mexico's plan for hydropower renovation

In Mexico, most hydropower plants are <u>older than 50 years</u>. The Mexican government announced <u>a new national electricity program</u> in late 2018, placing an emphasis on hydropower. It aims to increase hydropower installed capacity through modernisation and upgrades to 60 existing hydropower plants. To implement this plan, an additional investment of USD 985 million was also announced. The stateowned power utility of Mexico, Comisión Federal de Electricidad (CFE), estimated that the renovation of hydropower plants could add another 3 300 MW of capacity, increasing the country's generation capacity by 26%.

Source: Hydroreview (2018), Mexico's new energy plan places strong emphasis on hydroelectric generation; Godoy, E. (2020), Mexico's Plan to Upgrade Hydropower Plants Faces Hurdles.

Build and strengthen climate risk insurance

Because hydropower generation is susceptible to a changing climate, the question is often raised about how it can be insured against adverse climate impacts such as extreme precipitation events. As damages from extreme weather events to hydropower plants are often too broad and serious, private insurance options might not be able to cover the full cost. For instance, a considerable damage to the Ituango hydropower plant caused by heavy rainfall and landslides in 2018, made the largest claims in the history of engineering: USD 2 556 million for recovery of infrastructure and equipment, plus profit loss of USD 628 million. Moreover, even if private insurance options could cover the damage to physical assets and lost revenue, the entire damage to society, national economy and attendant costs can hardly be compensated by private insurance.

Governments can consider public options for climate risk insurance. For instance, <u>Caribbean Catastrophe Risk Insurance Facility</u> (CCRIF), a multinational program, facilitates access to low cost, high quality disaster risk insurance for governments in Central America. Since 2007, it has offered insurance against tropical cyclones and excess rainfall, providing immediate financing resources and allowing governments to implement immediate emergency response and continue to provide critical services. An accessible and affordable climate risk insurance for hydropower infrastructure will significantly improve preparedness against climate hazards while helping to avoid excessive financial burdens on utilities.

Support scientific research to increase accuracy of climate projections

Comprehensive and scientific projections of climate risks and impacts on hydropower generation are essential to build climate resilience. Decision makers at governments and utilities would have difficulty choosing the most effective set of resilience measures for hydropower plants without accurate data and information about potential climate risks and impacts. According to <u>a recent study</u> from World Bank, a project to build a resilient infrastructure without appropriate climate risk data will cost ten times more than a project that has sufficient information.

However, climate models often present a low agreement and even conflicting results about future precipitation and runoff in certain parts of Latin America. For instance, some of the latest models anticipate less precipitation and decreasing runoffs in the Amazon of Brazil under a high GHG concentration scenario (RCP 8.5), while previous models have forecasted a wetter climate.

To minimise disparities and improve climate projection accuracy, governments need to support scientific research on future climate patterns and their impacts. Governments can support climate scientists by increasing access to national climate data sources, consistently updating information systems, developing guidelines and providing financial support for climate research. For instance, governmental support for the expansion of <u>climate monitoring networks</u> in Central America where climate and hydrometric measurement stations are sparsely scattered will improve the understanding of water availability for hydropower generation.

Already, several governments, international organisations and academia are working together to create more accurate climate projections and more comprehensive models. For instance, IPCC and World Meteorological Organisation (WMO) have dedicated to combine modelling results and observation data on climate change across the world, overcoming gaps in data availability, quality and consistency. Europe-South America Network for Climate Change Assessment and Impact Studies (CLARIS) and its subsequent project, CLARIS-La Plata Basin, are a collaborative research projects of research organisations of Europe and South America for a high-quality climate database for temperature and precipitation, and improved prediction capacity of climate change in South America.

Annex: Methodology of the climate impact assessment

Scope

This report assessed the climate impacts on the hydropower plants in 13 Latin American countries between 2020 and 2100, comparing the results with the values of the baseline period from 1970 to 2000. The baseline period was selected reflecting the maximum availability of historical climate records.

The assessment focuses on 13 Latin American countries with the largest installed capacity of hydropower. The selected countries consist of four groups reflecting their climatic characteristics: Central America and Mexico (Mexico, Costa Rica, Panama and Guatemala), Andean region (Colombia, Ecuador and Peru), Southern South America (Argentina and Chile) and the rest of South America (Brazil, Venezuela, Paraguay, and Uruguay).

The total hydropower installed capacity in these 13 countries is over 193 000 MW, which accounts for 98% of total installed capacity in Latin America (IHA, 2020). Brazil takes up over 55% of the total hydropower installed capacity, followed by Venezuela, Mexico, Colombia and Argentina.

Around 90% of selected hydropower plants are impoundment facilities with reservoirs. Around 10% of selected plants are mostly diversion (run-of-river) facilities with a small fraction of pumped hydropower storage. 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).

Dy	country			
Countries	Number of selected plants	Installed capacity of selected plants [MW]	Total installed capacity [MW]**	Coverage
Argentina	40	9 903	11 310	88%
Brazil	88	92 398	109 058	85%
Chile	44	6 075	6 739	90%
Colombia	38	10 422	11 918	87%
Costa Rica	38	2 014	2 343	86%
Ecuador	11	4 039	5 074	80%
Guatemala	25	1 321	1 559	85%
Mexico	34	10 959	12 126	90%
Panama	17	1 434	1 786	80%
Paraguay	3	8 810	8 810	100%
Peru	35	4 370	5 396	81%
Uruguay	4	1 538	1 538	100%
Venezuela	4	15 049	15 393	98%
Total	378*	168 331	193 050	87%

Table 5.1Share of selected hydropower plants in terms of hydropower installed capacity,
by country

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* The number is calculated by aggregating the number of selected plants per each country and subtracting the number of plants under co-ownership between two countries to avoid double counting.

* * Sources: International Hydropower Association (2020), 2020 Hydropower Status Report

Models and data

High-resolution (15"x 15") global monthly discharge maps are developed by combining low-resolution (0.5° x 0.5°) monthly runoff 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 runoff.

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 Latin American 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 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. Further studies using downscaled GCMs to regional or local levels and then combining GHMs could advance the accuracy of results (Maceira, M.E.P. et al., 2018).

Table 5.2 Over view of the of	CINS, GHINS and KCFS COnsider	ed in the assessment
General Circulation Models (GCM)	Global Hydrological Models (GHM)	Representative Concentration Pathways (RCP)
GFDL-ESM2M	H08	RCP 2.6
HadGEM2	LPJmL	RCP 4.5
IPSL-CM5	MPI-HM	RCP 8.5
MIROC-ESM	PCR-GLOBWB	
NorESM1		

Table 5.2 Overview of the GCMs, GHMs and RCPs considered in the assessment

General Circulation Models (GCM)

<u>GFDL-ESM2M</u> was developed by scientists at the Geophysical Fluid Dynamics Laboratory to make projections of the behaviour of the atmosphere, the 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.

<u>IPSL-CM5</u> 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. <u>MIROC-ESM</u> 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.

<u>NorESM1</u> 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)

<u>H08</u> 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 landatmosphere exchange flows of carbon and water, for both natural and agricultural ecosystems.

<u>MPI-HM</u> 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.

<u>PCR-GLOBWB</u> 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.

In the forthcoming IPCC Sixth Assessment Report will use <u>Shared Socioeconomic</u> <u>Pathways (SSPs)</u> 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 piece 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. Although this report decided to use RCPs instead of SSPs, given that still more data resources are available for RCPs rather than SSPs across various GCMs and GHMs. This impact assessment could be updated soon 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 Latin America.

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 **Below 3°C** scenario follows the trajectory of the RCP 4.5 which assumes a radiative forcing value of around 4.5 W/m² in the year 2100. The Below 3°C scenario is associated with a rise by 2.4 (\pm 0.5) °C in global annual mean temperature for the period 2080 to 2100 compared to the pre-industrial level. The Below 3°C scenario assumes a peak in global GHG emission trends by mid-century and a subsequent 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 (\pm 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.

Table 5.3Overview of the scenarios

Scenario	Below 2°C	Below 3°C	Above 4°C
Representative Concentration Pathway	RCP 2.6	RCP 4.5	RCP 8.5
Targeted radiative forcing in the year 2100	2.6 W/m ²	4.5 W/m ²	8.5 W/m ²
CO ₂ -equivalent concentrations (ppm)	430-480	580-720	> 1 000
Global temperature change	1.6 (±0.4)°C	2.4 (±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	Likely to stay below 3°C	More unlikely than likely to stay below 4°C

Source: IPCC (2014), Climate Change 2014 Synthesis Report, https://www.ipcc.ch/report/ar5/syr/.

Abbreviations and acronyms

CCRIF	Caribbean Catastrophe Risk Insurance Facility
CFE	Comisión Federal de Electricidad
CLARIS	Europe-South America Network for Climate Change Assessment and Impact
	Studies
CO ₂	carbon dioxide
CMIP5	Coupled Model Intercomparison Project Phase 5
ENSO	El Niño-Southern Oscillations
GCM	General Circulation Models
GHG	greenhouse gas
GHM	Global Hydrological Models
IDB	Inter-American Development Bank
IHA	International Hydropower Association
IPCC	Intergovernmental Panel on Climate Change
PES	Payment for Ecosystem Services
PPP	Public Private Partnership
RCP	Representative Concentration Pathways
SDS	Sustainable Development Scenario
STEPS	Stated Policies Scenario
WMO	World Meteorological Organisation

Glossary

bbl	barrel
bbl/d	barrels per day
bcm	billion cubic metres
bcm/yr	billion cubic metres per year
cm/s	centimetres per second
gCO ₂	gram of carbon dioxide
gCO ₂ /kWh	grams of carbon dioxide per kilowatt hour
GJ	gigajoule
Gt/yr	gigatonnes per year
GtCO ₂	gigatonne of carbon dioxide
GtCO ₂ /yr	gigatonnes of carbon dioxide per year
GW	gigawatt
GWh	gigawatt hour

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