POLITECNICO DI TORINO

Master of Science in Energy and Nuclear Engineering Classe LM-30

Master Degree Thesis

ANALYSIS OF THE CLIMATE IMPACTS ON LATIN AMERICAN HYDROPOWER

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ACADEMIC YEAR 2020-2021

Abstract

This thesis is about a quantitative analysis of the climate impacts on Latin American hydropower held at the International Energy Agency (IEA) in Paris during my six-months internship which turned into an external consultant job. The aim of the work was to understand how the capacity factors of hydroelectric power plants would vary in the 13 selected countries by combining data from different climate models.
Five General Circulation Models and four Global Hydrological Models have been analyzed, and four Representative Concentration Pathways scenarios have been considered in order to analyze all possible future perspectives. These 80 total combinations have been applied to 17 time-steps comparing the value of the capacity factors in the baseline period 1970-2000 with the values of the 5-years time-steps from 2020 up to 2100.

Data analysis is essential to assess climate impacts, to identify similar behaviors among countries and link them to possible common causes, in order to provide potential solutions to enhance climate resilience. Data analysis is combined with a qualitative analysis about climate risks, and a policy analysis that compares Latin American countries according to the coverage of energy sector in their National Adaptation Plans.

Contents

List of Figures

List of Tables

List of Acronyms

CVI	Climate Change Vulnerability Index
ENSO	El Nino-Southern Oscillations
GCM	General Circulation Model
GHG	Greenhouse gas
GHM	Global Hydrological Model
HSAP	Hydropower Sustainability Assessment Protocol
IEA	International Energy Agency
IHA	International Hydropower Association
INDC	Intended Nationally Determined Contribution
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
LDC	Least Developed Country
NAP	National Adaptation Plan
NAS	National Adaptation Strategy
NAPA	National Adaptation Programme of Action
OLADE	Latin American Energy Organization
PES	Payment for Ecosystem Services
RCP	Representative Concentration Pathway
SSP	Shared Socioeconomic Pathway
UNEP	United Nations Environment Programme
WMO	World Meteorological Association

Chapter 1

Introduction

Hydropower is particularly susceptible to the adverse impacts of climate change because it is directly affected by changing patterns in rainfall and temperatures. Latin America, on its side, is one of the most vulnerable region and hydropower still accounts for around 80 per cent of its renewable energy mix. That is why it is crucial to analyze future climate impacts on energy production in this region.

1.1 Hydropower worldwide

Hydropower remains the largest renewable source. In 2019, hydropower accounted for nearly half of the global renewable energy capacity with over 1,300 GW and approximately 16% of global electricity generation - more than all other renewable sources combined, followed by wind (6%), solar PV (4%), and bioenergy (3%) [2]. If hydropower was replaced with burning coal for electricity generation, analysis by the International Hydropower Association (IHA) suggests that around 3.5 to 4.0 billion metric tonnes of additional greenhouse gases would be emitted annually, and global emissions from fossil fuels and industry would be around 10% higher.

In order to limit the global temperature rise to below 2°C above pre-industrial levels, the International Renewable Energy Agency (IRENA) in its *Transforming Energy Scenario* [3] suggests global hydropower capacity would need to increase by 25 per cent by 2030, and by 60 per cent by 2050. This equates to around 850 GW in additional installed capacity over the next 30 years - roughly the same as adding the European Union's entire power system capacity. Those are almost the same numbers seen in the IEA's *Sustainable Development Scenario* with 800 GW to be commissioned by 2040, which are compatible with the objectives of the Paris Agreement [1].

To reach the 2050 target, the yearly average growth in hydropower capacity would need to reach an estimated 2.0% a year on average. In the five years between 2015 and 2019, the average year-on-year growth in installed capacity was 2.1%. In 2019, the growth rate was 1.2% [1]. Annual growth in installed capacity can however vary considerably depending on when major hydropower projects, which take years to develop, become operational. Notwithstanding, this underlines the need for investment in hydropower to increase significantly over the next decade and more. *Hydropower will continue playing a role in climate change mitigation and adaptation of the energy sector* - the World Water Development Report [4] stated - acknowledging the need for low-carbon renewable energy.

Hydropower holds a double relationship with climate change. On the one hand, it contributes to the avoidance of greenhouse gas (GHG) emissions from the burning of fossil fuels. On the other hand, water availability and hydropower generation are likely to be affected by changing rainfall patterns, which can reduce the flow of rivers [5]. Like other types of infrastructure, hydropower is starting to experience negative impacts due to climate risks. Water availability and hydropower generation are affected by changes in hydrological patterns and extreme weather events. Hydropower projects are directly influenced by meteorological, hydrological, geotechnical, glacial and geological processes, all of which are susceptible to climate change. Given the long design life of hydropower projects and their susceptibility to climate impacts, hydropower projects must be developed, operated and maintained to be resilient for a range of potential climate change scenarios [6].

1.2 Latin American hydropower

In Latin America hydropower still accounts for around 80% of the renewable energy mix and meets 47% of Latin America's total electricity needs compared to an average of 16% worldwide [7]. Moreover, even if non-conventional renewables are continuing their rapid expansion, hydropower is still under development.

Indeed, Brazil surpassed China in 2019 as the largest single contributor of added capacity with 4,919 MW, becoming the first country in the world for hydropower production [1]. This was mainly attributed to the completion of the 11,233 MW Belo Monte hydropower plant, with the installation of its 18th turbine. It is the largest hydropower plant in Brazil (excluding Itaipu Binational) and the fourth largest in the world. The facility that actually generates globally the most electricity annually is the Itaipu plant situated on the Paranà River between Brazil and Paraguay. That currently contributes to 15% of the electricity consumed in Brazil and 86% in Paraguay [5].

The region is moving to a diversified renewable electricity mix. Countries like Colombia, Venezuela and Ecuador in the Andean subregion have installed hydropower capacity exceeding two thirds of the electricity share. Chile and Argentina are also moving away from fossil fuel generation with large untapped renewable energy resources of hydropower, wind, solar and geothermal. In Argentina and Chile 33 per cent and 28 per cent respectively of installed capacity is from hydropower [1]. Chile currently has almost 16 GW and Argentina almost 33 GW of hydropower potential. As part of the Peruvian government's commitment to become self-sufficient in energy by 2040, several hydropower plants are expected to enter into operation in the coming years.

The share of hydropower in the energy mix of Latin American countries is very different from each other, as well as the hydropower installed capacity in absolute terms. As we can see from the Figure 1.1, Brazil takes up over 100 GW, followed by Venezuela, Mexico, Colombia and Argentina that exceed 10 GW. The same results are presented in percentage on the right.

However, the increased climate variability associated with El Nino-Southern Oscillations (ENSO) events in this area is challenging the strong reliance on hydropower, as described in more detail in section 3.1.1 about climate hazards. During the last few decades, shifts in temperature and precipitation have occurred. Rainfall has increased in coastal regions of Andean countries, such as Peru, Ecuador and Colombia. Rain has declined in Central America, southern Chile, southwest Argentina [8]. Projections of hydropower generation will have to consider that too.

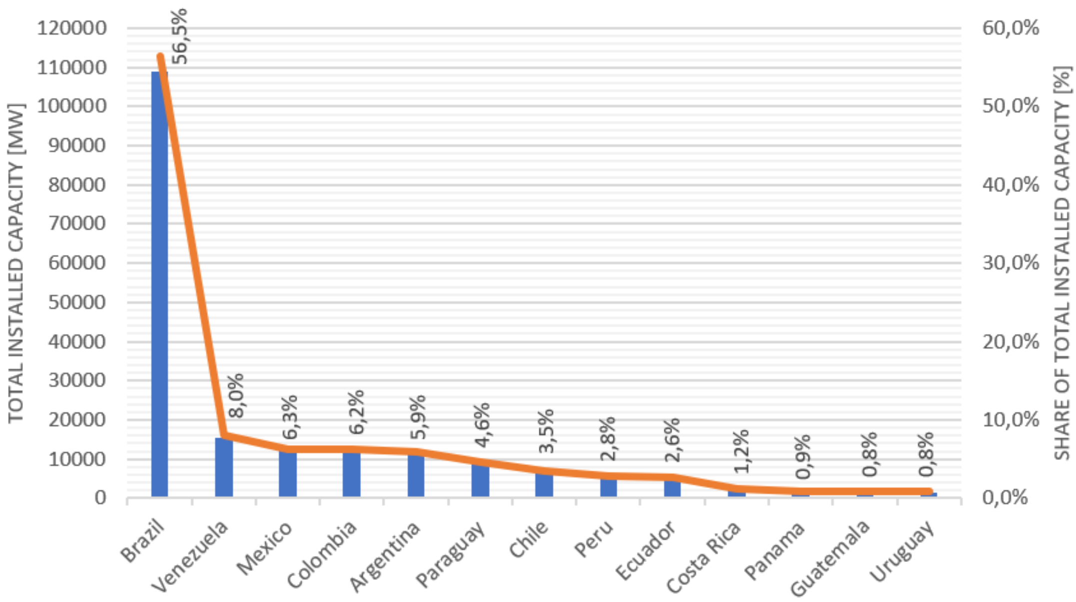


Figure 1.1: Total hydropower installed capacity [MW] and [%] by countries [1]

1.3 Aim of the thesis

This thesis mainly consists of a quantitative analysis of the climate impacts on Latin American hydropower, along with a qualitative analysis of the climate risks in the same context and a policy analysis regarding the National Adaptation Plans. I performed the data analysis during my six-months internship started in March 2020 within the Environment and Climate Change (ECC) unit at the International Energy Agency (IEA) in Paris, a work carried out almost entirely remotely due to the exceptional circumstances. After the internship, I had the opportunity to pursue with further analysis as an external consultant, conducting policy readiness assessment for climate resilience in both Latin American countries, and in the IEA member and association countries, focused on the coverage of the energy sector.

The aim of the thesis is to understand how the capacity factors of hydropower plants would vary in the 13 selected countries by combining data from different climate models and scenarios, according to the future greenhouse gas (GHG) concentration trajectories.

Five General Circulation Models and four Global Hydrological Models have been analyzed, and four Representative Concentration Pathways scenarios have been considered in order to analyze a large set of possible future perspectives. The resulting 80 combinations have been applied to 17 time-steps comparing the value of the capacity factors in the baseline period 1970-2000 with the values of the 5-years time-steps from 2020 up to 2100. The assessment aims to help improve the resilience of hydropower in Latin America by providing a policy analysis and a data analysis, essential to assess climate impacts, to identify similar behaviors among countries and link them to possible common causes.

The thesis begins with a description of the methodology adopted for the climate impacts analysis, discussed in Chapter 2. Then, in the first section of Chapter 3, climate risks to Latin American hydropower have been qualitatively assessed based on three dimensions: hazard, exposure and vulnerability. Whereas, in the second section of the same chapter, the potential climate impacts on Latin American hydropower have been quantitatively examined, showing changes in annual and monthly capacity factors for the next 80 years. The projected results have been compared with the values of the baseline period - selected reflecting the maximum availability of historical climate record - to understand in which way the productivity was going to change. Finally, Chapter 4 presents examples of measures to enhance climate resilience, Chapter 5 analyses the national adaptation policies in place and Chapter 6 suggests policy recommendations.

Chapter 2

Methodology

2.1 Data collection

The study assesses the climate impacts on more than 370 hydropower plants in 13 Latin American countries: Argentina, Brazil, Chile, Colombia, Costa Rica, Ecuador, Guatemala, Mexico, Panama, Paraguay, Peru, Uruguay and Venezuela. They were chosen since they are the countries with the highest installed capacity of hydropower in both Central and South America.

According to the 2020 Hydropower Status Report, those countries cover the 98% of the total installed capacity in Latin America reaching more than 193 GW. Out of this share we have analyzed the 87% of such capacity considering only the selected plants in the 13 selected countries, with a final coverage of 86% with respect to the total installed capacity of the whole Latin America (Figure 2.1).

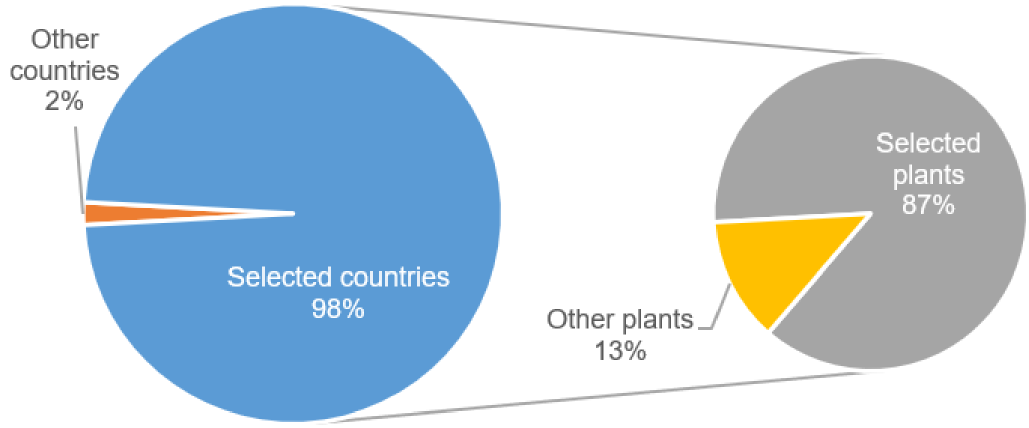


Figure 2.1: Share of covered hydropower installed capacity

The coverage in percentage is not the same for all the countries taken into account: for all of them it is not lower than 80% (which was established to be our minimum to have a reliable analysis) and in the case of countries with few hydroelectric power plants it reaches even 100% as shown in Table 2.1. The values in the total installed capacity column came from the latest official data published by the International Hydropower Association [1].

Brazil has the highest number of power plants, which is easy to explain given the highest installed capacity. It is interesting to see how Costa Rica, Guatemala, Panama and Uruguay, which have comparable installed capacity (they are the four countries with the lowest values among those considered), have very different number of power plants, which is obviously reflected in their size, as shown in Table 2.3. Costa Rica, Guatemala and Panama have almost all their power plants below 100 MW, while the few ones in Uruguay all exceed this threshold.

Table 2.1: Share of selected hydropower plants in terms of hydropower installed capacity, by country

Countries	Number of selected plants	Installed capacity of selected plants [MW]	Total installed capacity [MW]	Coverage
Argentina	40	9903	11310	**88%**
Brazil	88	92398	109058	**85%**
Chile	44	6075	6739	**90%**
Colombia	38	10422	11918	**87%**
Costa Rica	38	2014	2343	**86%**
Ecuador	11	4039	5074	**80%**
Guatemala	25	1321	1559	**85%**
Mexico	34	10959	12126	**90%**
Panama	17	1434	1786	**80%**
Paraguay	3	8810	8810	**100%**
Peru	35	4370	5396	**81%**
Uruguay	4	1538	1538	**100%**
Venezuela	4	15049	15393	**98%**
Total	**368***	**168331**	**193050**	**87%**

The asterisk on the total number of selected plants points that the sum was made by subtracting the power stations shared between two countries, so as not to consider them twice. It is the case of the bi-national plants Itaipu (14,000 MW shared between Brazil and Paraguay), Salto Grande (1890 MW shared between Argentina and Uruguay) and Yacyreta (3200 MW shared between Argentina and Paraguay). Their installed capacities are equally shared between the countries involved.

The list of power plants and data such as installed capacity, year in which the operations started and type of plant were compiled using information sourced from (by priority order):

- official websites from governments, regulation agencies, transmission network operators and asset owners;
- scientific articles and reports;
- daily news reports involving hydropower plant development, official declarations of contracts, and equipment deals; and
- Global Energy Observatory that is a set of free interactive databases.

The total list of plants divided per country can be found in the Annex.

In Table 2.2 there is an overview showing the type of hydroelectric power plants selected including impoundment facilities with reservoirs, diversion (run-of-river) facilities and pumped hydropower storage.

Table 2.2: Type of selected hydropower plants, by country

Country	Dam on river with reservoir [MW]	Dam with run-of-river generation [MW]	Pumped storage [MW]	Unknown [MW]	Total installed capacity [MW]
Argentina	8717,8	57	974	154,4	9248,2
Brazil	83248,3	8930	0	219,4	85397,7
Chile	3810,8	2037,2	0	226,9	6074,9
Colombia	9638,5	379,8	0	403,9	10422,2
Costa Rica	728	562	0	723,8	2013,8
Ecuador	1733	1500	0	806	4039
Guatemala	621,8	337	0	345,6	1304,4
Mexico	7864	0	0	3111,5	10975,5
Panama	949,9	304	0	179,7	1433,6
Paraguay	8810	0	0	0	17410
Peru	1275,4	698,5	0	2396	4369,9
Uruguay	1538	0	0	0	593
Venezuela	15049	0	0	0	15049
Total [MW]	143984,5	14805,5	974	8567,2	168331,2
Total [%]	**85,5%**	**8,8%**	**0,6%**	**5,1%**	**100%**

The analysis was made considering the different types of power plants related to their installed capacity and not their amount. In that case the percentage of plants of unknown type would have been much higher, since generally the most difficult information to find are those on smaller plants that did not contribute significantly to the energy generation.

Instead, in Table 2.3 there is an overview of the size of the central units divided into 4 categories according to their installed capacity: less than 20 MW, from 20 to 100 MW, from 100 to 500 MW, more than 500 MW. Costa Rica, Guatemala and Panama have zero plants larger than 500 MW; while Brazil, Paraguay and Venezuela have more than 40% of their plants that belong to this category. The data obtained from the different models are not influenced by size, nor by the type of the hydropower plant. Therefore those tables (2.2 and 2.3) are provided only to have a complete view of the analyzed power plants and the situation in Latin America.

Table 2.3: Size of selected hydropower plants, by country

Country	Less than 20 MW	From 20 to 100 MW	From 100 to 500 MW	More than 500 MW	Total number of plants
Argentina	13	10	11	5	39
Brazil	1	7	39	40	87
Chile	5	23	14	2	44
Colombia	6	11	14	7	38
Costa Rica	17	13	8	0	38
Ecuador	1	3	5	2	11
Guatemala	13	11	2	0	25
Mexico	5	13	9	7	34
Panama	1	11	5	0	17
Paraguay	0	0	1	2	3
Peru	11	11	11	2	35
Uruguay	0	0	3	0	3
Venezuela	0	1	0	3	4
Total	73	114	122	70	378
Total [%]	**19,3%**	**30,2%**	**32,3%**	**18,5%**	**100%**

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).

2.2 Models and scenarios

To analyse climate impacts on Latin American hydropower, this study examined as many combinations of models as possible to enhance the reliability of results. The assessment considers four Representative Concentration Pathways (**RCPs**) scenarios that correspond to different global temperature outcomes [9], five General Circulation Models (**GCMs**) and four Global Hydrological Models (**GHMs**), that we will analyse later in this chapter. The 80 total combinations were compared and aggregated in order to minimize the probability of misleading outcomes and distortions, also because the assumptions within each model are not the same.

Table 2.4: Models and scenarios overview

4 Representative Concentration Pathways (RCP) scenarios:	5 General Circulation Models (GCM):	4 Global Hydrological Models (GHM):
2,6	**GFDL-ESM2M**	**H08**
4,5	**HadGEM2**	**LPJmL**
6,0	**IPSL-CM5**	**MPI-HM**
8,5	**MIROC-ESM**	**PCR-GLOBWB**
	NorESM1	

For each of the 17 time-steps up to 2100 (because RCPs values extend only until 2100), we have the average annual and monthly capacity factors, getting 1360 annual results for each plant and 16,320 monthly results. Considering the total number of selected plants, we reach a huge amount of data (over 6 million values) that was managed through the use of Macros on Excel, by using Visual Basic for Application (VBA) to program, and Pivot tables to better organize the data.

High-resolution ($15'' \times 15''$) global monthly discharge maps are developed by combining low-resolution (0.5×0.5) monthly runoff data from each ensemble of GCMs, GHMs and RCPs with high-resolution ($15'' \times 15''$) area accumulation and drainage direction maps available from the HydroSHEDS project [10], and a low-resolution (0.5×0.5) map of monthly runoff.

The discharge maps were used to extract the design discharge and design load factors per hydropower plant [11]. 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.

The raw data from the consultants arrived divided into folders, each relating to a combination of models, for a total of 80 folders. Therefore information on individual GCMs or GHMs was not received.

2.2.1 General Circulation Models (GCM)

GCMs are climate models made for weather forecasting, using a mathematical model of the general circulation of atmosphere and ocean. Many of them contributed to the modelling for the *IPCC Fifth Assessment Report* [9].

The following are the ones used in this analysis:

- **GFDL-ESM2M** [12] was developed by the *Geophysical Fluid Dynamics Laboratory* to understand how the Earth's biogeochemical cycles, including human actions, interact with the climate system. It is based on an atmospheric circulation model coupled with an oceanic circulation model, with representations of land, sea ice and iceberg dynamics. The atmospheric component of the ESMs (Earth System Models) includes physical features such as aerosols (both natural and anthropogenic), cloud physics, and precipitation. The land component includes precipitation and evaporation, streams, lakes, rivers, and runoff as well as a terrestrial ecology component to simulate dynamic reservoirs of carbon and other tracers. The oceanic component includes features such as free surface to capture wave processes; water fluxes, or flow; currents; sea ice dynamics; iceberg transport of freshwater; and a state-of-the-art representation of ocean mixing as well as marine biogeochemistry and ecology. The Laboratory has contributed to each assessment of the IPCC since 1990.

- **HadGEM2** [13] stands for the *Hadley Centre Global Environment Model* version 2. The HadGEM2 family of models includes a coupled atmosphere-ocean configuration, with or without a vertical extension in the atmosphere to include a well-resolved stratosphere, and an Earth-System configuration which includes dynamic vegetation, ocean biology and atmospheric chemistry. Members of the HadGEM2 family were used in the IPCC Fifth Assessment Report.

- **IPSL-CM5** [14] is a full earth system model and the last version of the *Institut Pierre Simon Laplace* (IPSL) that is a consortium of nine research laboratories on climate and the global environment. Based on a physical atmosphere-land-ocean-sea ice model, it also includes a representation of the carbon cycle, the stratospheric chemistry and the tropospheric chemistry with aerosols. The IPSL-CM5 model contributed to the modelling for the IPCC Fifth Assessment Report.

- **MIROC-ESM** [15] 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.* It is an earth system model based on a global climate model MIROC (Model for Interdisciplinary Research on Climate): an atmospheric general circulation model including an on-line aerosol component, an ocean GCM with sea-ice component, and a land surface model that are interactively coupled in MIROC. In addition, an atmospheric chemistry component, a nutrient-phytoplankton-zooplankton-detritus type ocean ecosystem component, and a terrestrial ecosystem component dealing with dynamic vegetation are included in MIROC-ESM.

- **NorESM1** [16] 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.

2.2.2 Global Hydrological Models (GHM)

GHMs [17] differ in the detail of description of processes, parameter estimation approaches, time scales and spatial resolution (all four GHMs considered in our analysis have a spatial resolution of 0.5°x0.5° globally). They may provide spatial and temporal estimates of global water resources and help to analyse possible projections of changes of those estimates.

The following are the ones used in this analysis:

- **H08** is a grid-cell based global hydrological model developed by the *National Institute for Environmental Studies* of Japan. It consists of six sub-models, namely land surface hydrology, river routing, reservoir operation, crop growth, environmental flow and water abstraction. In the standard simulation settings, H08 spatially covers the whole globe at a resolution of $0.5° \times 0.5°$ in order to assess geographical heterogeneity of hydrology and water use. The six sub-models exchange water fluxes and updates water storage at each calculation interval with the complete closure of water balance (the error is less than 0.01% of the total input precipitation). Source code and the manuals of H08 is open to public, available at [18].

- **LPJmL** (*Lund-Potsdam-Jena managed Land*) [19] is a multi-sectoral dynamic global vegetation model, suited to address the water sector as it includes the full terrestrial water balance with irrigation modules. It is managed by the *Potsdam Institute for Climate Impact Research*. It is designed to simulate vegetation composition and distribution as well as stocks and land-atmosphere exchange flows of carbon and water, for both natural and agricultural ecosystems.

- **MPI-HM** [20] is a global hydrological model developed by the *Max Planck Institute* to investigate hydrological research questions mostly related to high resolution river routing. While hydrological processes are implemented in similar complexity as in full land surface models, the MPI-HM does not compute any energy-related fluxes.

- **PCR-GLOBWB** [21] stands for PCRaster Global Water Balance. It 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 for each grid cell (0.5 degree globally over the land) and for each time step (daily) the water storage in two vertically stacked 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. Water use for agriculture, industry and households is dynamically linked to hydrological simulation at a daily time step. The simulated local direct runoff, interflow, and baseflow are routed along the river network that is also linked to water allocation and reservoir operation scheme.

2.2.3 Representative Concentration Pathways (RCP)

The Intergovernmental Panel on Climate Change (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 [22]. The word *representative* signifies that each RCP provides only one of many possible scenarios that leads to the specific radiative forcing characteristics. The radiative forcing is the difference between the amount of energy that enters the Earth's atmosphere and the amount of energy that leaves it. The term forcing is used to indicate that Earth's radiative balance is pushed away from its normal state. It depends on several factors that affect climatic effects that are associated with increased atmospheric GHG concentrations [23]. In the IPCC Fifth Assessment Report [9], four RCPs are presented: **RCP 2.6**, **RCP 4.5**, **RCP 6.0** and **RCP 8.5**, based on the RCP of the Coupled Model Intercomparison Project Phase 5 (CMIP5). 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 Shared Socioeconomic Pathways (SSPs) which show how societal choices will affect GHG emissions and how the climate goals of the Paris Agreement could be met. SSPs are expected to fill the missing 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 in the near future reflecting the new trajectories of SSPs [24].

This report developed four scenarios based on four different RCPs. Each of them leads to a different global average temperature outcome: Below 2°C, Below 3°C, Around 3°C and Above 4°C, respectively. Mean global surface temperature provides a general description of the anthropogenic warming of the Earth's atmosphere - it is both a symbol and a valuable indicator for overall climate change.

By comparing these four 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 (global radiative forcing levels reach a maximum before 2050) 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(±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 is based on the assumption of reaching a peak in global GHG emission trends by mid-century and then decline (global radiative forcing levels are stabilized after around 2080).

- The **Around 3°C** scenario follows the trajectory of the RCP 6.0 which assumes a radioactive forcing value of around 6.0 W/m2 in the year of 2100. The RCP 6.0 is associated with a rise of 2.8(±0.5) °C in global annual mean temperature for the period of 2080-2100 compared to the pre-industrial level. The RCP 6.0 is based on the assumption of stabilisation of total radiative forcing after 2100. Under the scenario global GHG emission would peak during the latter half of the century and then decline (global radiative forcing levels are stabilized after around 2150).

- 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 2.5: Overview of the scenarios

Representative Concentration Pathway	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Targeted radiative forcing in the year of 2100	2.6 W/m^2	4.5 W/m^2	6.0 W/m^2	8.5 W/m^2
CO_2 - equivalent concentrations (ppm)	430-480	580-720	720-1000	>1000
Global temperature change	1.6(±0.4)°C	2.4(±0.5)°C	2.8(±0.5)°C	4.3(±0.7)°C
Likelihood of staying below a specific temperature level over the 21st century	Likely to stay below 2°C	Likely to stay below 3°C	More unlikely than likely to stay below 3°C	More unlikely than likely to stay below 4°C

Chapter 3

Data Analysis

The first step in enhancing climate resilience of the electricity system is performing a comprehensive and systematic assessment of risks and impacts based on scientific evidence. Climate risk refers to the factors which are associated with the potential consequences of climate change, and largely determines the actual consequences of climate change, which are referred to as climate impacts.

3.1 Climate risks

Climate risk indicates the factors associated with the potential consequences of climate change. According to the Intergovernmental Panel on Climate Change (IPCC), created in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP), climate risk results from the interaction of hazard, exposure and vulnerability [25].

- **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 [24].

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.

3.1.1 Hazards

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 [24].

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 IPCC Fifth Assessment Report, 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 [26]. 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 a consistent reduction in precipitation and runoff [27] over the coming century, which would consequently have negative implications to hydropower generation. Similarly, overall reductions to hydropower generation [28] 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.

> *70% of the models projected that, by the end of the 21st century, extreme events would occur more than 10 times in 30 years.* (Chile NAP, 2015)

> *Changes in river flows can generate significant impacts on hydroelectric generation and severe winds can affect the network infrastructure. Towards the end of century there could be a negative impact on hydroelectric generation in the regions of the Andes of Cuyo, Comahue and Patagonia, since the projections of precipitation in these areas are negative for the long term. [...] The greater frequency of intense rainfall would aggravate the damage to the electrical distribution system.* (Argentina NAP, 2019)

Conversely, coastal regions of Andean countries, such as Peru, Ecuador and Colombia, are projected to have more rainfall [27]. For example, in Colombia the annual average rainfall is projected to increase from 0.8% to 1.6% overall, although some areas of Colombia could suffer from decreasing precipitation [29]. An increment in precipitation in the Paute River basin of Ecuador would lead to an increase in hydropower generation capacity.

> *In the last 50 years, 90% of disasters have been due to hydrometeorological phenomena. There is evidence that both the number of disasters associated with climate variables and the intensity of extreme events are increasing.* (Colombia NAP, 2016)

> *The country faces a high exposure to hydro-meteorological threats, where 72% of total national emergencies are related to this kind of phenomena, such as severe droughts, rains, floods, frost, among others. [...] These phenomena are exacerbated and expanded due to climate change, including greater difficulties in forecasting their cycles and intensities.* (Peru INDC, 2015)

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 data from several models provides a disparate rainfall variance ranging from between +40 mm to -38 mm across the country [30]. For southeast Brazil, different models calculated a vague precipitation pattern between -30% to +30%. And for the Amazon in Brazil, 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. A study 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 [31].

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 increased, 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 [32].

Climate models 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 [29], while Chile is projected to experience more extreme events by over 10 times in the next 30 years [33].

El Niño-Southern Oscillations could exacerbate those extreme precipitation events, although there are ongoing debates on how anthropogenic climate change and ENSO interact [34]. 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. The 2015-16 El Niño phenomenon, one of the three strongest El Niño events since 1950, led to one of the worst droughts in Mexico and Central America, where precipitation and runoff were already declining due to climate change [35]. 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 one of the main causes of marked inconsistency in precipitation projections in South America. As modelling improves, biases in ENSO would be reduced while increasing the accuracy of future streamflow and hydropower generation projections [36].

3.1.2 Exposure

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. The total 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. In countries such as Panama, Ecuador and Paraguay, hydropower's share of electricity generation exceeds 70% [37].

The role of hydropower in Latin America is likely to remain significant or potentially increase. According to the IEA's Renewables 2020, hydropower additions in Latin America are expected to be stable during the next five years (2021-25) at 2 GW per year [38]. 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 World Energy Outlook 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 [39].

Already in 2019 significant hydropower capacity was added in Latin America. South America saw the fastest hydropower growth rate and became the region with the second highest capacity added in the world. Brazil alone added 4,919 MW hydropower capacity, which was mainly attributed to the completion of the 11,233 MW Belo Monte hydropower plant [1].

A **strong reliance on hydropower** 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 operation of hydropower by increasing variability in streamflow, shifting seasonal flows and augmenting evaporation losses from reservoirs [25]. 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.

3.1.3 Vulnerability

Vulnerability describes the extent to which an exposed system is susceptible to disruptions or stress; it also refers to how restricted that system is in its ability to cope with or overcome these challenges. As such, it is a measure of the sensitivity of the human-environment system to the negative effects of climate change at any given stage; it also describes its ability or lack of ability to overcome the consequences of climate change. Vulnerability is counteracted by resilience.

Over 50% of the installed capacity in Latin America is over 30 years old [40]. In Mexico, most hydropower plants are older than 50 years [41]. Given the limited availability of capital and increasing environmental constraints for new hydropower projects across the region, an extended lifetime of existing hydropower plants is likely to become common practice in Latin America [42]. For instance, the typical average technical lifetime of a hydropower facility in Peru is estimated to be between 81 and 104 years, which is longer than a usual lifespan of hydropower, 30 to 80 years.

Ageing of hydropower assets in Latin America drives the trend to modernise the hydropower fleet. According to a recent study 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 for modernisation** [40].

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 due to extreme precipitation events can accelerate equipment ageing [43]. 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.

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 increase up to 55% on average [44]. In fact, when a drought hit southeast Brazil in 2014, the shortage of water created conflicts between different users. The drought affected hydropower generation, urban supply and wastewater treatment until it was finally settled by an agreement among sectors [45].

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%) [46]. To avoid further deforestation, some Latin American countries including Mexico, Costa Rica, Ecuador, Brazil and Colombia have implemented Payment for Ecosystem Services (PES) programmes [47].

The document *Index of Vulnerability and Adaptation to Climate Change in the Latin American and Caribbean Region* [48], prepared by the Latin American Development Bank (CAF) analysed vulnerability to climate change and places Guatemala and Paraguay in the category of **extreme risk**, in position number 2 and 8 among 33 countries in Latin America and the Caribbean. In Table 3.1 the info on the 13 selected countries are summarized.

Table 3.1: Index of Vulnerability and Adaptation to Climate Change

Country	Vulnerability index position	CVI	Risk category
Guatemala	2	0.75	extreme
Paraguay	8	1.58	
Venezuela	11	3.64	high
Ecuador	12	3.76	
Colombia	16	4.3	
Mexico	17	4.47	
Peru	18	4.98	
Panama	19	5.57	medium
Brazil	21	5.77	
Argentina	24	6.66	
Costa Rica	26	7.7	low
Uruguay	28	8.33	
Chile	30	9.54	

The Climate Change Vulnerability Index (CVI) is made up of three indices.
- **Exposure index** (50%): assessing a region's risk of being impacted by climate-related extreme events (drought, wildfires, tropical cyclones and storms, etc).
- **Sensitivity index** (25%): assessing the population's susceptibility to the impacts of climate change.
- **Adaptive Capacity Index** (25%): assessing the ability or potential of a country's institutions, economy and society to adjust to existing or expected pressures resulting from climate change or to take advantage of them.

Related to this study, Guatemala is the most exposed country (among the 13 selected) to the potential impacts of climate change and the most sensitive (it is the only country that is in the extreme risk category both for exposure index and the sensitivity index).

3.2 Climate impacts

The actual consequences of the changing climate are called climate impacts. The increasing anomalies in climate patterns directly affect all stages of the entire energy value chain of electricity systems, including fuel supply, generation, transmission and distribution, and demand. They can change resource availability, reduce generation efficiency, increase physical risks to grids and assets and alter demand patterns.

The recent trends of increasing renewable energy penetration as an effort to mitigate climate change, may also have unintended impacts on electricity systems, intensifying the level of climate-related stress. An electricity system with a high share of renewable sources could become more susceptible to climate change since renewables such as solar, wind and hydro tend to be sensitive to climate impacts [49]. Hydropower plants operate for multiple decades, sometimes even beyond 100 years, and as such are likely to be impacted by climate change during their lifespan. So, the changes in long-term climate patterns directly affect hydropower generation.

3.2.1 Plant level analysis

The first step in conducting the impact analysis was to look at each power plant within each country, analyzing the raw data provided by the consultants in CSV format. The main passages were to select the targeted countries, define which data might be useful and must be maintained (without considering the design discharge and the monthly discharge rates), organize them clearly in separate sheets. As there were repetitive actions to be performed for 80 files with the same layout, it was useful to program a macro with Visual Basic for Application in Excel that analyses every file without doing it manually and then put the data relative to the same country in a single sheet, merging the information.

For every hydropower plant we have 1360 rows (the combinations of 5 GCMs * 4 GHMs * 4 RCPs * 17 timesteps), so for countries like Brazil we can end up with more than 250.000 rows, only considering the annual load factor without splitting it into months. A Pivot table is essential in order to organize data and easily divide them by time-steps. In Table 3.2 the 150 MW Agua del Toro plant in Argentina has been taken as an example. At this point, we have to consider the variation of the capacity factor as a percentage with respect to the base period data, which of course represents 0% (Table 3.3).

The analysis of the capacity factor performance was carried out taking as reference only the trends for the different RCP scenarios, without considering the differences among the five GCMs and the four GHMs. We use the multitude of data to be more accurate in our estimates and we merged the outcomes from the climate models together with a sample average. In Table 3.3 the most important parameters highlighted are the mean annual variability and the mean uncertainty (calculated as an average among the relative standard deviation of each time-step) for all RCPs, while the values in the Trends row were used to build the outcome of this preliminary analysis: a bar chart like the one in Figure 3.1 for the plant Agua del Toro in Argentina, obtained by repeating the analysis for each of the 4 RCP scenarios.

In this case, from 2050 onwards, the CO_2 concentration directly influences the capacity factor, leading to a potential reduction of almost 50% in 100 years.

Table 3.2: Time-steps division for RCP 2.6

Agua del Toro	Baseline	2020-2025	2025-2030	2030-2035	2035-2040	2040-2045	2045-2050	2050-2055	2055-2060	2060-2065	2065-2070	2070-2075	2075-2080	2080-2085	2085-2090	2090-2095	2095-2100
h08																	
gfdl	0.555	0.509	0.466	0.530	0.453	0.400	0.536	0.445	0.415	0.504	0.422	0.516	0.537	0.471	0.497	0.454	0.429
hadgem	0.547	0.508	0.524	0.489	0.463	0.469	0.475	0.511	0.504	0.543	0.560	0.473	0.553	0.455	0.594	0.424	0.431
ipsl	0.555	0.609	0.502	0.513	0.497	0.453	0.539	0.513	0.504	0.497	0.582	0.463	0.503	0.514	0.516	0.524	0.534
miroc	0.572	0.507	0.577	0.607	0.565	0.460	0.555	0.515	0.477	0.563	0.499	0.580	0.507	0.559	0.548	0.476	0.578
noresm	0.553	0.576	0.513	0.496	0.535	0.585	0.477	0.541	0.529	0.475	0.535	0.610	0.500	0.563	0.540	0.505	0.478
lpjml																	
gfdl	0.564	0.460	0.457	0.571	0.385	0.374	0.596	0.470	0.404	0.469	0.423	0.533	0.529	0.407	0.534	0.430	0.412
hadgem	0.592	0.573	0.663	0.566	0.538	0.492	0.589	0.570	0.617	0.593	0.639	0.503	0.649	0.512	0.691	0.559	0.448
ipsl	0.637	0.677	0.567	0.560	0.487	0.466	0.639	0.578	0.504	0.460	0.602	0.442	0.570	0.590	0.620	0.557	0.609
miroc	0.577	0.528	0.526	0.624	0.533	0.454	0.537	0.455	0.454	0.573	0.457	0.542	0.417	0.513	0.514	0.425	0.601
noresm	0.648	0.619	0.526	0.511	0.451	0.660	0.463	0.626	0.621	0.473	0.647	0.693	0.482	0.626	0.518	0.537	0.518
mpihm																	
gfdl	0.752	0.541	0.564	0.732	0.455	0.275	0.709	0.445	0.409	0.573	0.543	0.650	0.691	0.520	0.551	0.588	0.397
hadgem	0.716	0.735	0.816	0.617	0.589	0.491	0.643	0.708	0.640	0.756	0.676	0.535	0.810	0.574	0.912	0.524	0.475
ipsl	0.674	0.674	0.619	0.595	0.464	0.370	0.593	0.617	0.490	0.532	0.724	0.459	0.566	0.616	0.673	0.610	0.619
miroc	0.701	0.612	0.727	0.661	0.667	0.475	0.656	0.605	0.492	0.658	0.531	0.631	0.522	0.652	0.622	0.542	0.717
noresm	0.751	0.728	0.597	0.474	0.434	0.763	0.418	0.629	0.586	0.537	0.713	0.793	0.445	0.738	0.585	0.526	0.502
pcrglobwb																	
gfdl	0.930	0.777	0.710	0.928	0.660	0.487	0.875	0.692	0.560	0.697	0.739	0.852	0.954	0.770	0.691	0.863	0.606
hadgem	0.885	0.981	0.873	0.867	0.687	0.731	0.822	0.945	0.775	0.942	1.000	0.854	0.961	0.814	0.989	0.836	0.644
ipsl	0.913	0.960	0.969	0.843	0.648	0.614	0.767	0.774	0.729	0.643	0.961	0.701	0.701	0.910	0.863	0.829	0.908
miroc	0.920	0.821	0.936	0.994	0.828	0.767	0.801	0.775	0.708	0.913	0.717	0.819	0.651	0.838	0.869	0.721	0.928
noresm	0.936	0.995	0.814	0.779	0.818	0.956	0.739	0.834	0.803	0.803	0.936	1.000	0.779	0.938	0.825	0.670	0.786

Table 3.3: Combination of climate models for RCP 2.6

GHM	GCM	Baseline	2020-2025	2025-2030	2030-2035	2035-2040	2040-2045	2045-2050	2050-2055	2055-2060	2060-2065	2065-2070	2070-2075	2075-2080	2080-2085	2085-2090	2090-2095	2095-2100	Annual Variability	
h08	gfdl	0%	-8%	-16%	-4%	-18%	-28%	-3%	-20%	-25%	-9%	-24%	-7%	-3%	-15%	-10%	-18%	-23%	0.084	
	hadgem	0%	-7%	-4%	-11%	-15%	-14%	-13%	-7%	-8%	-1%	2%	-14%	1%	-17%	9%	-22%	-21%	0.085	
	ipsl	0%	10%	-10%	-8%	-11%	-18%	-3%	-8%	-9%	-10%	5%	-17%	-9%	-7%	-7%	-6%	-4%	0.067	
	miroc	0%	-11%	1%	6%	-1%	-20%	-3%	-10%	-17%	-2%	-13%	1%	-11%	-2%	-4%	-17%	1%	0.074	
	noresm	0%	4%	-7%	-10%	-3%	6%	-14%	-2%	-4%	-14%	-3%	10%	-9%	2%	-2%	-9%	-14%	0.069	
lpjml	gfdl	0%	-18%	-19%	1%	-32%	-34%	6%	-17%	-28%	-17%	-25%	-5%	-6%	-28%	-5%	-24%	-27%	0.121	
	hadgem	0%	-3%	12%	-4%	-9%	-17%	0%	-4%	4%	0%	8%	-15%	10%	-13%	17%	-6%	-24%	0.106	
	ipsl	0%	6%	-11%	-12%	-24%	-27%	0%	-9%	-21%	-28%	-5%	-31%	-10%	-7%	-3%	-13%	-4%	0.105	
	miroc	0%	-8%	-9%	8%	-8%	-21%	-7%	-21%	-21%	-1%	-21%	-6%	-28%	-11%	-11%	-26%	4%	0.103	
	noresm	0%	-4%	-19%	-21%	-30%	2%	-29%	-3%	-4%	-27%	0%	7%	-26%	-3%	-20%	-17%	-20%	0.119	
mpihm	gfdl	0%	-28%	-25%	-3%	-39%	-63%	-6%	-41%	-46%	-24%	-28%	-14%	-8%	-31%	-27%	-22%	-47%	0.168	
	hadgem	0%	3%	14%	-14%	-18%	-31%	-10%	-1%	-11%	6%	-6%	-25%	13%	-20%	28%	-27%	-34%	0.167	
	ipsl	0%	0%	-8%	-12%	-31%	-45%	-12%	-8%	-27%	-21%	7%	-32%	-16%	-9%	0%	-10%	-8%	0.133	
	miroc	0%	-13%	4%	-6%	-5%	-32%	-7%	-14%	-30%	-6%	-24%	-10%	-26%	-7%	-11%	-23%	2%	0.107	
	noresm	0%	-3%	-21%	-37%	-42%	2%	-44%	-16%	-22%	-28%	-5%	6%	-41%	-2%	-22%	-30%	-33%	0.163	
pcrglobwb	gfdl	0%	-17%	-24%	0%	-29%	-48%	-6%	-26%	-40%	-25%	-21%	-8%	3%	-17%	-26%	-7%	-35%	0.141	
	hadgem	0%	11%	-1%	-2%	-22%	-17%	-7%	7%	-12%	6%	13%	-3%	9%	-8%	12%	-5%	-27%	0.117	
	ipsl	0%	5%	6%	-8%	-29%	-33%	-16%	-15%	-20%	-30%	5%	-23%	-23%	0%	-6%	-9%	-1%	0.128	
	miroc	0%	-11%	2%	8%	-10%	-17%	-13%	-16%	-23%	-1%	-22%	-11%	-29%	-9%	-6%	-22%	1%	0.100	
	noresm	0%	6%	-13%	-17%	-13%	2%	-21%	-11%	-14%	-14%	0%	7%	-17%	0%	-12%	-28%	-16%	0.098	
	Trends	0%	-4%	-7%	-7%	-19%	-23%	-10%	-12%	-19%	-12%	-8%	-9%	-11%	-10%	-5%	-17%	-16%	11%	**Mean annual variability**
	Uncer-tainty	0.000	0.098	0.109	0.100	0.116	0.170	0.106	0.098	0.116	0.116	0.125	0.117	0.137	0.085	0.131	0.079	0.142	0.115	**Mean uncertainty**

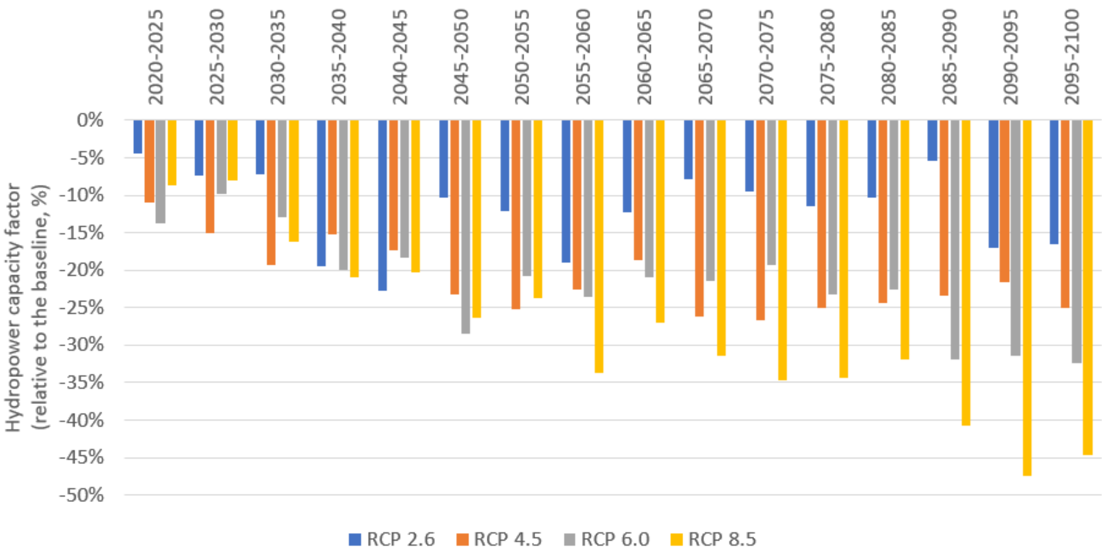


Figure 3.1: Outcome for Agua del Toro plant in Argentina

The change in capacity factor has to be linked with the variation in the energy produced by the hydropower plant. But it is not very useful to analyze information at such a detailed level, while it is interesting to have an overall picture of the national status. Therefore, plant level analysis is the starting point for country level analysis.

3.2.2 Country level annual analysis

After analyzing the outcomes for each plant, we can combine them through a weighted average of all the power plants taken into account, considering the installed capacity of each one in order to weigh their contribution to the country's total. The aggregated weighted data are shown in Table 3.4, where the only values above zero are written in red, marking an increase (although slight) in productivity. We can observe that those are all Andean countries, that are projected to have more rainfall; while the biggest negative variations are in Chile, Guatemala and Mexico, projected to see a consistent reduction in precipitation and runoff [27].

Table 3.4: Country level analysis

	Average trend				Annual variability			
	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Argentina	-8.2%	-11.7%	-12.4%	-18.3%	2.55%	4.24%	4.48%	8.05%
Brazil	-9.5%	-8.9%	-9.3%	-14.0%	3.54%	4.00%	3.51%	5.56%
Chile	-9.9%	-17.2%	-18.1%	-24.3%	3.98%	6.19%	7.48%	11.99%
Colombia	1.4%	1.9%	1.1%	0.5%	2.25%	2.64%	2.80%	2.23%
Costa Rica	-3.7%	-10.6%	-7.5%	-15.9%	4.17%	6.19%	5.15%	11.29%
Ecuador	-1.9%	1.1%	-0.3%	1.4%	2.30%	2.36%	1.64%	3.15%
Guatemala	-6.5%	-13.3%	-16.5%	-26.1%	6.94%	7.34%	7.97%	14.73%
Mexico	-9.7%	-16.8%	-15.5%	-23.1%	4.41%	5.23%	5.75%	11.09%
Panama	-1.5%	-5.5%	-3.7%	-9.5%	2.81%	3.64%	3.33%	7.63%
Paraguay	-8.0%	-6.1%	-8.1%	-14.9%	4.75%	5.62%	4.72%	6.25%
Peru	-0.2%	1.1%	1.1%	2.2%	2.90%	1.70%	2.11%	2.09%
Uruguay	-4.7%	-5.5%	-6.2%	-6.9%	3.56%	4.85%	3.53%	3.39%
Venezuela	-1.1%	-5.6%	-5.1%	-8.8%	3.65%	5.28%	5.87%	7.92%

As we can see in Figure 3.2, the differences between RCP 4.5 and RCP 6.0 are very small. Because of that, we will only consider 3 scenarios for future analysis, taking RCP 4.5 as a representative. Another consideration to be made when looking at the graph is that the differences between 2020-2060 and 2060-2100 are almost zero in the RCP 2.6 scenario and become more and more pronounced until they reach 90.4% in the first 40 years versus 82.6% in the second 40 years in the RCP 8.5 scenario.

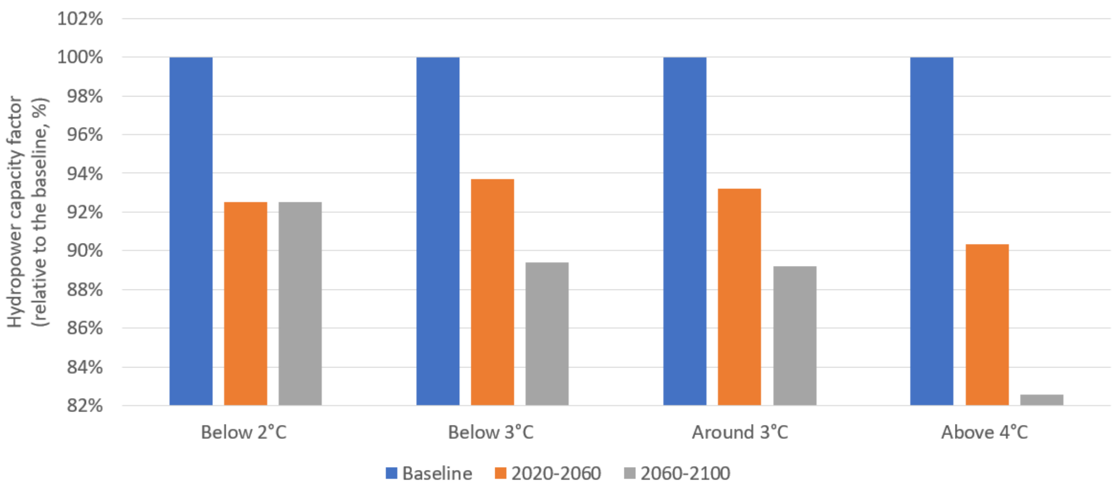


Figure 3.2: Overall analysis by RCP scenarios

Looking at the graphs from Figure 3.3 to Figure 3.15 it is possible to have a clearer view of the temporal trend of hydropower production for each country. They are ordered according to similarity in trend profile. Comments on this regard are in section 3.3 named Key Results.

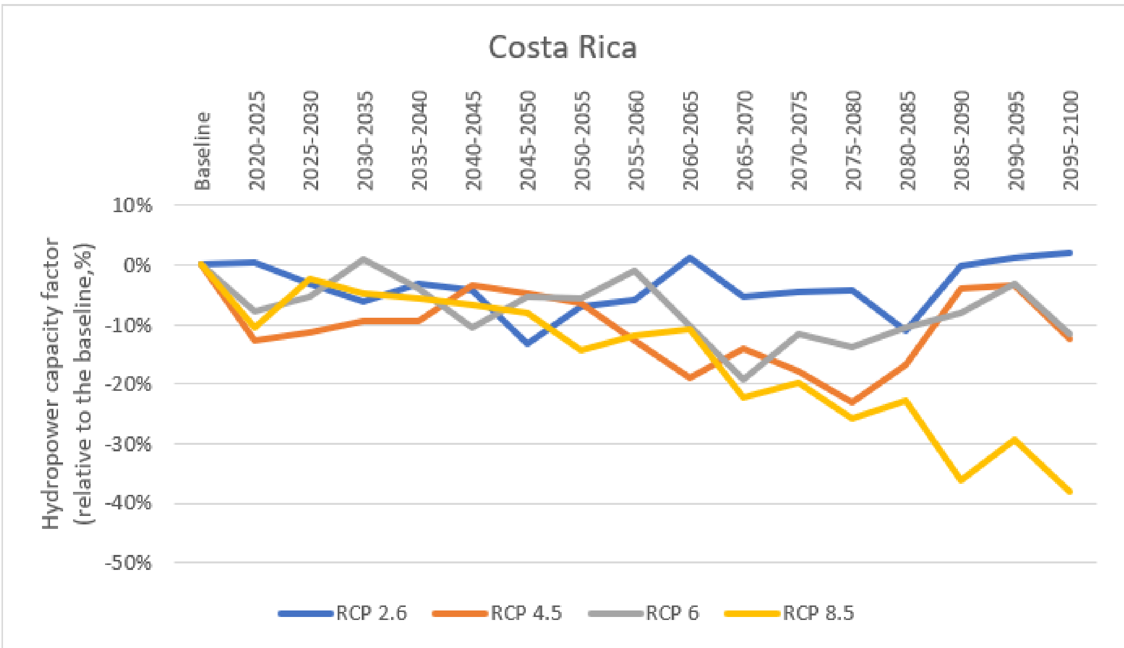


Figure 3.3: Country level annual analysis - Costa Rica

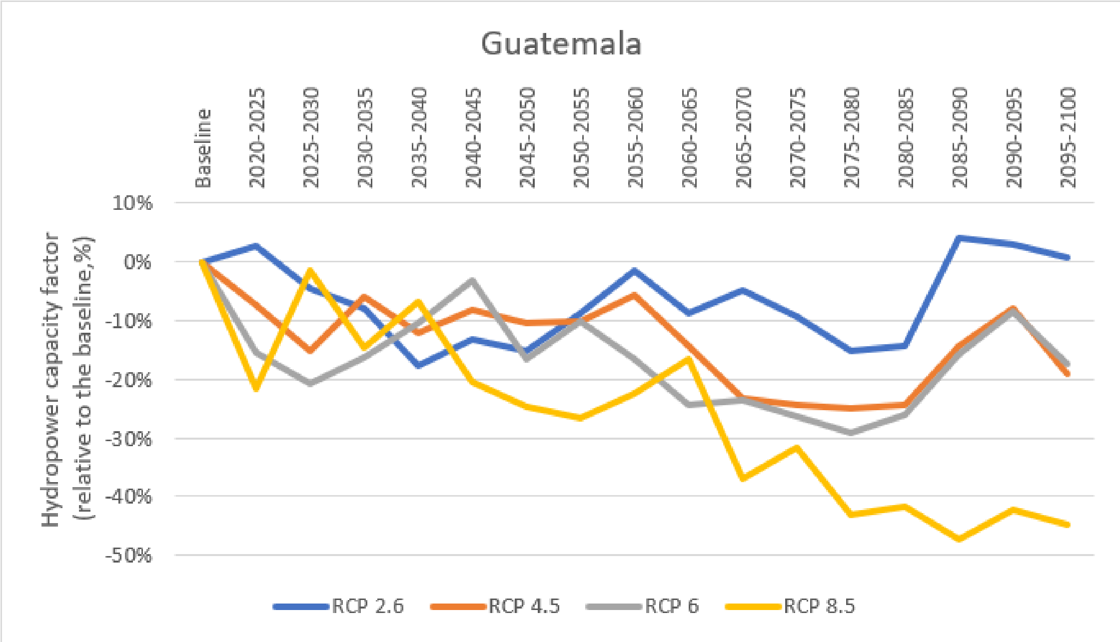


Figure 3.4: Country level annual analysis - Guatemala

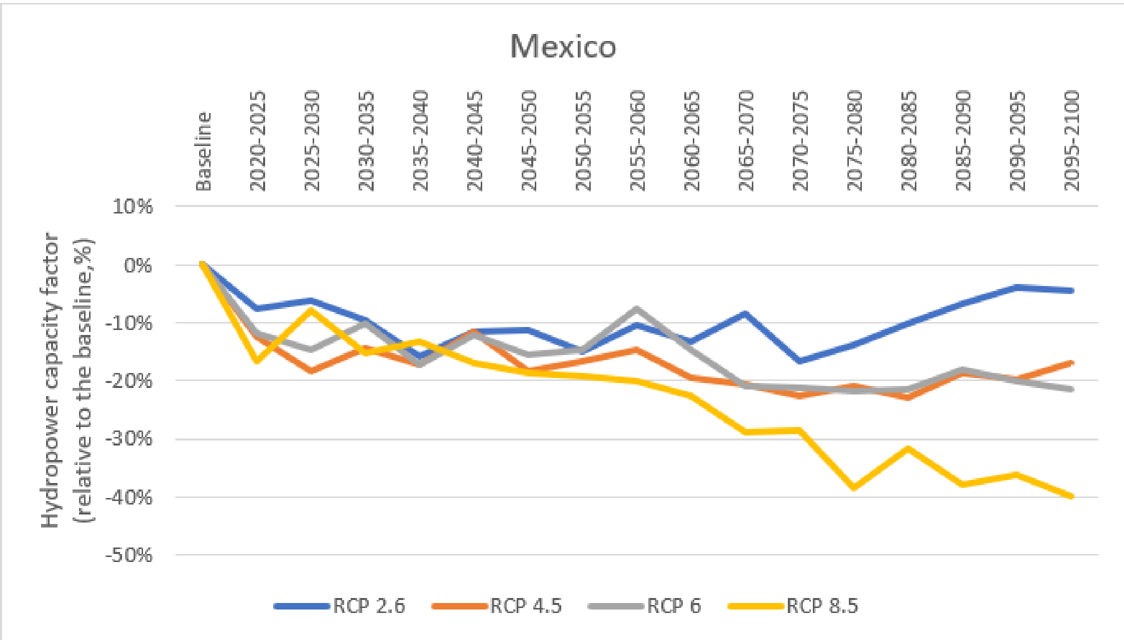


Figure 3.5: Country level annual analysis - Mexico

Costa Rica, Guatemala, Mexico and Panama are located in Central America: in Guatemala and Mexico the reduction in hydroelectric generation is most marked, while Panama, which is furthest south, already sees higher values.

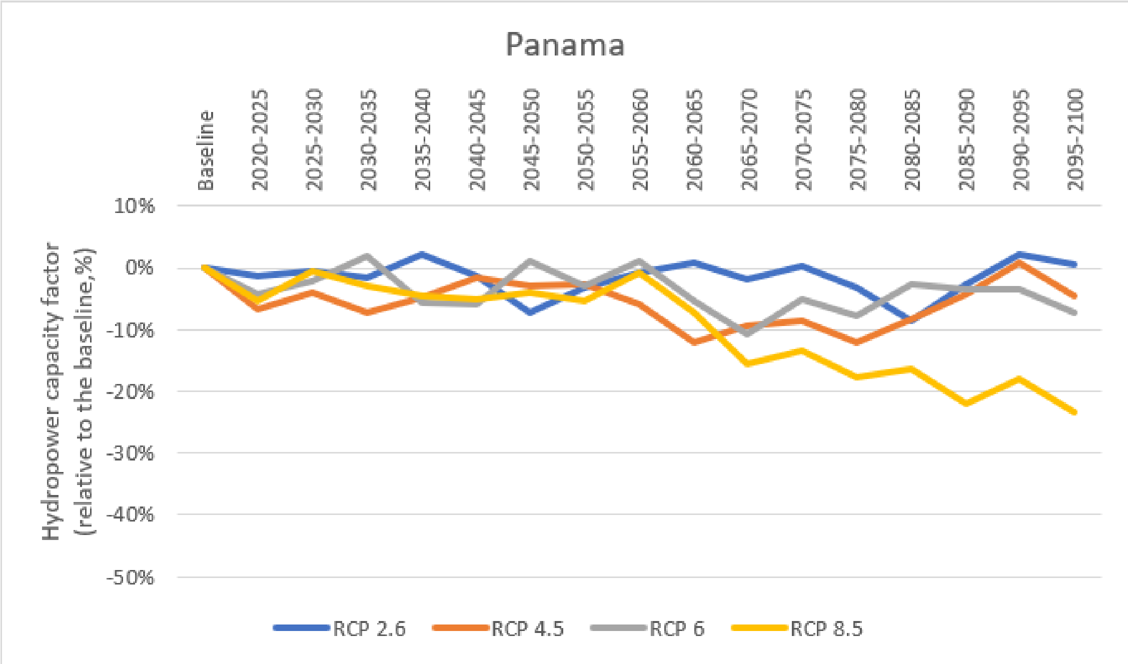


Figure 3.6: Country level annual analysis - Panama

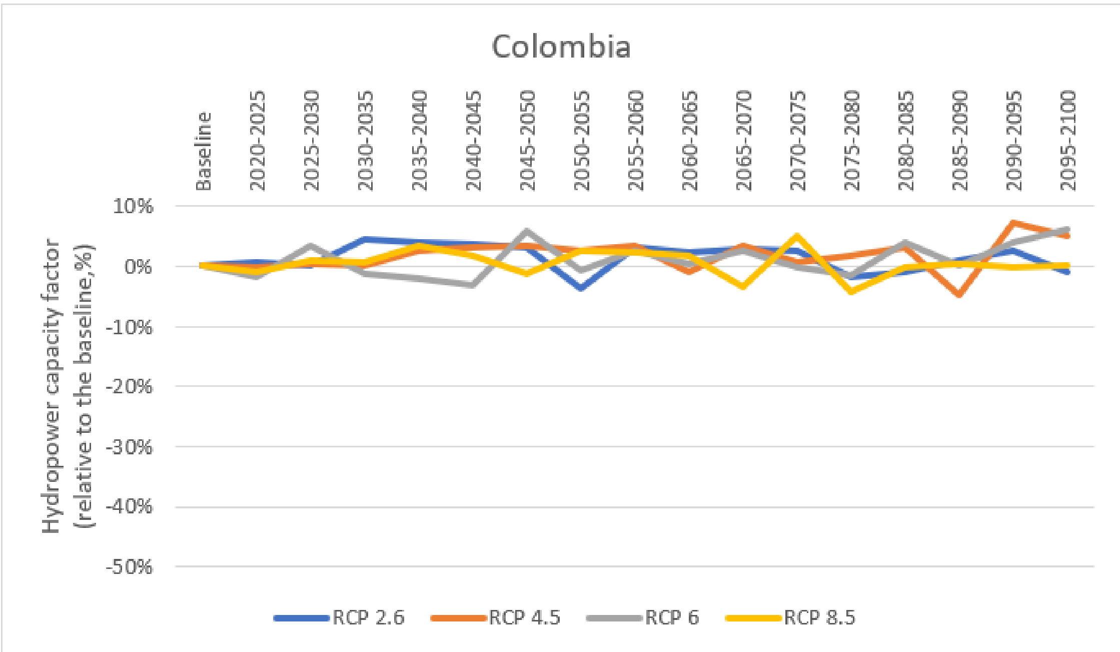


Figure 3.7: Country level annual analysis - Colombia

Colombia, Ecuador and Peru form the Andean region, the northern part of South America. There, productivity does not vary significantly, fluctuating around zero both in positive and negative values.

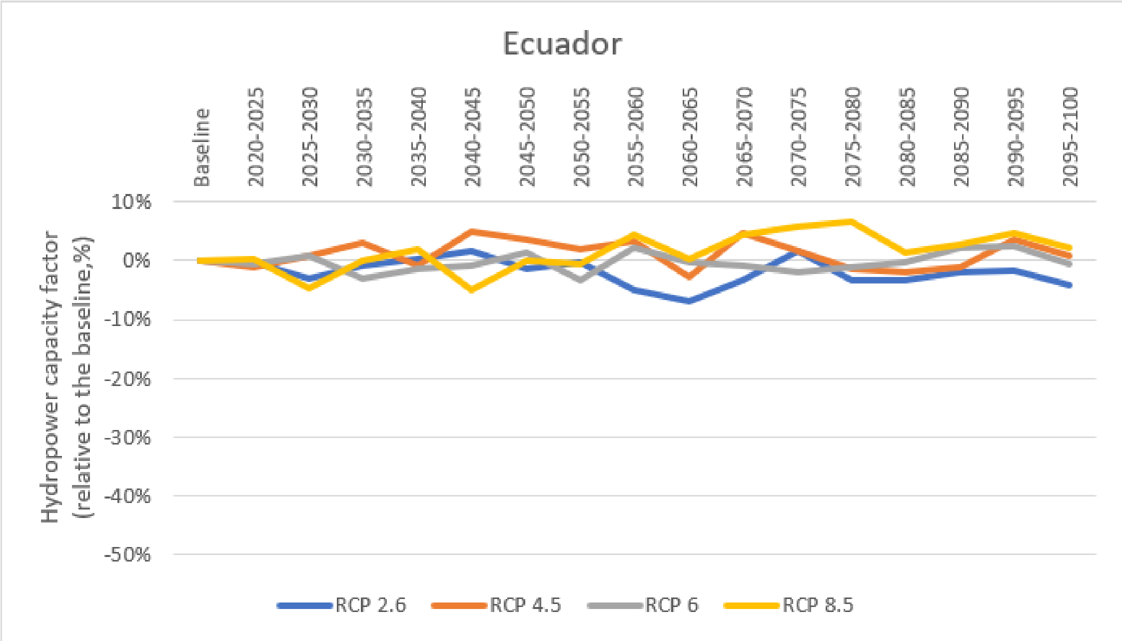


Figure 3.8: Country level annual analysis - Ecuador

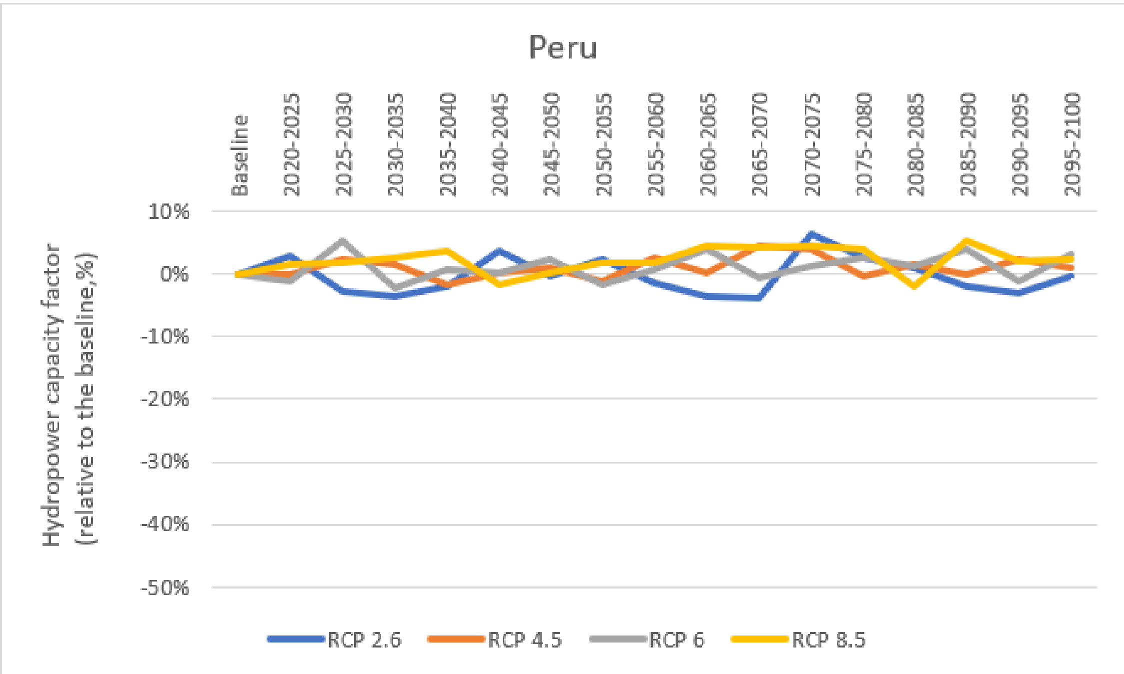


Figure 3.9: Country level annual analysis - Peru

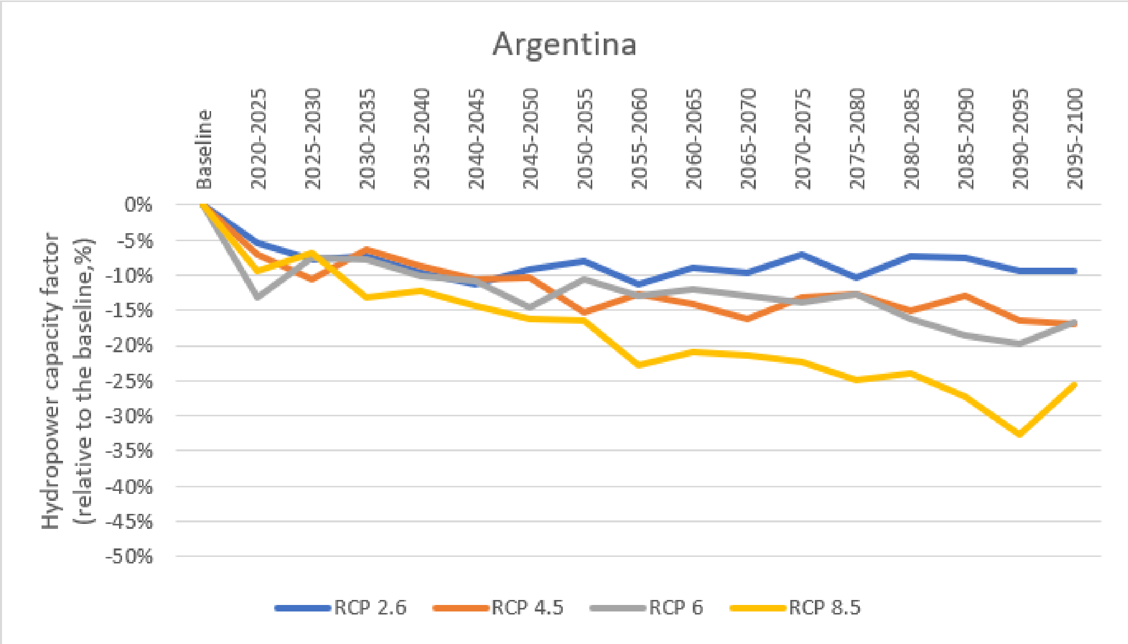


Figure 3.10: Country level annual analysis - Argentina

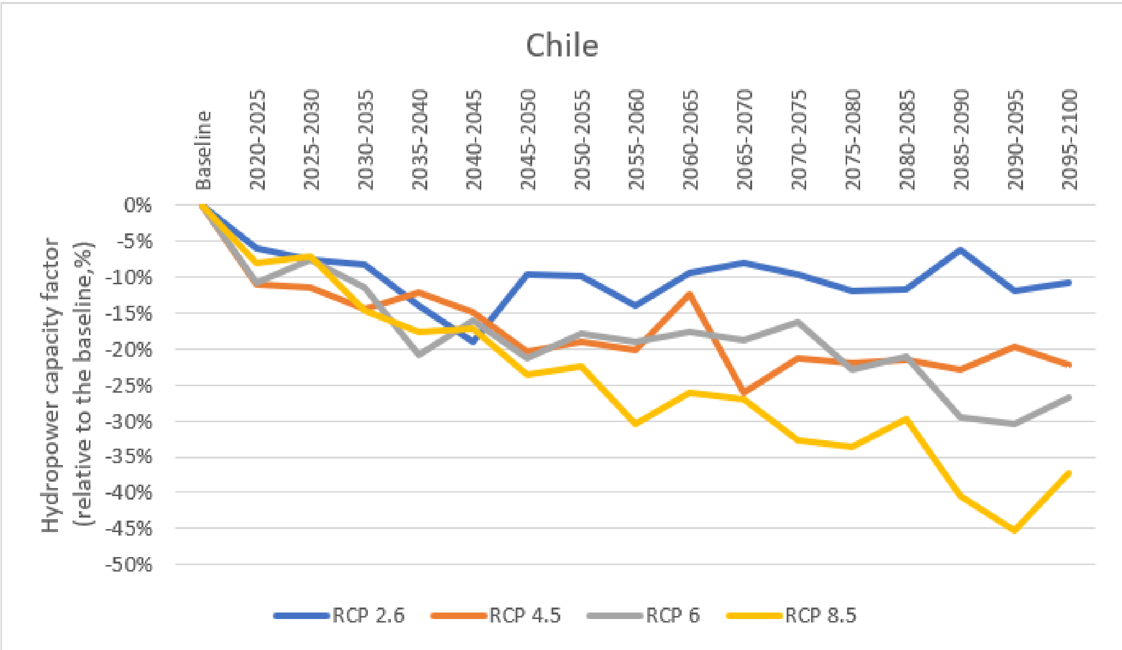


Figure 3.11: Country level annual analysis - Chile

Chile and Argentina are the most southern countries in Latin America and have a similar trend, characterised by significant capacity factor reductions, with large differences among power plants within the countries because of their stretched shape.

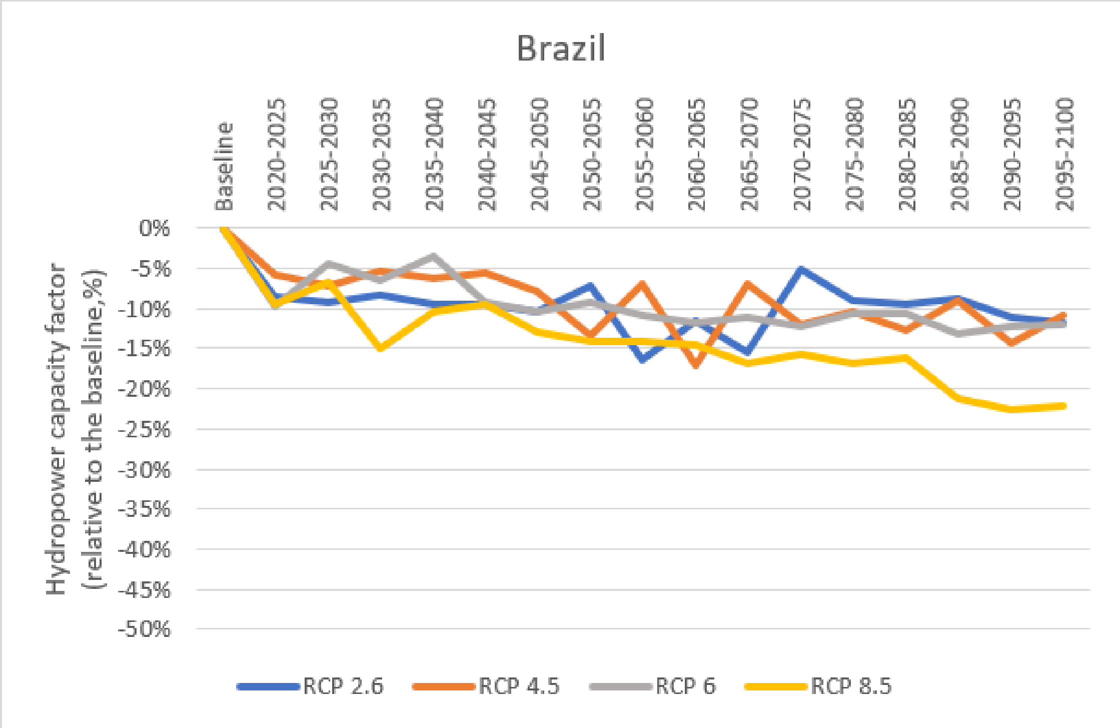


Figure 3.12: Country level annual analysis - Brazil

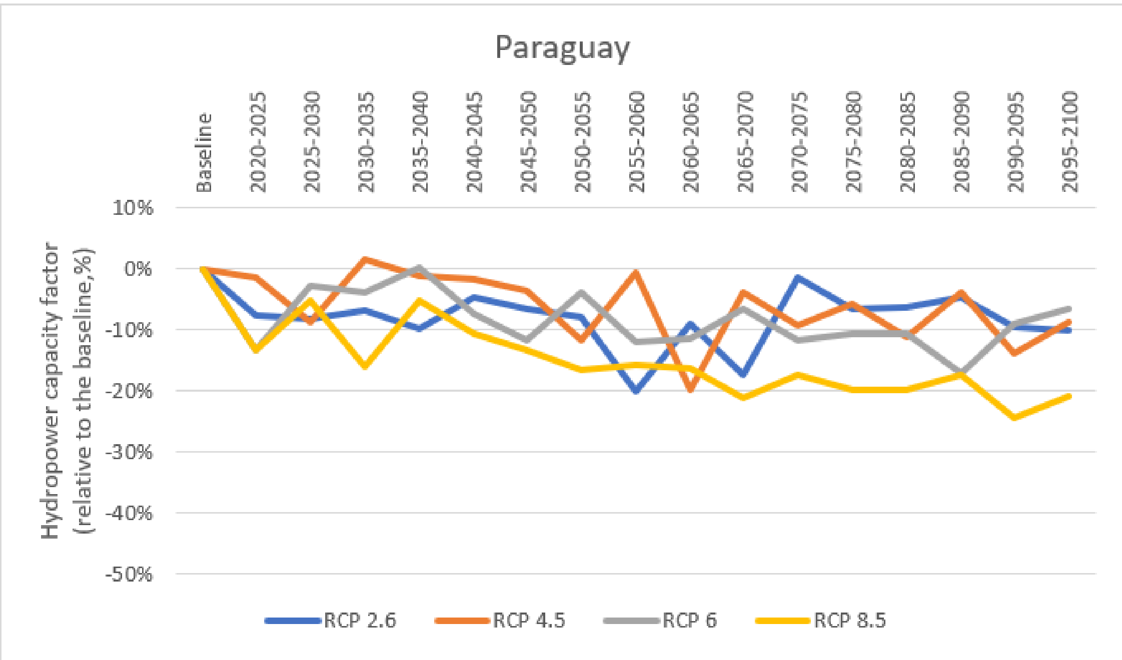


Figure 3.13: Country level annual analysis - Paraguay

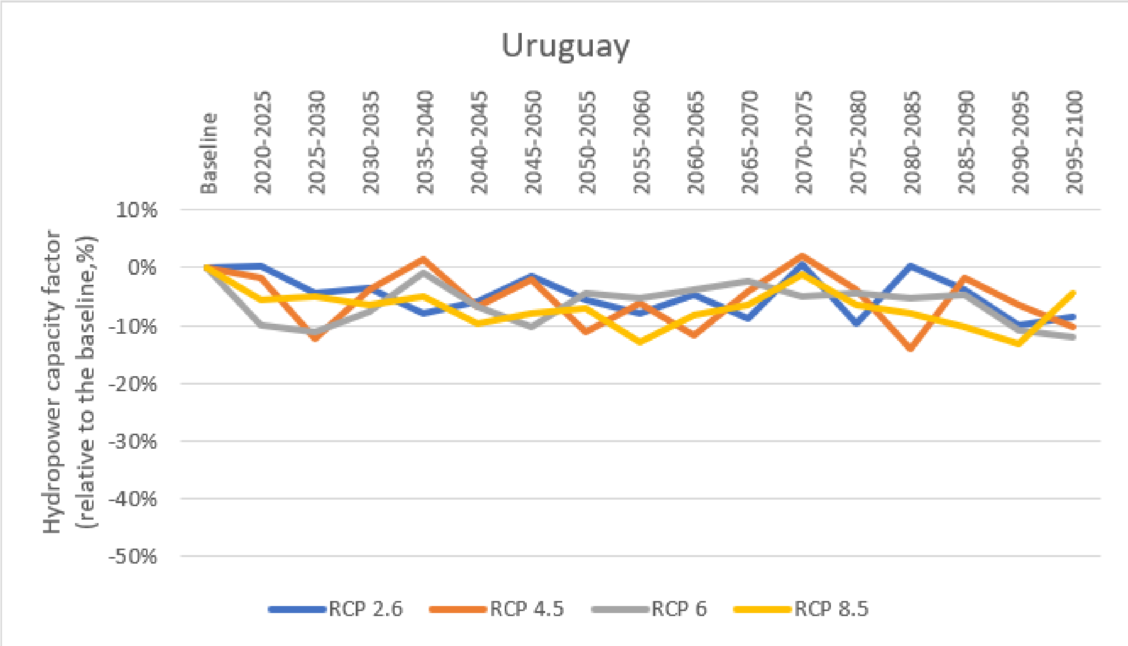


Figure 3.14: Country level annual analysis - Uruguay

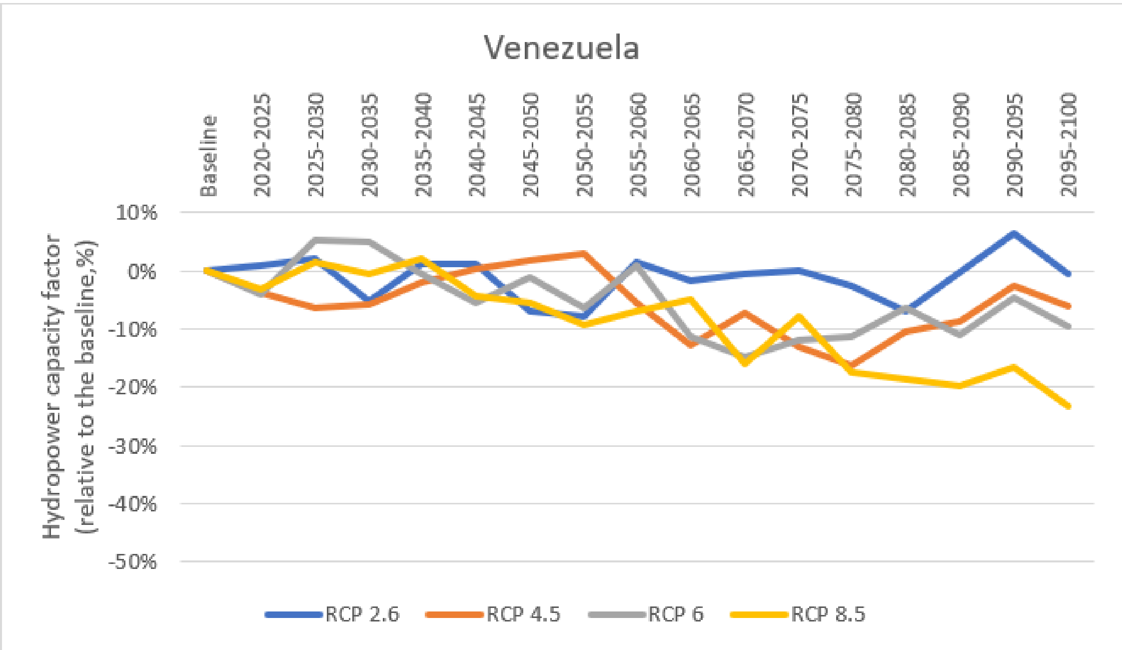


Figure 3.15: Country level annual analysis - Venezuela

Brazil, Paraguay, Uruguay and Venezuela are the remaining countries that do not belong to a specific region, varying from Venezuela in the north to Uruguay which is further south, through Brazil in the middle. Values never get too negative even in the scenario with the highest GHG concentration (never below -25%).

3.2.3 Sub-regional level analysis

Looking at the trends in the graphs and the data in the Table 3.4, it is possible to find some similarities between countries, which may be a key to grouping them into sub-regions. By dividing countries into 4 sub-regions according to geographical location (Figure 3.16), we can analyse the different trends over time (using weighted data and 3 RCPs scenarios).

Table 3.5: Sub-regional division

		RCP 2.6		RCP 4.5		RCP 8.5	
		2020-2060	2060-2100	2020-2060	2060-2100	2020-2060	2060-2100
Central America	Costa Rica	5%	3%	9%	14%	8%	26%
	Guatemala	8%	6%	9%	19%	17%	38%
	Mexico	11%	10%	15%	20%	16%	33%
	Panama	2%	2%	4%	7%	4%	17%
Andean countries	Colombia	-2%	-1%	-2%	-2%	-1%	0%
	Ecuador	1%	3%	-2%	0%	0%	-3%
	Peru	0%	0%	-1%	-2%	-2%	-3%
Southern South America	Argentina	9%	9%	10%	15%	14%	25%
	Chile	11%	10%	15%	21%	18%	34%
Rest of South America	Brazil	10%	10%	7%	12%	12%	18%
	Paraguay	9%	8%	3%	10%	12%	20%
	Uruguay	4%	6%	5%	6%	7%	7%
	Venezuela	2%	1%	2%	10%	3%	16%

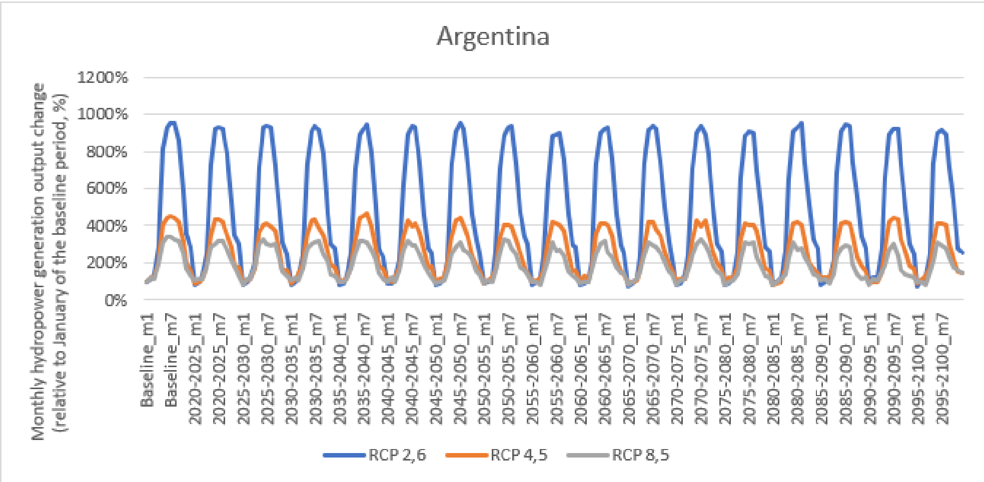
The major negative contributions in Central America are given by Guatemala and Mexico; the 3 Andean countries (at Equator level) act in the same way with very slight variations; the major negative contributions in the rest of South America are given by Brazil and Paraguay. In Chile, the most extended country in terms of length, trends for individual power plants vary a lot within the country. In case of RCP 8,5 they go from -19% (Los Molles plant) to -33% (Canutillar plant) according to the latitude (30,7°S and 41,5°S respectively).

Figure 3.16: Map of Latin America

3.2.4 Country level monthly analysis

The reason why it could be useful to perform a monthly analysis together with the annual analysis is that we can see seasonal differences more or less severe according to the scenario or the country. It is needed to be highlighted that these info were not added to the report released by the IEA, mainly because they do not add any extraordinary info with respect to what we found out before. In the raw data we had also the info divided per months, but in order to arrive at the final result, it was necessary to analyse again plant by plant, then considering the weight of each power station on the national total, with the same procedure followed in the annual analysis.

All countries, with the exception of Argentina, follow the same seasonal pattern in the three scenarios considered. The percentage refers to January of the baseline period (which represents 100%), the scale of values is so wide that we are unable to see variations between years in the order of 20% (ideally we should see the curves sloping downwards, but it is an imperceptible change in these graphs).
What we can analyze, however, is the order of magnitude of the variations throughout the year. We go from Brazil, Ecuador, Paraguay and Peru, where variations are in a small range, to Chile and Costa Rica where variations reach 10000%, so the capacity factor changes by a factor of 100 in a year, with very deep differences between summer and winter.



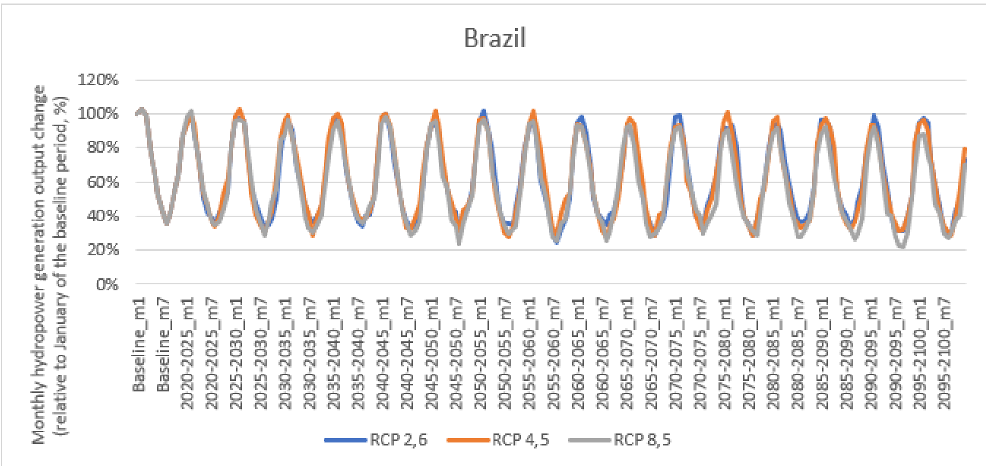


Figure 3.17: Country level monthly analysis - Argentina, Brazil

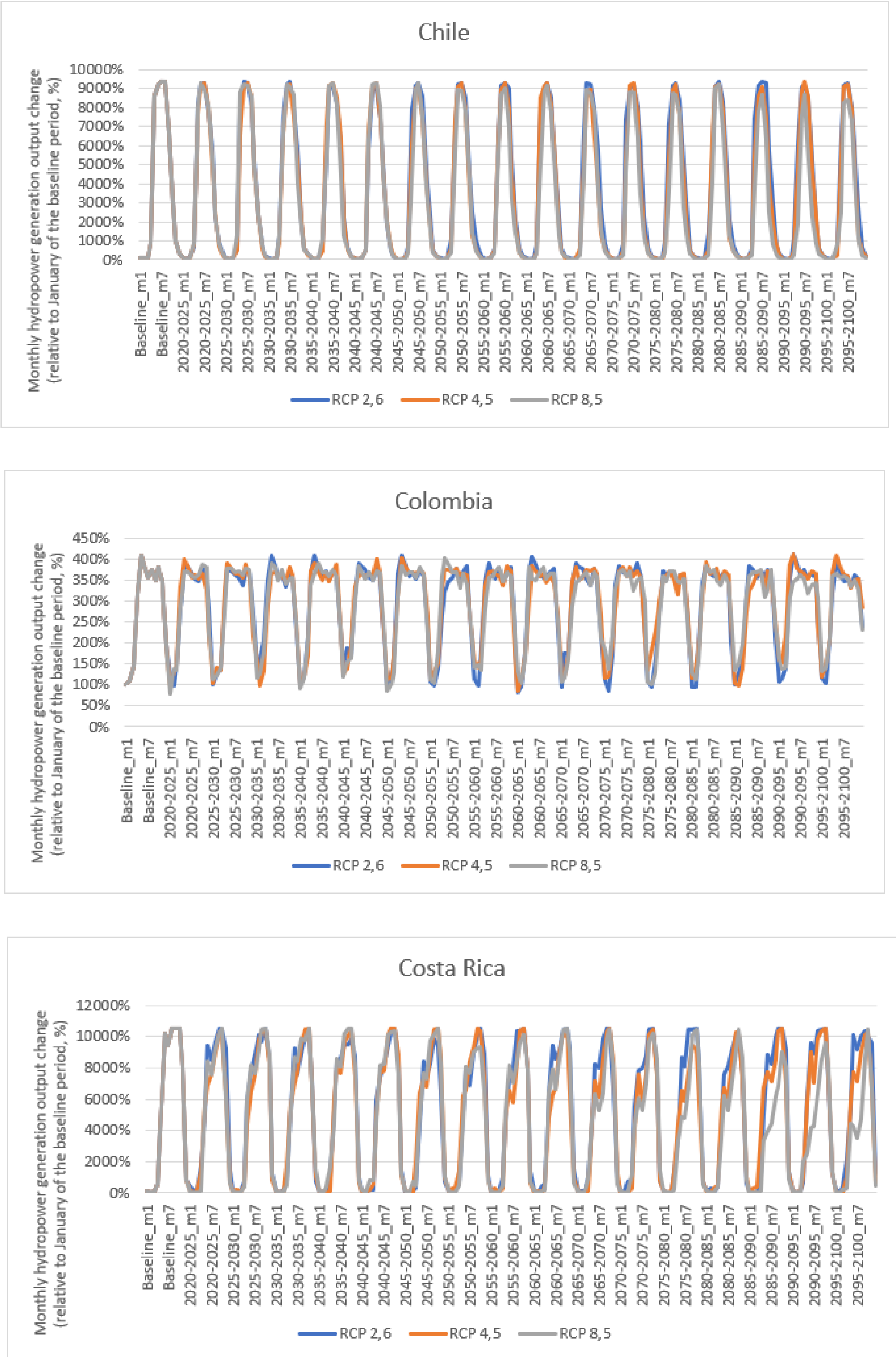


Figure 3.18: Country level monthly analysis - Chile, Colombia, Costa Rica

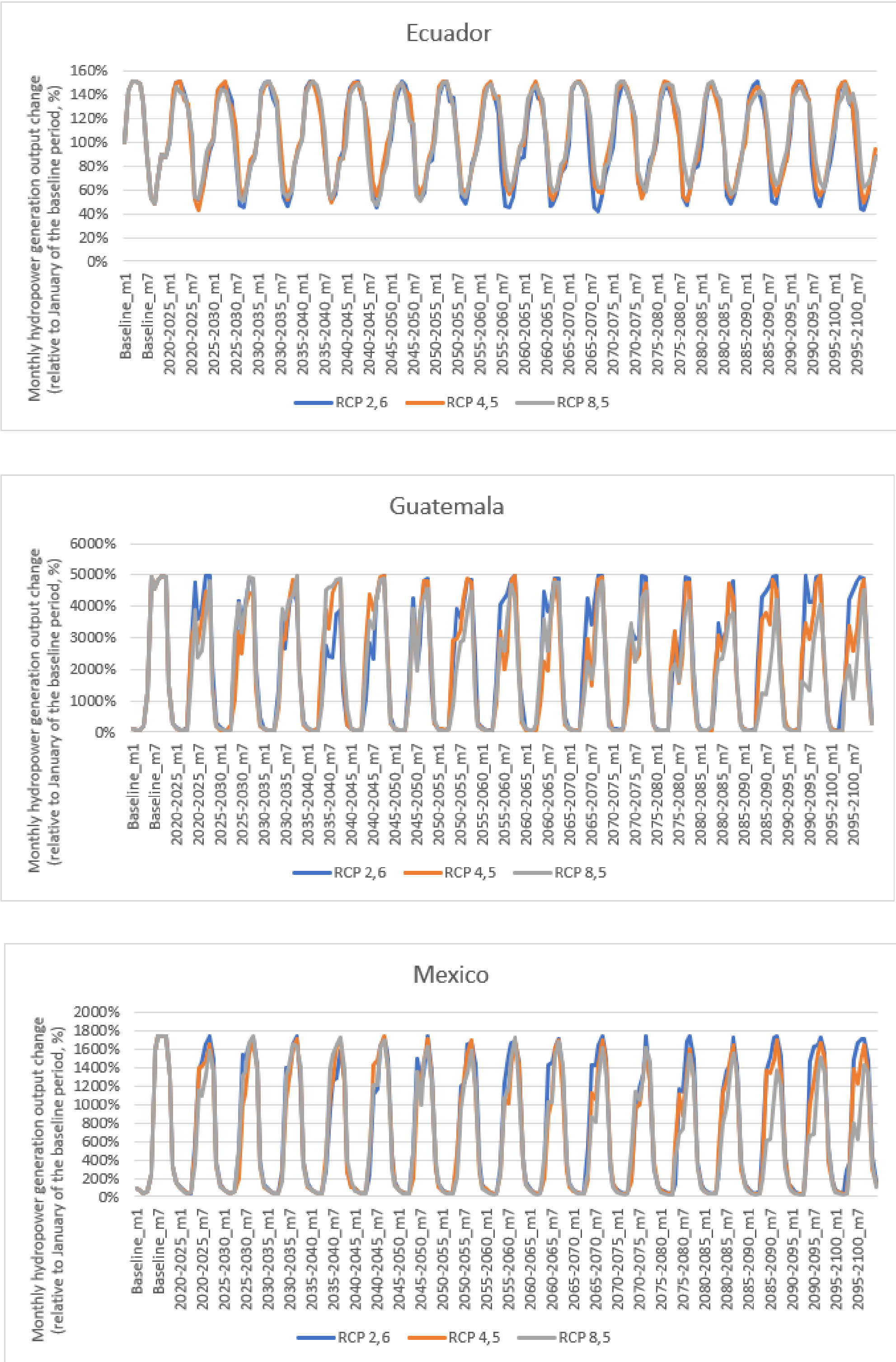


Figure 3.19: Country level monthly analysis - Ecuador, Guatemala, Mexico

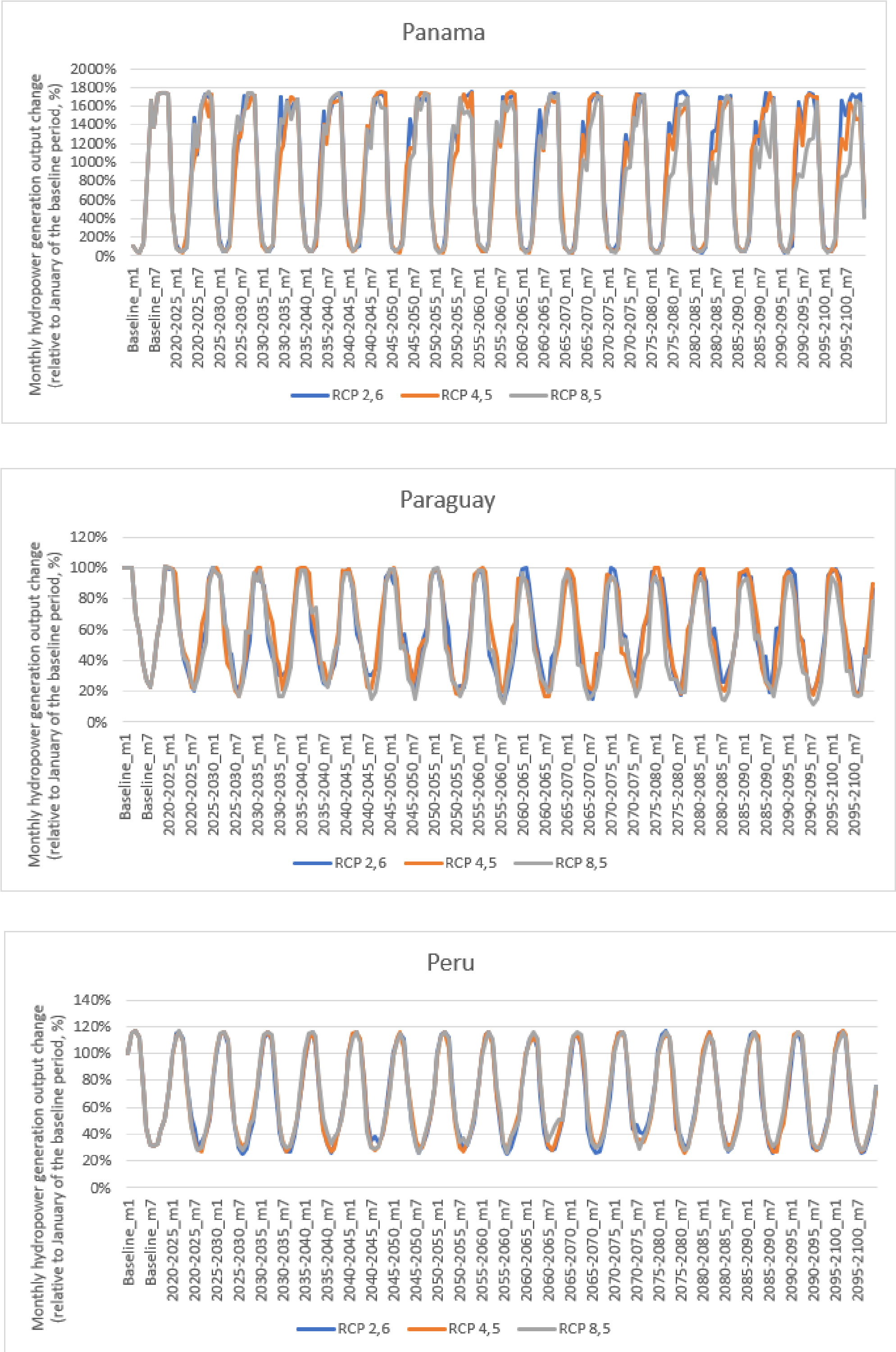


Figure 3.20: Country level monthly analysis - Panama, Paraguay, Peru

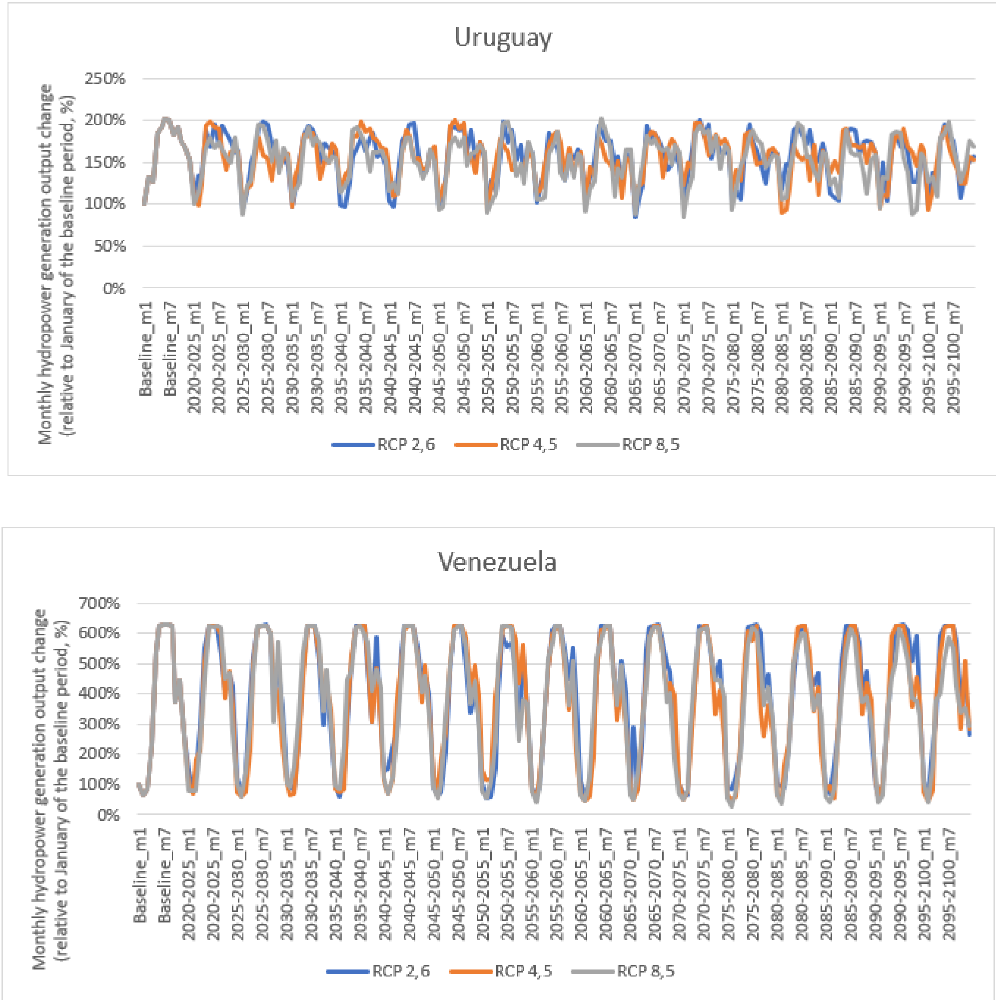


Figure 3.21: Country level monthly analysis - Uruguay, Venezuela

3.3 Key results

If we want to point to an end result for the whole of Latin America, it is definitely a decrease in the capacity factor due to changing climate conditions, which worsens with time. 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 to 17.4% in the Above 4°C scenario).

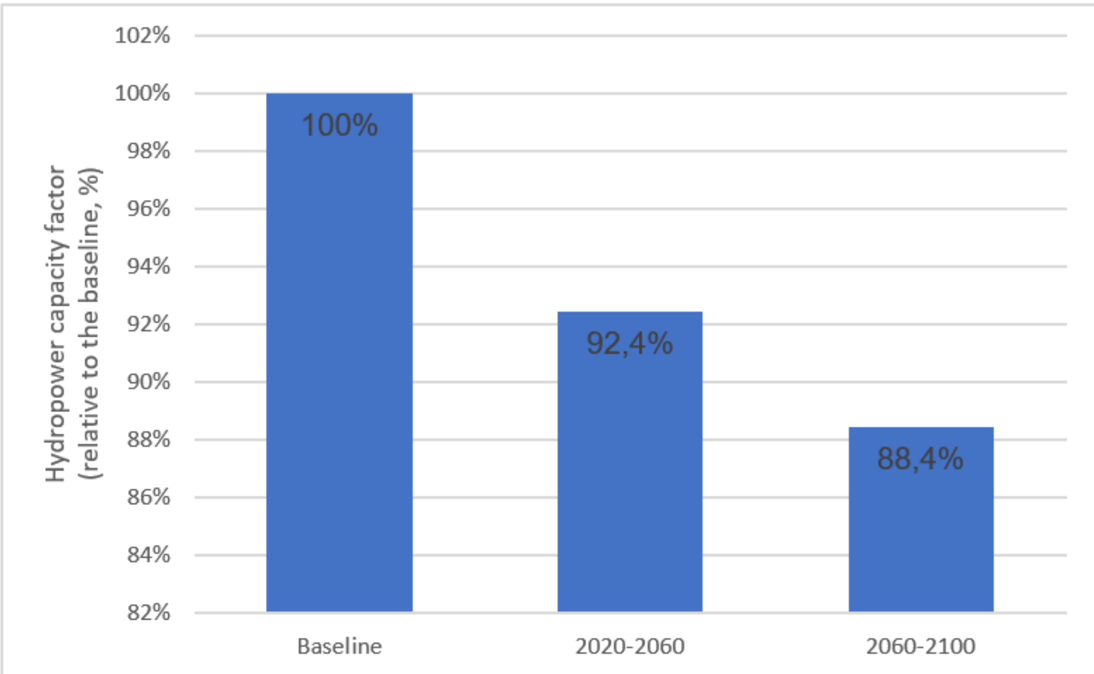


Figure 3.22: Annual trend in the average capacity factor

The graph in the Figure 3.22 shows neither the difference between the 13 countries nor the difference between the 3 climate scenarios, which are both very marked. 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 climate projections included in this analysis show that two sub-regions, 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.
In the Figure 3.23 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.

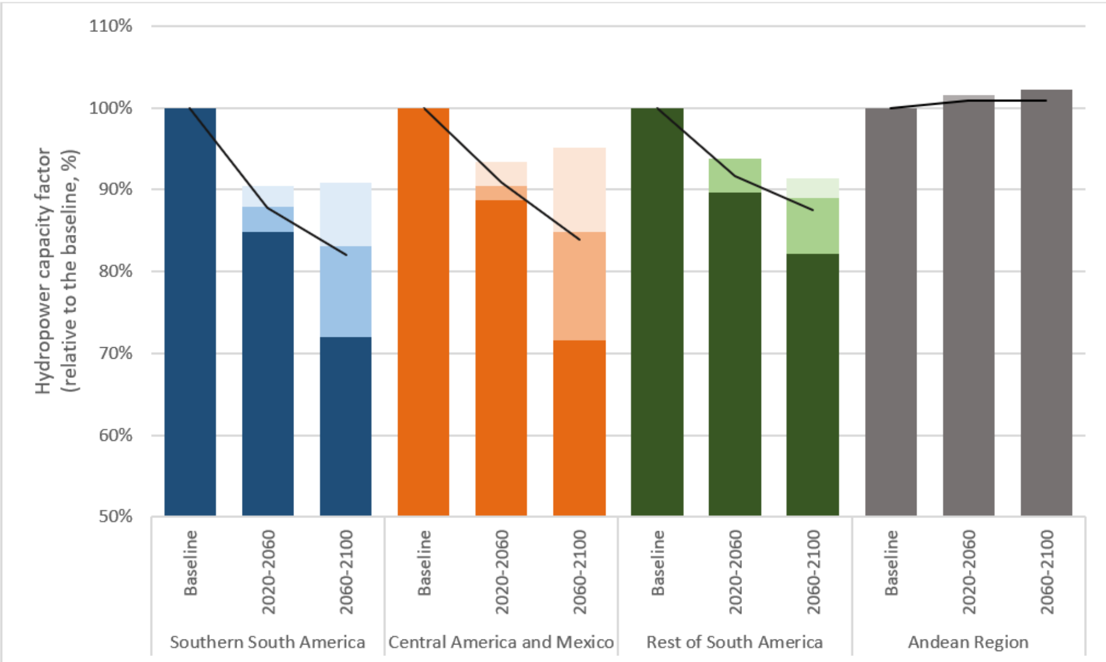


Figure 3.23: Changes in hydropower capacity factor by Latin American sub region

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 in Figure 3.24 show how unmitigated global GHG emissions can have adverse impacts on electricity security in some Latin American countries and why they should be regulated.

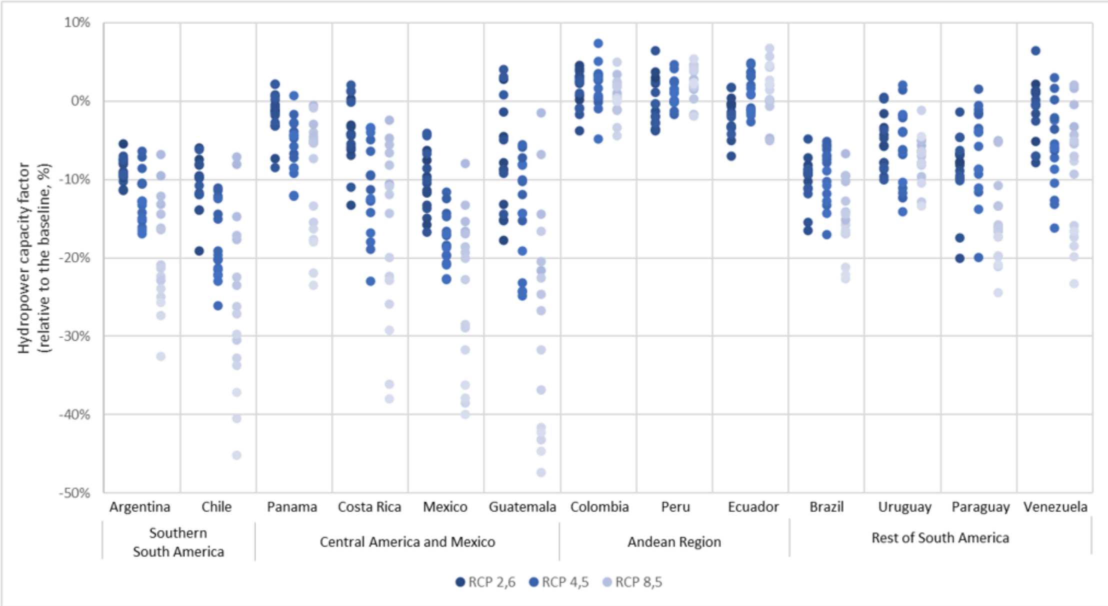


Figure 3.24: Inter-annual variability of hydropower capacity factors by country

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, as shown in Figure 3.25. 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.

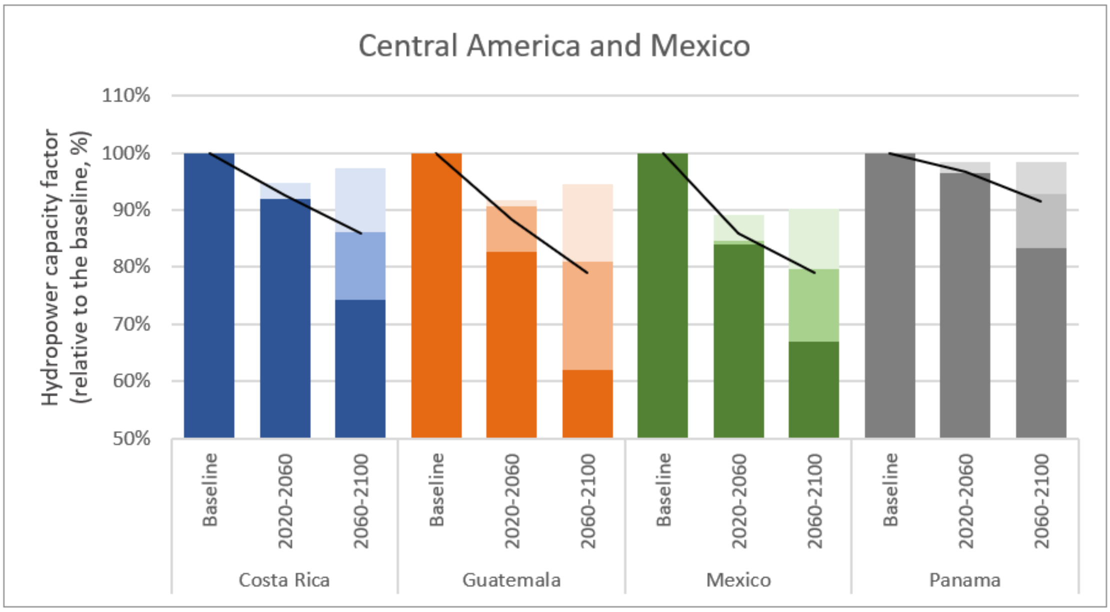


Figure 3.25: Central America and Mexico analysis

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, as shown in Fugure 3.26. 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 glacier loss. 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 exacerbate seasonal variations, 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, posing a greater challenge to hydropower plants that do not have seasonal storage capacity. Colombia is expected to see more extreme precipitation events by 26-37% by 2050. An ENSO phenomenon 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.

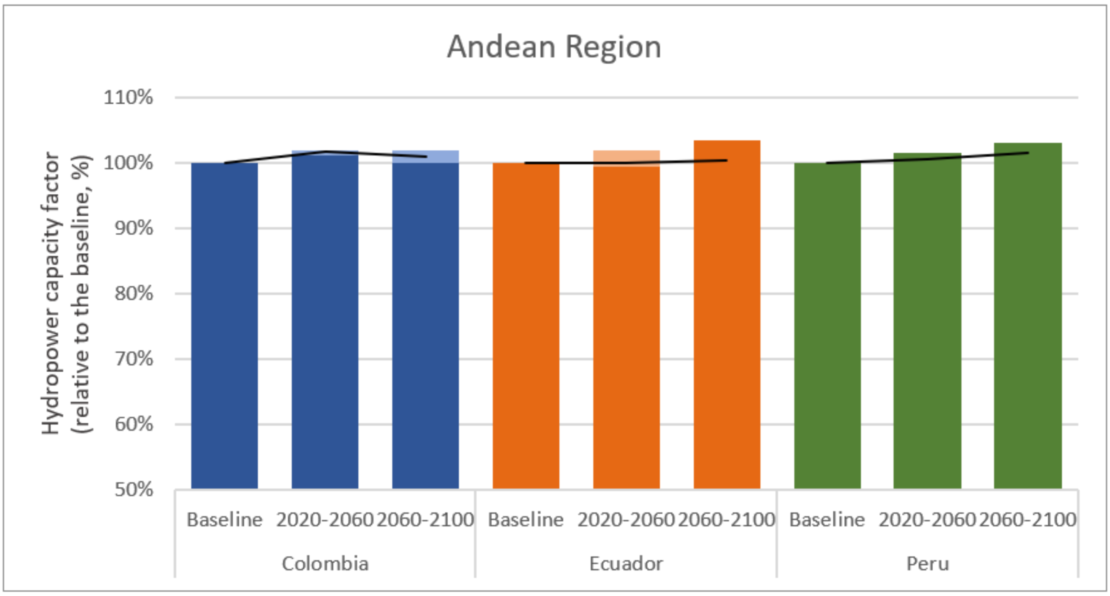


Figure 3.26: Andean Region analysis

Southern South American countries, Chile and Argentina, are projected to experience notable reductions in hydropower generation between 2020 and 2100 in most models, as shown in Figure 3.27. 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 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.

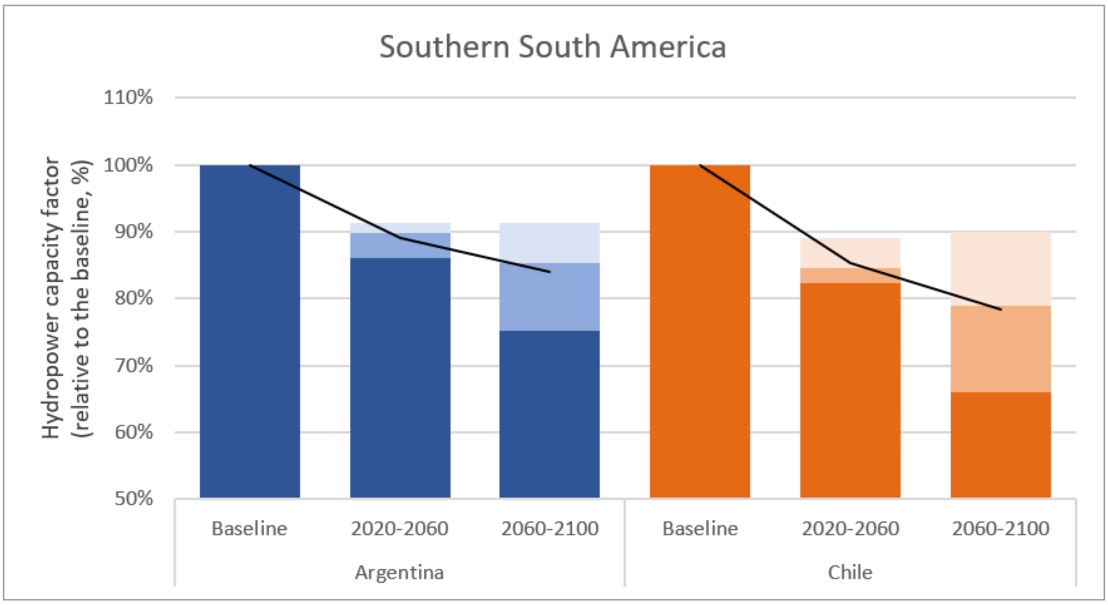


Figure 3.27: Southern South America analysis

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 a large spread 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, as shown in Figure 3.28.

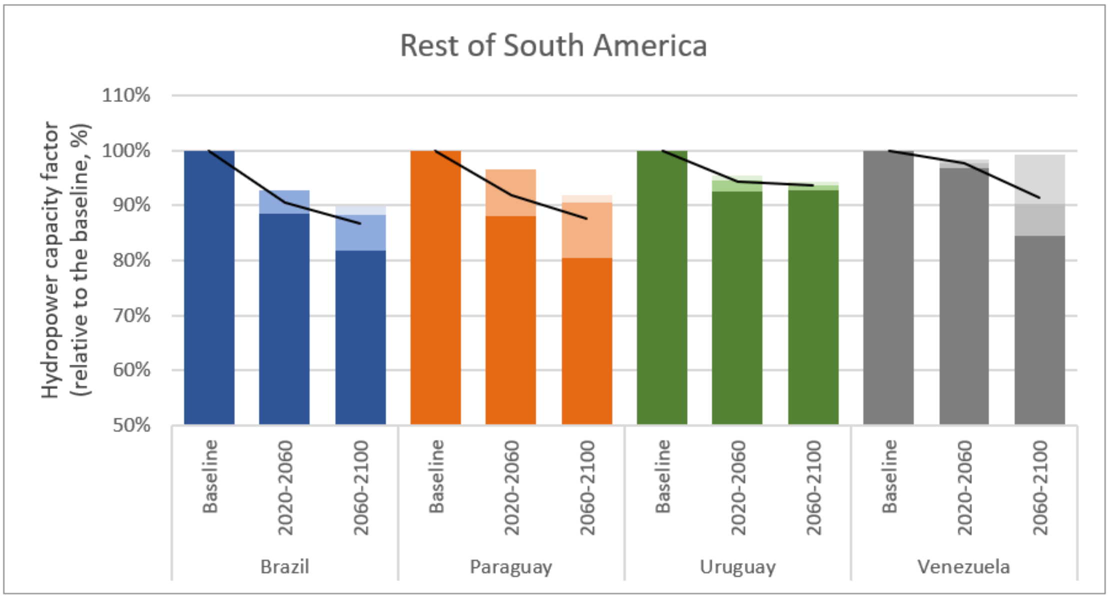


Figure 3.28: Rest of South America analysis

Chapter 4

Climate Resilience

This chapter presents examples of measures to strengthen climate resilience. Resilience expresses the ability of an individual, society, or system to cope with or overcome an adverse influence. The idea of resilience was based originally on the concept of ecosystems' ability to withstand disruptions without changing in structure or collapsing. More recently, the concept of resilience has also been used with respect to social systems, for example, in the field of natural hazards and risks. Here the focus is on capacity building, which then can contribute to the adaptation to changing conditions in the sense of adaptive capacity. Adaptation to climate change is necessary to cushion or deter negative impacts and avoid ruptures in the system. Despite all the efforts to mitigate a further increase in the human-induced greenhouse effect, climate change in the 21st century is inevitable; only its scale is still undetermined.

Adaptation is a guiding principle that is essential for survival and that can contribute to avoiding ruptures in, or a collapse of, the human-environment system. Adaptation activities are goal-orientated and aim either to reduce risks or to achieve positive developmental potential. Mitigation and adaptation to climate change are closely connected - the need for adaptation becomes greater, the less mitigation measures take effect.

4.1 Measures to enhance the resilience of Latin American hydropower

Changing climate patterns and extreme weather events pose an increasing threat to **electricity security**. Climate change directly affects all domains of the entire electricity system, impacting generation potential and efficiency, testing physical resilience of transmission and distribution networks, and altering demand patterns. Adverse climate impacts could lead to long-lasting electricity outages which would trigger further effects in other key economic and social sectors. The embedded uncertainty and complexity of climate systems make it often challenging to assess future climate impacts on electricity systems and identify effective measures to maximize the availability of electricity.

Governments can encourage utilities to include climate resilience in their construction plans and operational regimes by mainstreaming climate resilience as a core element in their own **long-term energy and climate policies**. Identification of cost-effective resilience measures and creation of an incentivisation mechanism would also encourage utilities to adopt resilience measures [50]. Governments can also support implementation of resilience measures, such as physical system hardening, grid meshing and advanced islanding, recovery planning and capacity building through technical support, better coordination, and future-proof regulations.

The ability of a system to adapt depends on the one hand on vulnerability, resilience, and capacity, and on the other hand on the intensity of climate change. In general, the **adaptive capacity** of a system needs to be considered in medium- to long-term time scales; it therefore possesses, comparable to the sustainability principle, a generation-spanning dimension.

The benefits of climate resilience and the costs of climate impacts tend to be distributed unevenly across the electricity value chain. It inevitably raises the question who should be responsible for delivering resilience measures and pay for them. In principle, utilities have responsibility and direct interests in protecting their own assets and providing reliable services to their customers. While some utilities have taken efforts to align their business interests with climate adaptation efforts, there are several factors that may deter some from adopting resilience measures in practice. First, the benefits of investment in enhancing climate resilience are likely to become tangible only after a few years or even decades, while the capital cost of implementation is incurred immediately [51]. Second, when climate impacts interrupt electricity supply and lead to large costs to society, generators and operators are expected to bear only a fraction of the entire social costs. Third, a lack of competition and monopolistic market conditions in some countries discourages service providers to invest in climate resilience measures for enhanced quality of electricity services [52].

However, recent studies suggest that the **benefits of resilient electricity systems** are much greater than the costs in most of the scenarios considering the growing impacts of climate change. It is estimated that for every dollar invested in climate-resilient infrastructure, six dollars can be saved. According to the World Bank, if the actions needed for resilience are delayed by ten years, the cost will almost double [53]. Electricity plays a critical role in the transition to a low-carbon energy system. A lack of resilience in electricity systems can also obstruct clean energy transitions, as some renewable energy technologies could be sensitive to a changing climate.

Hydropower could offer a cost-effective **flexibility** solution to balance the variability of other renewables. Reservoir and pumped storage hydropower can be used to provide flexibility, energy storage and ancillary services. Although coal- and gas-fired power plants still provide the bulk of power system flexibility, hydropower already offers the largest portion of flexibility in some countries, including Brazil [39].

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, as we can see from Table 4.1 [24]. 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.

CASE STUDY: DAMAGES IN COLOMBIA AND PERU

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 [54]. In September 2019, the insurance company Mapfre concluded that the incident at the Ituango hydropower plant in 2018 was within its policy coverage. This allows up to US$2,556 million of infrastructure and equipment damage, plus US$628 million in lost profits. The claim's value is still to be determined but it will be one of the largest claims in the history of engineering. The project is still in construction, and expected to start operating in 2021, with an additional estimated cost of US$1 billion. It will support 17 per cent of the country's electricity demand, being the largest hydroelectric generation plant in the country, with an installed capacity of 2,400 MW [1]. 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 [55].

4.1 Measures to enhance the resilience of Latin American hydropower

Table 4.1: Examples of possible soft and hard measures for resilience

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

CASE STUDY: COSTA RICA BEST PRACTICE

The United Nations climate conference (COP25) in Madrid brought special attention to climate resilience and adaptation, highlighting the need for capacity building to prepare for climate change. Aiming to ensure the long-term operational viability of new and existing assets, IHA launched the *Hydropower Sector Climate Resilience Guide* in May 2019 to provide good practice guidance on how to incorporate climate resilience measures into project planning, design and operations. This guide positions hydropower ahead of other renewable energies in their adaptation to climate change. **Reventazón** hydropower plant in Costa Rica was the first station to be assessed in Central America using the Hydropower Sustainability Assessment Protocol (HSAP). It is the largest hydropower project in Central America with 305.5 MW of installed capacity and it was awarded the 2019 IHA Blue Planet Prize in recognition of its excellence in sustainable hydropower development. The assessment was conducted by a team of independent accredited assessors with financial and technical support from the World Bank Group. This involved 90 interviews with relevant stakeholders and a review of over 470 related project documents [1].

4.1.1 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 [56], the International Hydropower Association (with the HSAP) and the World Bank [57] provide tools for climate risk and impact assessments, along with guides for building and enhancing the climate resilience of hydropower.

Governments can also encourage power generators to pay more attention to climate resilience by creating a regulatory framework that incentives the implementation of resilience measures [51]. 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.

4.1.2 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.

Chapter 5

Policy Analysis

In this chapter, an assessment of the political preparedness of the countries considered in the thesis is presented, in relation to their National Adaptation Plans. To minimise the adverse impacts of climate change, governments are expected to play a central role in enhancing the resilience of electricity systems. A few countries have already introduced tools and guidelines to anticipate, absorb, accommodate and recover from existing and projected climate impacts. However, many countries still have a significant policy gap in mainstreaming climate resilience in long-term energy planning.

5.1 National Adaptation Plans (NAP)

The National Adaptation Plan (NAP) process was established in 2010 under the Cancun Adaptation Framework (CAF), an outcome of the COP16 [58]. It enables Parties to formulate and implement National Adaptation Plans as a means of identifying medium- and long-term adaptation needs and developing and implementing strategies and programmes to address those needs.

The objectives of the NAP process are:
(a) To reduce vulnerability to the impacts of climate change, by building adaptive capacity and resilience; (b) To facilitate the integration of climate change adaptation, in a coherent manner, into relevant new and existing policies, programmes and activities, in particular development planning processes and strategies, within all relevant sectors and at different levels, as appropriate [59].

Something similar to the NAP was already introduced in 2001 for the Least Developed Countries (LDCs) under the name National Adaptation Programmes of Action (NAPA). The main difference between NAPs and NAPAs is that while NAPAs focused on short-term adaptation needs and priorities, the NAP process seeks to identify and address medium- and long-term adaptation needs. So, NAP processes in LDCs should be built on the experience of their NAPAs.

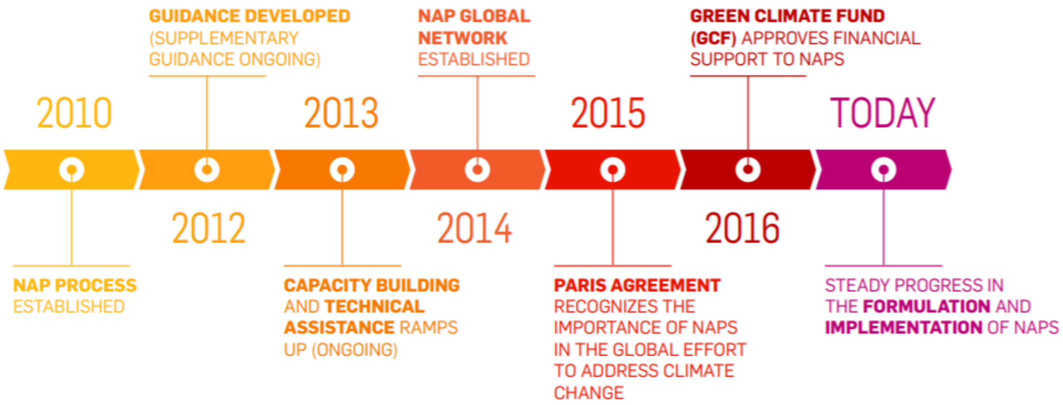


Figure 5.1: NAP Process evolution

Among the Latin American countries considered in this study, the ones that have published a NAP are Brazil, Chile, Colombia, Guatemala and Paraguay [60]. Nonetheless Uruguay has published only the sectoral NAP on agriculture, and Mexico has published only the National Adaptation Strategy (NAS).
The proposed actions in these documents are all aimed at a better understanding of climate impacts and climate risks, the development of adaptation proposals and improvements, and the creation of technical criteria that consider climatic variations. They are more focused on a future assessment in order to be able to take concrete action, than the concrete actions themselves.

In **Argentina** the elaboration process for the "Plan Nacional de Adaptación y Mitigación al Cambio Climático" (PAMCC) was concluded, but the NAP has to be approved before the official release. Argentina has a sectoral plan dedicated to the energy sector, but it deals with impacts more than solutions. The electricity is mentioned mostly to talk about the impacts and the effects of climate change, not about the actions to enhance resilience. Some measures involve energy efficiency improvement and renewable energy increase, but they are much more related to mitigation rather than adaptation.

In **Brazil** the current NAP includes a chapter on "Strategy for Infrastructures" with a focus on energy sector driven by hydropower. The generation, transmission and distribution segments are addressed. There are guidelines for the electricity sector mainly focused on measures such as "deepen impact studies on specific areas of interest to the electricity sector in relation to climate change trends", "promote a greater engagement of electricity-sector institutions in themes relating to adaptation, with a view to adapting institutional policies to new climatic parameters" or "conduct studies to define and improve planning tools, with a view to adapting parameters in response to scientifically verified climate change impacts".

Chile has published its "Plan Nacional de Adaptación al Cambio Climático" (PNACC) in 2015. The Climate Change Adaptation Plan covers 7 priority sectors, including Water Resources and Energy that are closely related, both with a focus on hydropower generation. The Energy section is in the stage of generation of information necessary for its elaboration and confirmation of the technical work teams. Electricity is mentioned in terms of supply, distribution and consumption, but only covering the effects of climate change on these issues without submitting any action.

The same for **Colombia** that published its NAP in 2016. The Plan does not deal specifically with the energy sector: it investigates the repercussions of climate change also in hydroelectric generation, but there is no list of specific actions. The general goals are to manage knowledge about climate change and its potential impacts; to incorporate adaptation to climate change into environmental, territorial and sectoral planning and to promote the transformation of development for climate change resilience.

In **Costa Rica** and **Ecuador** the NAP process is in progess: the Green Climate Fund (GCF) gave almost 3 million dollars to Costa Rica to support the NAP process (a three-year project started in 2019), while Ecuador began the development of its NAP in February 2017.

Guatemala published its "Plan de Acción Nacional de Cambio Climático" in 2018. The energy sector has a specific chapter in the mitigation part, while for the adaptation there are two sectors in which it is included: Infrastructures and Water Resources. In the first one, it is said that the emergency preparedness plan for each hydropower plant must be reviewed and updated to include in its design guidelines the effects of extreme hydro-meteorological events, but it's the only action related only to the energy sector.

Mexico released only the National Climate Change Strategy in 2013, that includes lines of action to increase resilience of strategic infrastructures and productive systems, but energy sector is briefly mentioned. Several actions involved electricity sector, but only in terms of mitigation measures (e.g. accelerate the energy transition toward clean energy sources, reduce energy intensity through efficiency and responsible consumption).

For **Panama** it was possible to find only the "Plan National de Cambio Climatico" for agriculture sector. In **Paraguay** the "Plan Nacional de Adaptación al Cambio Climático" was published in 2017. There is a sectoral vulnerability analysis that also involves the energy sector. The actions consist in the proposal of improvements in the system of transmission and distribution of electricity, in the preparation of vulnerability maps in order to reduce climate risk in energy systems, in the study of current situation and demand projections for the energy sector, in the development of standards and technical criteria that consider climatic variations in infrastructures. Climate resilience actions on electricity sector consist mainly in the assessment and the evaluation of the effects of climate change in generation, T&D and demand.

In **Peru**, **Uruguay** and **Venezuela** the process is ongoing: NAP-GSP and UNDP have provided technical assistance to Peru to advance their NAP process; in Uruguay the NAP for energy sector is in the initial stages of development, while currently the one on agriculture is available; regarding Venezuela I found only a document that attested Venezuela participation in a workshop for National Adaptation Plans in 2017, so I supposed the NAP is under development.

In Table 5.1 a colour code is provided to summarize and compare data from the different countries under review.

Table 5.1: Coverage of the climate resilience of electricity system in NAPs

Country	National adaptation plans • Green: in place • Yellow: under development • Red: not in place	Coverage of the energy sector resilience • Green: covered with concrete actions • Yellow: covered with limited information • Red: not covered	Coverage of electricity system resilience • Green: entire system is covered • Yellow: some parts are covered • Red: not covered
Argentina	Yellow	Yellow	Yellow
Brazil	Green	Green	Yellow
Chile	Green	Yellow	Yellow
Colombia	Green	Yellow	Yellow
Costa Rica	Yellow	Red	Red
Ecuador	Yellow	Red	Red
Guatemala	Green	Yellow	Yellow
Mexico	Yellow	Yellow	Yellow
Panama	Red	Red	Red
Paraguay	Green	Yellow	Yellow
Peru	Yellow	Red	Red
Uruguay	Yellow	Red	Red
Venezuela	Yellow	Red	Red

National plans and strategies which explicitly include climate resilience as a core element send a strong signal to utilities and investors to strengthen the resilience of electricity systems in design, operation and maintenance phases.

5.2 Focus on Brazil

Brazil is the country with the highest installed hydroelectric capacity and the largest surface area in Latin America, so an assessment of its adaptation policies is particularly relevant. Brazil submitted its Intended Nationally Determined Contribution

(INDC) in 2015 in which it intends to commit to reduce greenhouse gas emissions by 37% below 2005 levels in 2025. In 2020 Brazil confirmed its original commitment with the updated NDC and additionally, it committed to reduce its emissions in 2030 by 43%, compared with 2005.

The first INDC states that Brazil considers adaptation to be a fundamental element of the global effort to tackle climate change and its effects. The implementation of policies and measures to adapt to climate change contributes to building resilience of populations, ecosystems, infrastructure and production systems, by reducing vulnerability and through the provision of ecosystem services. The NAP was then in its final elaboration phase and in this context, risk areas, housing, basic infrastructure, especially in the areas of health, sanitation and transportation, constituted key areas for adaptation policies. The energy sector was not mentioned, neither in the 2015 INDC nor in the 2020 NDC. The National Policy on Climate Change (NPCC) was established in 2009 and it is implemented by means of several action and sectoral plans for the mitigation and adaptation to climate change.

The National Adaptation Plan (NAP) aims to implement knowledge management systems, to promote research and technology development for adaptation, to develop processes and tools in support of adaptation actions and strategies, at different levels of government. Brazil already monitors extreme rainfall events for 888 municipalities and has in place an early warning system and action plans to respond to natural disasters, thanks to the Centre for Natural Disaster Monitoring and Alert (CEMADEN), whose mission is to develop, test and implement a system to predict natural disasters in susceptible areas in Brazil and provide alerts on natural disasters. The current NAS/NAP was published in 2016 by the Ministry of Environment and it is divided into two volumes: (i) General Strategy and (ii) Sector and Thematic Strategies. The second volume includes a chapter on 'Strategy for Infrastructures' with a focus on energy sector driven by hydropower; the generation, transmission and distribution segments are addressed. There are guidelines for the electricity sector mainly focused on measures such as "deepen impact studies on specific areas of interest to the electricity sector in relation to climate change trends", "promote a greater engagement of electricity-sector institutions in themes relating to adaptation, with a view to adapting institutional policies to new climatic parameters", "conduct studies to define and improve planning tools, with a view to adapting parameters in response to scientifically verified climate change impacts".

The First National Assessment Report of the Brazilian Panel on Climate Change (PBCM, 2013) is divided into three parts because the PBCM consists of three Working Groups, each one in charge of a section: scientific basis of climate change; impacts, adaptation and vulnerability; mitigation of climate change. In the second part, there is a small section on energy system in which it is stated that "the energy sector may be affected by climate change in different ways, both in regard to the energy resources base and transformation processes, as well as aspects of transportation and energy consumption" and that "the identification of the vulnerabilities of the energy sector to climate change is essential for the formulation of adaptation policies".

The Brazilian Network on Global Climate Change Research (Rede CLIMA) involves dozens of research groups in universities and institutes throughout the country. Its scientific focus covers all relevant issues on climate change, notably: i) the scientific basis of climate change: detection and assignment of causes; understanding of the natural variability versus human-induced climate change; hydrological cycle and global biogeochemical cycles and aerosols; modelling capacity of the climate system; ii) impact, adaptation and vulnerability studies for relevant systems and sectors: agriculture and forestry, water resources, biodiversity and ecosystems, coastal zones, cities, economy, renewable energy, health; and iii) development of knowledge and technologies to mitigate climate change. It is currently addressing the integrative scientific themes such as climate change and food, water and energy safety; human health, cities and natural disasters.

Chapter 6

Conclusions and Final Remarks

This thesis addressed the issue of how to strengthen climate resilience in the hydropower sector, the most important share of energy supply for many Latin American countries. After analysing the climate risks and impacts, the policies still in place to better adapt to the future were assessed. This chapter presents some policy recommendations for countries and outlines future work at the IEA on this issue.

6.1 Policy recommendations

Governments can send a strong signal to service providers and developers by mainstreaming climate resilience in their national policies, and they can also encourage developers and operators by incorporating resilience standards into construction codes to pay attention to climate resilience from an early stage of a hydropower project. Further recommendations are:

- **Financial investments on modernisation.** The wide presence of ageing hydropower plants in Latin America requires modernisation of hydropower infrastructure (Section 3.1.3 Vulnerability). 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. Access to financing is considered the main barrier for modernisation. Public investment has been playing a major role in financing modernisation of hydropower plants in some Latin American countries. While 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; 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 [24]. A Public Private Partnership (PPP) approach with a pledge of sharing an appropriate portion of the profit with private investors in return for the investment could attract more private investment [43].

- **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. 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, Caribbean Catastrophe Risk Insurance Facility (CCRIF), a multinational program, facilitates access to low cost, high quality disaster risk insurance for governments in Central America [61]. 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.

- **Scientific research support.** Comprehensive and scientific projections of climate risks and impacts on hydropower generation are essential to build climate resilience. According to a recent study 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 [56]. 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, in the Amazon less rainfall is expected in the future under the RCP 8,5 scenario, 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.

6.2 Future work on Asian hydropower

The Environment and Climate Change (ECC) Unit starts to analyse the climate impacts on hydropower in 2020 with the release of the work on African hydropower, although the number of plants selected was much lower than that involved in this study. Given the growing interest in this topic, the climate impacts analysis will be replicated again this year with an analysis of power plants in Asia Pacific.

During the work on Latin American hydropower, we had problems with the reception of data from the consultants: the raw data initially were related to water basins instead of power plants, so it was difficult to identify them because the same basin, especially if large, could refer to several plants and the names often did not match with the official ones. So, for the Asian report we decided to provide in advance a list of all the plants still in operation with an indication of latitude and longitude to allow the correct location. I will be working on it from February to April 2021, the analysis has not yet begun, nor has anything been released by the IEA, but the number of plants I have identified so far reaches 500, far exceeding the numbers in the Latin American report. The 13 selected countries are: Bhutan, Cambodia, India, Indonesia, Lao People's Democratic Republic (Lao PDR), Malaysia, Myanmar, Nepal, Pakistan, Philippines, Sri Lanka, Thailand and Vietnam.

With almost 650 GW installed, Asia is home to half of the world's hydropower capacity and hydropower accounts for almost 20% of total electricity generation of Asia Pacific [37]. According to IEA's Renewable 2020, excluding China, global hydropower additions are expected to be stable during the remainder of the forecast period (2021-25), ranging from 10 GW to 13 GW per year. Asia accounts for 43% of cumulative growth, led by India and Pakistan, with most of the remainder in Southeast Asian countries.

Countries such as Bhutan, Cambodia, Lao PDR, Myanmar and Nepal rely on hydropower for over half of annual generation. Hydropower accounts for more than 86% of electricity generation in Lao PDR and with new commissions totalling 1.89 GW in 2019, Lao PDR was highest in new added hydropower capacity across the region [1]. Hydropower provides almost all (99%) of Nepal's domestic electricity generation on the grid (with approximately 1 GW of installed capacity) and the government has an ambitious plan to reach 5 GW total hydropower capacity over the next five years, as recently set out in a white paper by the Ministry of Energy, Water Resources and Irrigation. Myanmar has 108 GW unexploited energy potential from the rivers for hydropower electrification, according to the Masterplan on ASEAN Connectivity 2025. Only one third of the people can get electricity, and 70% of the people who live in rural areas still live in darkness. Due to the growing demand, in Myanmar's 2015 Energy Master Plan the installed hydropower capacity in 2030 will almost triple to reach almost 9,000 MW [62]. Over-reliance on hydropower could lead to several problems. In Lao PDR, as hydropower plants need to be installed at specific locations along rivers, electricity has to be transferred via inefficient national transmission and distribution networks to reach the rest of the country. In some regions, as much as 20% of power supply can be lost during distribution, and the local governments are then forced to import electricity [63].

The International Hydropower Association (IHA) has conducted a study for the Asian Infrastructure Investment Bank (AIIB), estimating that over one-third of the continent's capacity will require, or have undergone, modernisation by 2030. This rises to 50% of existing capacity when excluding China, which has a larger proportion of newer hydropower plants with an average age of less than 20 years [64]. The over reliance on hydropower together with the modernisation requirement make also Asia Pacific a region where future climate impacts need to be analysed.

Appendix A

Annex

The following tables provide a list of the hydropower plants analysed in this thesis, the countries are in alphabetical order and the plants are in descending order in terms of installed capacity. The overall values are in Table 2.1 on page 6.

Country	Plant	Installed Capacity [MW]
Argentina	Salto Grande	1890
Argentina	Piedra del Aguila	1400
Argentina	El Chocon	1260
Argentina	Alicura	1050
Argentina	Rio Grande	750
Argentina	Futaleufu	472
Argentina	Planicie Banderita	472
Argentina	Pichi Picun Leufu	285
Argentina	Los Reyunos	224
Argentina	Agua del Toro	150
Argentina	Arroyito	127,8
Argentina	Caracoles	121,4
Argentina	Uruguay	120
Argentina	Potrerillos	120
Argentina	Nihuil II	110
Argentina	Cabra Corral	100,5
Argentina	El Nihuil	72
Argentina	Casa de Piedra	60
Argentina	Los Molinos 1	52
Argentina	Florentino Ameghino	46,8

Country	Plant	Installed Capacity [MW]
Argentina	Quebrada de Ullum	45
Argentina	Nihuil III	42
Argentina	Ullum	42
Argentina	Benjamin Reolin	33
Argentina	Escaba	24
Argentina	San Roque	24
Argentina	Valle Grande	18
Argentina	El Carrizal	17
Argentina	Cassafousth	16,2
Argentina	La Vina	16
Argentina	Rio Hondo	15
Argentina	Pueblo Viejo	15
Argentina	El Tigre	14
Argentina	El Cadillal	12,6
Argentina	El Tunal	10,6
Argentina	Fitz Simon	10,5
Argentina	Piedras Moras	6,3
Argentina	La Florida	2,4
Argentina	Cruz del Eje	1,1

Table A.1: Hydropower plants analysed in Argentina

Country	Plant	Installed Capacity [MW]
Brazil	Belo Monte	11233
Brazil	Tucurui	8370
Brazil	Santo Antonio	3568
Brazil	Ilha Solteira	3444
Brazil	Jirau	3300
Brazil	Xingo	3162
Brazil	Paulo Afonso 4	2642,4
Brazil	Itumbiara	2080,5
Brazil	Sao Simao	1710
Brazil	Bento Munhoz	1676
Brazil	Foz do Areia	1676
Brazil	Jupia	1551,2
Brazil	Porto Primavera	1540
Brazil	Itaparica	1479,6
Brazil	Ità	1450
Brazil	Marimbondo	1440
Brazil	Salto Santiago Main Dam	1420
Brazil	Agua Vermelha	1396
Brazil	Serra da Mesa	1275
Brazil	Segredo	1260
Brazil	Salto Caxias	1240
Brazil	Furnas	1216
Brazil	Emborcacao	1192
Brazil	Machadinho	1140
Brazil	Teles Pires	1092
Brazil	Estreito 2	1087
Brazil	Salto Osorio	1078
Brazil	Sobradinho Main Dam	1050,3
Brazil	Estreito	1050
Brazil	Lajeado	902,5
Brazil	Billings	889
Brazil	Campos Novos	880
Brazil	Foz do Chapeco	855
Brazil	Tres Irmaos	808
Brazil	Barra Grande	708
Brazil	Cachoeira Dourada	658
Brazil	Capivara	619
Brazil	Taquarucu	554
Brazil	Nova Ponte	510
Brazil	Itauba	500
Brazil	Mascarenhas de Moraes	476
Brazil	Cana Brava	465
Brazil	Pixie Angical	452
Brazil	Itapebi	450

Country	Plant	Installed Capacity [MW]
Brazil	Jaguara	424
Brazil	Chavantes	414
Brazil	Miranda	408
Brazil	Moxoto	400
Brazil	Tres Marias	396
Brazil	Volta Grande	380
Brazil	Corumba	375
Brazil	Rosana	372
Brazil	Maua	361
Brazil	Irapè	360
Brazil	Baixo Iguaçu	350
Brazil	Nova Avanhandava	347
Brazil	Colider	342
Brazil	Aimores	336
Brazil	Porto Colombia	320
Brazil	Promissao	264
Brazil	Dardanelos	261
Brazil	Balbina	250
Brazil	Sao Salvador	243,6
Brazil	Capim Branco I	240
Brazil	Boa Esperanca	237,4
Brazil	Igarapava	231
Brazil	Funil	216
Brazil	Samuel	216
Brazil	Manso	212
Brazil	Capim Branco II	210
Brazil	Jacui	180
Brazil	Passo Real	158
Brazil	Barra Bonita	140,8
Brazil	Bariri	136,8
Brazil	Ibitinga	132
Brazil	Dona Francisca	125
Brazil	Porto Estrela	112
Brazil	Euclides da Cunha	109
Brazil	Queimado	107,4
Brazil	Jurumirim	98
Brazil	Paraibuna	85
Brazil	Canoas 1	83
Brazil	Caconde	80
Brazil	Canoas 2	72
Brazil	Limoeiro	32
Brazil	Jaguari	28
Brazil	Mogi Guacu	7,2

Table A.2: Hydropower plants analysed in Brazil

Country	Plant	Installed Capacity MW]
Chile	Ralco	690
Chile	Pehuenche	570
Chile	Colbun	474
Chile	Pangue	467
Chile	El Toro	400
Chile	Rapel	378
Chile	Angostura	323,8
Chile	Antuco	320
Chile	Alfalfal	178
Chile	Rucue	178
Chile	Canutillar	172
Chile	La Confluencia	160
Chile	La Higuera	155
Chile	Abanico	136
Chile	Chacayes	112
Chile	Cipreses	106
Chile	Machicura	95
Chile	Curillinque	89
Chile	Peuchen	85
Chile	Sauzal	76,8
Chile	Quilleco	70
Chile	Isla	68

Country	Plant	Installed Capacity MW]
Chile	Hornitos	61
Chile	El Paso	60
Chile	Mampil	55
Chile	Blanco	53
Chile	Pullinque	51,4
Chile	Queltehues	49
Chile	Pilmaiquen	40,8
Chile	San Andres	40,3
Chile	Loma Alta	40
Chile	Los Quilos	39,9
Chile	San Ignacio	37
Chile	Rio Laja (Laja)	34,4
Chile	Palmucho	32
Chile	Maitenes	31
Chile	Juncal	29,2
Chile	Florida	28,5
Chile	Puntilla	21,8
Chile	Chiburgo	19,4
Chile	Los Molles	18
Chile	Volcan	13
Chile	Sauzalito	12
Chile	Paloma	4,6

Table A.3: Hydropower plants analysed in Chile

Country	Plant	Installed Capacity [MW]
Colombia	San Carlos I and II	1240
Colombia	Guavio	1150
Colombia	Chivor	1000
Colombia	Sogamoso	820
Colombia	Porce 3	660
Colombia	Guatapè	560
Colombia	Betania	540
Colombia	Porce 2	405
Colombia	Miel I (Patangoras)	396
Colombia	Alto Anchicaya	365
Colombia	Urra 1	340
Colombia	La Guaca	311
Colombia	La Tasajera	306
Colombia	Salvajina	285
Colombia	Guadalupe III	270
Colombia	Paraiso	270
Colombia	Guadalupe IV	216
Colombia	Las Playas	204
Colombia	Jaguas	170

Country	Plant	Installed Capacity [MW]
Colombia	San Francisco	135
Colombia	Calima	132
Colombia	Carlos Lleras Restrepo	80
Colombia	Rio Amoya	80
Colombia	Rio Grande 2	75
Colombia	Bajo Anchicaya	74
Colombia	Niquia	57
Colombia	Prado	55,5
Colombia	Cucuana	55
Colombia	Troneras	40
Colombia	Esmeralda	30
Colombia	Alto Tulua	20
Colombia	Bajo Tulua	20
Colombia	La Herradura	19,8
Colombia	Insula	18
Colombia	Sonson II	10
Colombia	Sonson I	8,5
Colombia	Caracoli	2,6
Colombia	Rio Calì	1,8

Table A.4: Hydropower plants analysed in Colombia

Country	Plant	Installed Capacity [MW]
Costa Rica	Reventazon	305,5
Costa Rica	Angostura	180
Costa Rica	Corobici	174
Costa Rica	Arenal	157,5
Costa Rica	Pirris	140
Costa Rica	Rio Macho	140
Costa Rica	Cachi	102
Costa Rica	Ventanas	100
Costa Rica	Cariblanco	82
Costa Rica	Toro II	66
Costa Rica	Virilla	53
Costa Rica	Chucas	50
Costa Rica	La Joya	50
Costa Rica	La Garita	40
Costa Rica	Balsa Inferior	38
Costa Rica	Penas Blancas	36
Costa Rica	Sandillal	31
Costa Rica	Los Negros II	28,6
Costa Rica	Toro I	25

Country	Plant	Installed Capacity [MW]
Costa Rica	Cubujuqui	23
Costa Rica	Daniel Gutierrez	20
Costa Rica	San Lorenzo	19
Costa Rica	Birris 1	18,6
Costa Rica	Bijagua	18
Costa Rica	Los Negros I	18
Costa Rica	Rio Volcan	17
Costa Rica	Aguas Zarcas	15
Costa Rica	Don Pedro	14
Costa Rica	Belen	10,5
Costa Rica	Nuestro Amo	7,5
Costa Rica	Cote	7
Costa Rica	Tacares	7
Costa Rica	Electriona	6
Costa Rica	Alberto Echandi	4,7
Costa Rica	Birris 3	4,4
Costa Rica	Brasil	3
Costa Rica	Birris 2	2
Costa Rica	Rio Segundo	0,5

Table A.5: Hydropower plants analysed in Costa Rica

Country	Plant	Installed Capacity [MW]
Ecuador	Coca Coda Sinclair	1500
Ecuador	Molino	1075
Ecuador	Sopladora	487
Ecuador	Minas San Francisco	275
Ecuador	Daule Peripa	213
Ecuador	Delsitanisagua	180

Country	Plant	Installed Capacity [MW]
Ecuador	Mazar	170
Ecuador	Manduriacu	65
Ecuador	Quijos	50
Ecuador	Mazar-Dudas	21
Ecuador	Poza Honda	3

Table A.6: Hydropower plants analysed in Ecuador

Country	Plant	Installed Capacity [MW]
Guatemala	Renace Complex	301
Guatemala	Pueblo Viejo-Quixal	300
Guatemala	Xacbal	94
Guatemala	Aguacapa	90
Guatemala	Palo Viejo	85
Guatemala	Jurun Marinala	60
Guatemala	Oxec II	60
Guatemala	El Canada	48
Guatemala	Las Vacas	45
Guatemala	El Recreo I	29,2
Guatemala	Oxec I	26
Guatemala	El Recreo II	23,5
Guatemala	Secacao	16,5

Country	Plant	Installed Capacity [MW]
Guatemala	Los Esclavos	14
Guatemala	Las Fuentes II	14
Guatemala	Montecristo	13,4
Guatemala	Pasabien	12,8
Guatemala	Santa Rosalia	12,7
Guatemala	Poza Verde	12,5
Guatemala	Matanzas	12
Guatemala	El Cafetal	11
Guatemala	El Cobano	11
Guatemala	Rio Bobos	10
Guatemala	Presa Panan	7,5
Guatemala	Santa Maria	6,8
Guatemala	Raax ha	5

Table A.7: Hydropower plants analysed in Guatemala

Country	Plant	Installed Capacity [MW]
Mexico	Manuel Moreno Torres	2400
Mexico	Malpaso	1080
Mexico	El Infiernillo	1000
Mexico	Agua Milpa	960
Mexico	La Angostura	900
Mexico	Cajon de Peda	750
Mexico	Carlos Ramirez Ulloa	600
Mexico	Huites	440
Mexico	Penitas	420
Mexico	Pres. Aleman Temascal	354
Mexico	Villita	300
Mexico	Zimapan	292
Mexico	Agua Prieta	240
Mexico	Mazatepec	220
Mexico	Plutarco Elias Calles	135
Mexico	Comedera	100
Mexico	Bacurato	92

Country	Plant	Installed Capacity [MW]
Mexico	Humaya	90
Mexico	Cupatitzio	72
Mexico	Int. Amistad Dam	66
Mexico	Manuel M. Dieguez	61
Mexico	El Fuerte	59
Mexico	Cobano	52
Mexico	Colimilla	51
Mexico	Tuxpango	36
Mexico	Int. Falcon Lake Dam	32
Mexico	La Venta	30
Mexico	Chilatan	26
Mexico	La Boquilla	25
Mexico	Oviachic	19
Mexico	El Salto	18
Mexico	Minas	15
Mexico	Salvador Alvarado	14
Mexico	Mocuzari	10

Table A.8: Hydropower plants analysed in Mexico

Country	Plant	Installed Capacity [MW]
Panama	Fortuna	300
Panama	Bayano	260
Panama	Changuinola 1	223
Panama	Esti	120
Panama	Dos Mares	118
Panama	Bajo de mina	56
Panama	Los Valles	54,8
Panama	Monte Lirio	51,6
Panama	La Estrella	47,2

Country	Plant	Installed Capacity [MW]
Panama	Madden	36
Panama	Pando	33,3
Panama	Bonyic Dam	32,6
Panama	Barro Blanco Dam	28,6
Panama	Panama Canal Dam	22,5
Panama	Las Cruces	20
Panama	Pedregalito 1	20
Panama	Concepcion	10

Table A.9: Hydropower plants analysed in Panama

Country	Plant	Installed Capacity [MW]
Paraguay	Itaipu	14000
Paraguay	Yacyreta	3200
Paraguay	Acaray Iguazu	210

Table A.10: Hydropower plants analysed in Paraguay

Country	Plant	Installed Capacity [MW]
Peru	Montaro	1008
Peru	Cerro del Águila	520
Peru	Chaglla	456
Peru	Canon del Pato	260,7
Peru	Huinco	258,4
Peru	Charcani 1-6	186,2
Peru	Cheves	174,2
Peru	Chimay	151
Peru	Yuncan	132
Peru	Matucana	128,5
Peru	Santa Teresa	118
Peru	Yaupi	108
Peru	El Platanal	105
Peru	Macchu Picchu	98
Peru	Huanza	96
Peru	Callahuanca	84
Peru	Carhuaquero 1-3	75
Peru	Moyopampa	69

Country	Plant	Installed Capacity [MW]
Peru	Malpaso	48
Peru	Cahua	43
Peru	Yanango	42,8
Peru	Gallito Ciego	37,4
Peru	Huampani	31,5
Peru	Aricota 1	23,8
Peru	Yarucaya	17,5
Peru	Poechos	15,4
Peru	Curumuy	12,8
Peru	Pias	12,6
Peru	Aricota 2	11,9
Peru	Carhuaquero 4	9,6
Peru	Pachachaca	9
Peru	La Oroya	9
Peru	Santa Cruz I	6
Peru	Santa Cruz II	6
Peru	Carhuaquero 5	5,6

Table A.11: Hydropower plants analysed in Peru

Country	Plant	Installed Capacity [MW]
Uruguay	Constitucion	333
Uruguay	Dr. Gabriel Terra	152
Uruguay	Rincon de Baygorria	108

Table A.12: Hydropower plants analysed in Uruguay

Country	Plant	Installed Capacity [MW]
Venezuela	Guri	10300
Venezuela	Macagua 2	2564
Venezuela	Caruachi	2160
Venezuela	Masparro	25

Table A.13: Hydropower plants analysed in Venezuela

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