Climate Impacts on African Hydropower

Abstract

Africa is projected to experience increasing climate hazards for the remainder of the 21st century, which are likely to pose a challenge to hydropower generation in Africa. To minimise the adverse effects of climate change, hydropower is needed to enhance Africa's resilience to climate change. Resilient hydropower can play a key role in allowing Africa to meet the Sustainable Development Goals (SDGs), implement clean energy transitions, and adapt to climate change. This report aims to enhance the climate resilience of African hydropower through a climate risk and impact assessment, and by introducing potential resilience measures. It qualitatively assesses climate risks to African hydropower and examines potential climate impacts quantitatively, comparing two climate scenarios. Based on the assessment, it identifies measures to enhance climate resilience and provides policy recommendations.

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Table of contents

List of figures

List of boxes

List of tables

Executive summary

Hydropower plays a significant role in Africa

Currently, hydropower accounts for 17% of the electricity generation in Africa on average. In some countries, such as the Democratic Republic of Congo, Ethiopia, Malawi, Mozambique, Uganda, and Zambia, the share of hydropower in electricity generation exceeds 80%. This share may potentially increase to more than 23% by 2040, as part of the ongoing effort towards clean energy transition and universal energy access in Africa.

Reliance on hydropower without assessing future climate impacts may increase risk

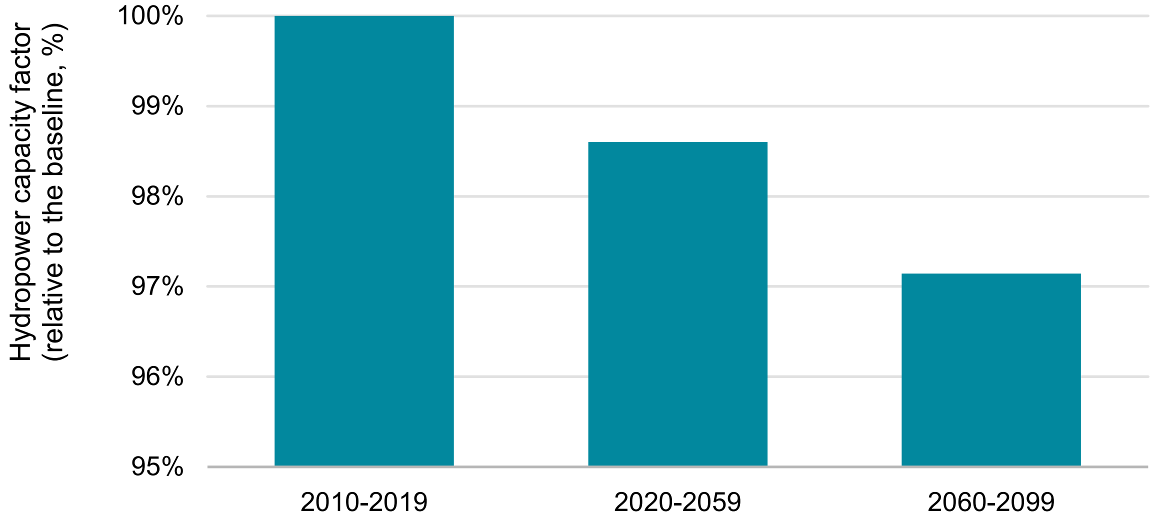
Expanding the share of hydropower in Africa may increase a country's exposure to climate hazards and risks to electricity systems if carried out without assessing the potential impacts of climate change. Africa is one of the regions most susceptible to climate change. The continent is already experiencing increased anomalies in climate patterns and is likely to experience greater climate impacts for the remainder of the 21st century. For instance, southern Africa is likely to experience a drier climate with more frequent incidences of low precipitation, while east Africa is predicted to experience a wetter climate with more frequent heavy rainfall. In addition to these future anomalies in climate patterns, the continent's high sensitivity to water availability and its low adaptive capacity compound African hydropower's vulnerability to climate change.

The regional mean of hydropower capacity factor is projected to decrease until 2100

This report assesses climate impacts on African hydropower generation using general circulation models (GCM) and global hydrological models (GHM) comparing two different greenhouse gas (GHG) concentration pathways (which are associated with the level of global warming of below 2°C and around 3°C by 2100, respectively). The assessment considers 80% installed hydropower capacity in 13 African countries between 2020 and 2099, comparing projected results with values from the baseline period from 2010 to 2019.

From now until the end of the century, the mean hydropower capacity factor of selected hydropower plants is projected to decrease due to climate change in both scenarios. The average capacity factor of analysed African hydropower plants is likely to decrease by approximately 3% between 2060-99 compared to the baseline period 2010-19. The projected accumulative loss in generation output due to climate change for the remainder of the 21st century is approximately 130 terawatt-hours (TWh); this is equivalent to the current total annual generation output from all African hydropower plants.

Figure 1 Average hydropower capacity factor of selected plants during 2020-99 relative to the baseline level of 2010-19



For the remainder of the 21st century, climate change is likely to decrease the average hydropower capacity factor of selected hydropower plants.

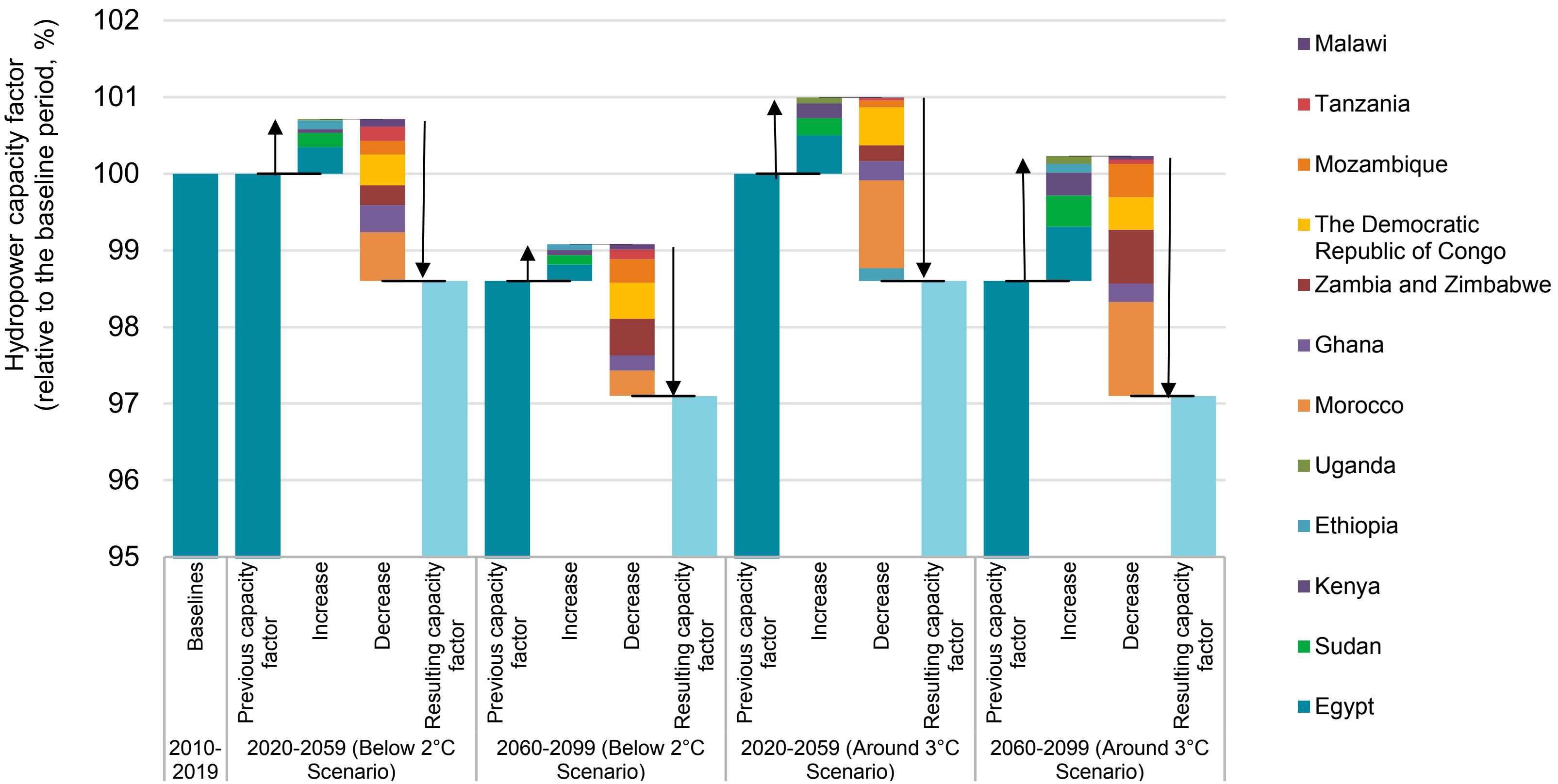
However, the projected decrease in the regional mean does not capture all aspects of climate impact

The projected decrease in the regional mean hydropower capacity factor may generate false impressions regarding future climate impacts on African hydropower. This may prompt the conclusion that climate change and different levels of global warming will have insignificant impacts on future hydropower capacity factors.

However, country-specific data show that climate change will have significant impacts on most African countries, although the patterns of change may vary from one country to the other. For example, the hydropower capacity factor in Morocco, Zambia, Zimbabwe, the Democratic Republic of Congo and Mozambique are projected to decline considerably, while the decrease would be offset by an increase in the hydropower capacity of the Nile basin countries, notably Egypt, Sudan and Kenya.

Country-specific data also show that these climate impacts will be largely affected by the level of GHG concentration. Morocco, Zambia and Zimbabwe are likely to experience a larger decrease in hydropower capacity factor with higher GHG concentrations. However, the larger decrease in the hydropower capacity factor in these countries will be offset by a higher increase in the Nile basin countries. This will eventually generate the same level of decline of approximately 3% in the regional mean hydropower capacity factor in both scenarios.

Figure 2 Comparison of changes in hydropower capacity factor during 2020-99 relative to the baseline period in both scenarios

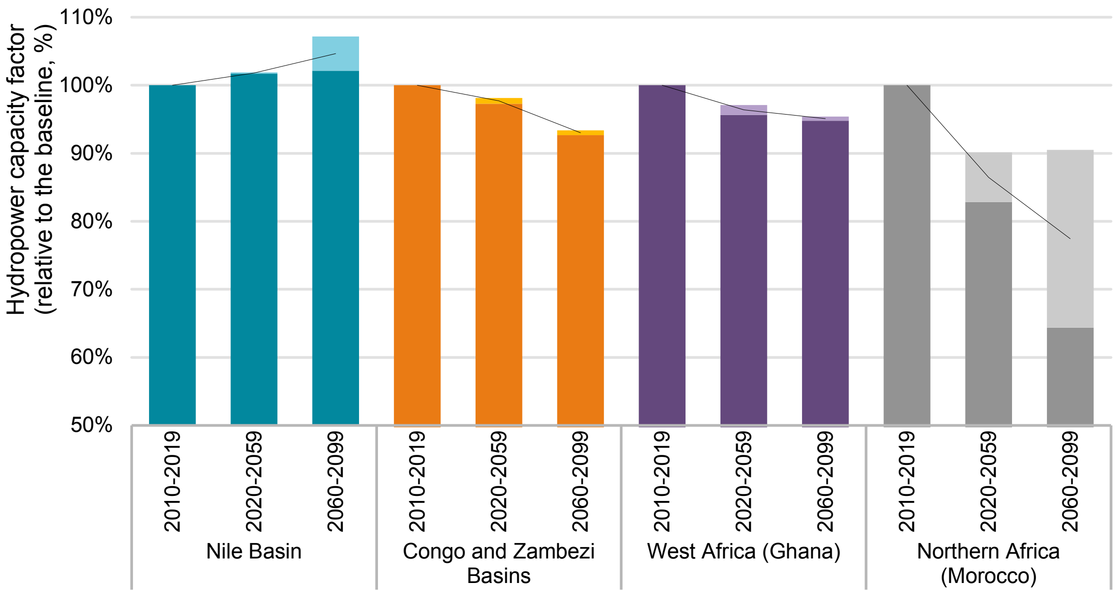


Country-specific data show that climate change will have different impacts on each country and are largely affected by GHG concentration pathways.

The hydropower capacity factor will present starker spatial variations with higher GHG concentrations

The uneven distribution of climate impacts across the continent will require a tailored approach for each country. Countries around the Congo and Zambezi basins will need to cope with a drop in the hydropower capacity factors while the Nile basin countries are projected to see an increase for the remainder of the 21st century.

Figure 3 Changes in hydropower capacity factor by African subregion

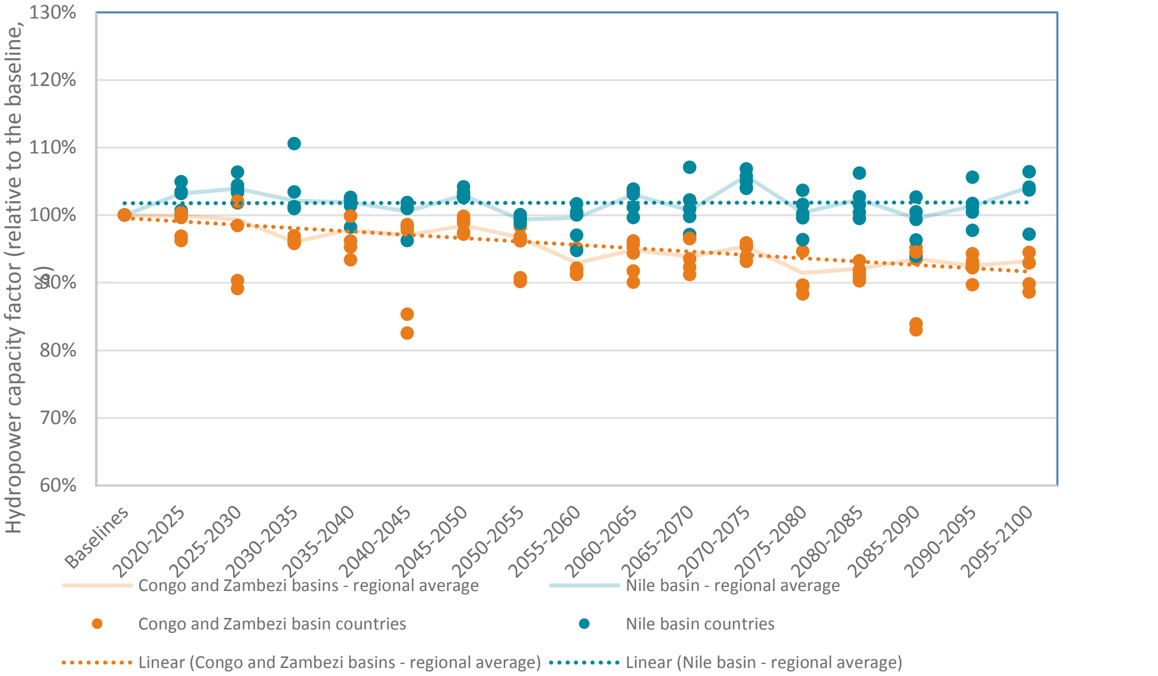


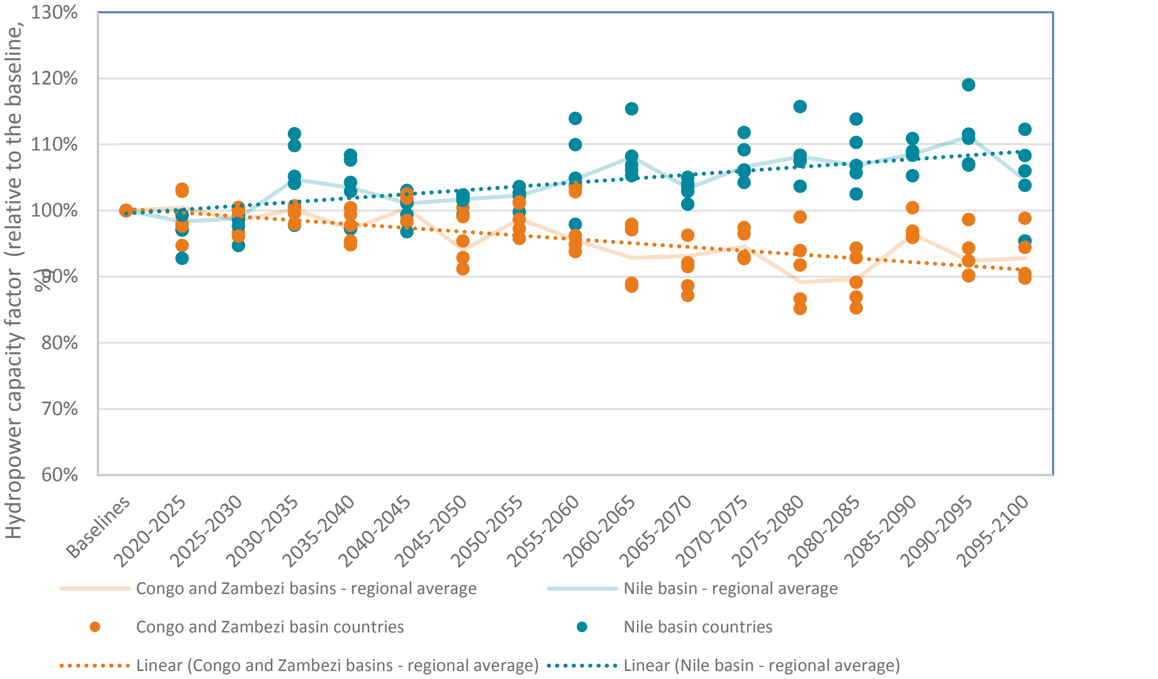
Note: Areas that are lightly coloured indicate the gap between projections of the Below 2°C scenario and the Around 3°C scenario.

The impacts of climate change are likely to be unevenly distributed across the continent, widening the gap in hydropower capacity factors between African subregions.

This spatial variation in the hydropower capacity factor is likely to be starker with a higher GHG concentration. Under the Below 2°C scenario, countries in the Congo and Zambezi basins are likely to see a decrease of over 6.5%, while the Nile basin countries experience an increase of over 2% between 2060-99. In the Around 3°C scenario, the Congo and Zambezi basin countries may see a greater drop, over 7% on average, in hydropower capacity. In contrast, the Nile basin countries are likely to see an increase by more than 7%.

Figure 4 Comparison of changes in hydropower capacity factors for the Congo and Zambezi basins and the Nile basin under low and high GHG concentration scenarios





Note: Each dot represents the relative value of the projected average hydropower capacity factor of selected plants in each country every five years.

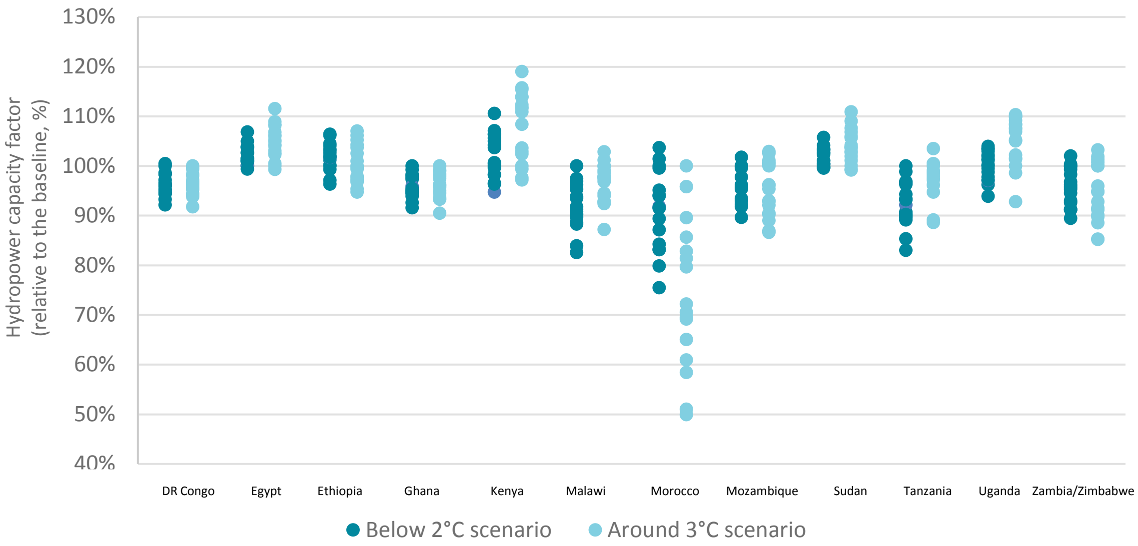
A higher GHG concentration is likely to accentuate differences in hydropower output between subregions.

Increased GHG concentrations are likely to intensify variability in hydropower capacity factors.

Another challenge caused by climate change is the increased year-to-year variability in hydropower capacity factors. Most hydropower plants studied in Egypt, Ethiopia, Ghana, Morocco, and Sudan are likely to experience increasing fluctuation in their capacity factors for the remainder of the century.

This variability is projected to be stronger with higher global GHG concentrations, and become an increasingly serious concern for reliable electricity supply. Under the Around 3°C scenario, the variability in hydropower capacity factors is likely to become exacerbated. Of the plants analysed, 85% present stronger fluctuations in hydropower capacity factors under the Around 3°C scenario than the Below 2°C scenario.

Figure 5 Variability of hydropower capacity factors in the Below 2°C and Around 3°C scenarios for 2020-99



Note: Each dot represents the relative value of the projected average hydropower capacity factor of the selected plants in each country every five years.

Increased GHG concentrations are likely to intensify variability in hydropower capacity factors.

Enhancing resilience requires systematic assessments and tailored measures, and both require strong governmental support

The enhanced climate resilience of African hydropower can bring multiple benefits. Resilient hydropower systems will help deliver the Sustainable Development Goals (SDGs) and minimise losses incurred by climate impacts. Resilient hydropower can also provide adaptation benefits by limiting climate impacts on water resources.

However, there is no one-size-fits-all solution to enhance the resilience of hydropower plants because of the wide range of patterns and magnitude of climate impacts. A tailored combination of resilience measures based on systematic assessments of climate risks and impacts will assist countries and operators in increasing the resilience of their systems.

Governments are expected to play a central role in identifying and implementing appropriate resilience measures for African hydropower. They can provide technical support for forecasting changes in climate patterns and offer financial support to increase the resilience of hydropower projects. Moreover, governments can introduce policies, regulations and guidelines to integrate climate resilience considerations into the planning, operation and maintenance of hydropower. Governments can also develop, support and implement capacity-building activities for risk and impact assessments, emergency response and recovery in the public and private sectors.

Chapter 1 Introduction

Why should we assess climate impacts?

The past decade (2010-19) was the hottest since records began in 1850 and the year 2019 was the second warmest year on record. The increasing level of heat accelerated the melting of ice sheets in Greenland and Antarctica, and resulted in the highest sea levels in 2019 since the introduction of the high-precision altimetry records in 1993. More erratic patterns of rainfall across the world and extreme weather events such as floods, droughts, heatwaves and tropical cyclones became more frequent or intensified in many countries (WMO, 2020).

These 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 (Ligtvoet et al., 2015). These changing conditions will require governments and utilities to better understand climate impacts on power systems, and to take appropriate actions to enhance their resilience to the adverse effects of a changing climate.

Why should we look at African hydropower?

The continent of Africa is one of the most susceptible regions to climate change. It is projected to experience increasing climate hazards during the remainder of the century. The majority of African countries are likely to see an increase in temperatures above the global average and more variations in precipitation patterns. Some countries in southern Africa have already experienced a notable level of warmth (more than 1°C above the average temperature of 1981-2010) and abnormally low precipitation in 2019 (WMO, 2020).

The projected changes in temperatures and precipitation patterns in Africa are likely to affect hydropower generation. For instance, the increasing variations in streamflows and evaporations are likely to result in stronger fluctuations in the generation output. In some African countries, hydropower operations could be even further restrained due to water scarcity. The limited adaptive capacity of local operators may aggravate the situation.

Despite the projected climate impacts, hydropower is likely to play an increasingly important role in Africa to support sustainable development and transitions to clean energy. Currently, 17% of electricity is generated from hydropower. This share is expected to increase to more than 23% by 2040 as a result of ongoing efforts to meet both climate goals and universal access to electricity (IEA, 2019). Indeed, Africa still has enormous remaining hydropower potential which is technically and economically feasible. Therefore, many countries have initiated new projects to tap into the continent’s enormous hydropower potential.

However, due to limited information and capacity, most planned hydropower projects in Africa rarely take into account potential climate impacts (CDKN, 2015). In some countries, there is a considerable level of uncertainty in assessing potential climate impacts on hydropower due to a lack of historical observation data and low agreement among climate scientists. Moreover, even when the data is available, public officials and utilities, particularly those in rural areas, have a low capacity to assess climate risks and impacts, and integrate the results into the planning and implementation of hydropower projects. Projects that are not attentive to climate impacts are likely to have difficulties in managing the stress created by a changing climate.

To minimise the adverse impacts of climate change, hydropower needs to enhance its resilience to climate change by incorporating systematic assessments of climate impacts. A resilient hydropower can play a key role in achievement of SDGs, clean energy transitions and climate change adaptation.

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

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Chapter 2 Climate risks to African hydropower

What is climate risk?

Climate risk indicates the factors which are associated with the potential consequences of climate change. According to the Intergovernmental Panel on Climate Change (IPCC), it results from the interaction of hazard, exposure and vulnerability (IPCC, 2014a).

- **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 power system has most of its grids located in a coastal area, it can be considered more exposed to climate risks of sea-level rise or coastal flooding than a system located further inland.
- **Vulnerability** is the propensity or predisposition to be adversely affected. It includes sensitivity to climate change impacts and lack of adaptive capacity which refers to the ability of a system to anticipate, prepare for and plan effectively for climate change. (DFID, 2011). If a power system is well equipped with a robust data system and capable human resources to anticipate and adapt to climate change impacts, the system can be considered less vulnerable.

A risk assessment of a power system can help governments and utilities understand the potential hazardous events; identify the assets and resources exposed to the hazards; and reduce vulnerability to a changing climate. Based on the understanding of climate-related risks, effective measures to enhance resilience to these risks can be identified to mitigate the potential impacts of climate change.

More climate hazards during the rest of this century

Africa is one of the regions most susceptible to the impacts of climate change. The continent is already seeing increased anomalies in climate patterns, and it is projected to experience more climate hazards during the rest of this century.

According to the IPCC Fifth Assessment Report (IPCC, 2014b), the mean annual temperature of Africa has steadily increased over the past century and is likely to rise faster than the global land average. Under a scenario which assumes a high GHG Representative Concentration Pathway (RCP 8.5), the mean annual temperature of Africa is likely to exceed 4°C above the 1986-2005 average by the end of the century, which is higher than the projected level of global warming (3.7°C) (IPCC, 2014c). Indeed, the majority of African countries are likely to see an increase in hot days. Some parts of southern Africa already experienced a warmer temperature in 2019 which was more than 1°C above the average temperature of 1981-2010 (WMO, 2020). The long-term changes in the mean annual temperature of Africa can increase evaporation losses from reservoirs, leading to a decrease in hydropower generation.

Changing precipitation patterns can also aggravate climate impacts on the continent. Southern Africa, where hydropower accounts for over 20% of the electricity of the regional power pool, is projected to experience electricity shortages due to a persistent occurrence of droughts in the forthcoming decades (Kuo, 2016). Indeed, last year, some southern African countries received lower than normal amounts of precipitation (WMO, 2020). On the other hand, in East Africa, a wetter climate with more frequent heavy precipitation (IPCC, 2014c) is projected to pose a challenge to the management of hydropower systems. It is likely to result in increasing inter-annual variability and uncertainty in hydropower generation in East Africa. These regional variations in precipitation patterns will exacerbate the existing gap in water availability among African countries (IPCC, 2014a). They will require tailored measures for each country to cope with these potential changes.

The increasing likelihood of extreme weather events could also raise the level of climate risk on African hydropower. Last year tropical cyclone Idai hit the east coast of Africa, resulting in strong winds, landfalls, storm surges and flooding in Mozambique, Malawi and Zimbabwe (WMO, 2020). Due to the flooding and excessive debris at the power stations, two major hydropower plants in Malawi went off line, reducing Malawi's hydropower capacity from 320 MW to 50 MW (Centre for Disaster Philanthropy, 2019; The Watchers, 2019). It caused widespread disruptions to electricity access for several days (ReliefWeb, 2019).

Table 2.1 Observed and projected future climate changes in African subregions

Region	Trends in daytime temperature extremes (frequency of hot and cool days)		Trends in heavy precipitation (rain, snow)		Trends in dryness and drought	
	Observed	Projected	Observed	Projected	Observed	Projected
West Africa	Significant increase in temperature of hottest day and coolest day in some areas	Increase in hot days (decrease in cool days)	Rainfall intensity increased	Slight or no change in heavy precipitation indicators in most areas	Increase but 1970s Sahel drought dominates the trend; greater inter-annual variation in recent years	Inconsistent signal
East Africa	Insufficient evidence	Increase in hot days	Insufficient evidence	Increase in heavy precipitation	Spatially varying trends	Decreasing dryness in large areas
Southern Africa	Increase in hot days (decrease in cool days)	Increase in hot days (decrease in cool days)	Increases in more regions than decreases but spatially varying trends	Low agreement	General increase in dryness	Increase in dryness, except eastern part, and consistent increase in areas of drought
Sahara	Insufficient evidence	Increase in hot days (decrease in cool days)	Insufficient evidence	Low agreement	Limited data, spatial variation of trends	Inconsistent signal

Note: Future changes are derived from global and regional climate model projections for 2071-2100 compared with 1961-90 or for 2080-2100 compared with 1980-2000. Subregions as defined in IPCC (2012), Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation; Special Report of the Intergovernmental Panel on Climate Change.

Source: IPCC (2014a), AR5 Climate Change 2014: Impacts, Adaptation, and Vulnerability; IPCC (2012), Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change.

Wider exposure to climate hazards and increasing reliance on hydropower

Hydropower is particularly susceptible to the adverse impacts of climate change because it is directly affected by changing patterns in rainfall and temperatures. For instance, hydropower generation output can fluctuate due to variations in the mean annual streamflow, shifts of seasonal flows, and increased evaporation from reservoirs (IPCC, 2014a). Therefore, an increasing reliance on hydropower could mean a higher probability of exposure to climate hazards.

Hydropower currently plays a significant role in Africa, accounting for 17% of electricity generation on average (IEA, 2019a). In countries such as the Democratic Republic of Congo, Ethiopia, Malawi, Mozambique, Uganda and Zambia, hydropower's share in electricity generation exceeds 80% (IEA, 2019b; International Hydropower & Dams, 2019). The share of hydro in Africa's electricity generation is likely to increase to more than 23% by 2040 thanks to its low-carbon nature and cost-effectiveness. The expansion of the share of hydropower will also contribute to ongoing efforts towards the mitigation and adaptation goals of the Paris Agreement, as well as the Sustainable Development Goals (SDGs) (IEA, 2019a).

Some African countries have already initiated large hydropower projects tapping into their enormous hydropower potential. Africa holds considerable technical potential for hydropower, with only 11% of this potential utilised (IHA, 2019). The maximum of the technically feasible hydropower potential of the continent is over 12 times today's hydropower generation. About two-thirds of the technical potential is likely to be economically feasible (Gernaat et al., 2017; International Hydropower & Dams, 2019). The Democratic Republic of Congo and Ethiopia have the greatest hydropower potential, followed by other countries such as Egypt, Zambia, Mozambique, Tanzania and Sudan (International Hydropower & Dams, 2019).

In 2018, 1 009 MW of installed capacity was added in Africa, bringing the region's total installed capacity to 36.3 GW (IHA, 2019). Two new hydropower stations in Uganda are projected to double Uganda's total installed hydropower capacity from 764 MW to 1 552 MW (IHA, 2019). One of the two new hydropower stations, the Isimba Dam, was already commissioned in March 2019, and the other one, Karuma Dam, is scheduled to be commissioned in 2020. These dams will contribute to meeting the increasing electricity demand in Uganda and advancing the electricity access rate, currently at less than 30%.

However, tapping into this hydropower potential without considering exposure to climate hazards may increase risk. Indeed, past hydropower projects in Africa rarely took into account the future increase in exposure to climate hazards. Few studies assessed risks and impacts of climate change on hydropower resources in Africa (IPCC, 2014a). Most projects relied on past meteorological and hydrological records to assess climate risks due to a low human capacity and limited information on climate projections (CDKN, 2015; Trace, 2019).

However, the long lifespan of hydropower assets, which generally ranges from 50 to 100 years, mandates that new hydropower projects consider the long-term implications of climate change (Trace, 2019). During the lifespan, most African hydropower plants are likely to be increasingly exposed to climate impacts. Given the growing role of hydropower in the continent, the issue of increasing exposure needs to be taken into account from the initial planning to the overall management of hydropower.

Some recent attempts have been made to incorporate future climate conditions into the design and operations of hydropower projects in Africa. For instance, the World Bank conducted a climate risk assessment for hydropower generation in five river basins of Cameroon (World Bank, 2014). Based on the findings from this assessment, the Bank has implemented the Nachtigal Hydropower Project since 2018. The project is expected to step up climate resilience against erratic precipitation in dry seasons by ensuring all-season flow on the Sanaga river basin with a new regulating dam and main reservoir upstream (World Bank, 2019).

Vulnerability of African hydropower

In addition to climate hazards and the level of exposure, vulnerability must be considered to manage climate risks. Vulnerability stems from the sensitivity and limited adaptive capacity of a power system and the stakeholders involved in the system. *Sensitivity* is the extent to which a system is impacted by a sector or a source that could be negatively affected by climate hazards. *Adaptive capacity* refers to the ability of a system and stakeholders to anticipate, prepare for and plan in advance to cope with potential climate impacts.

African hydropower is particularly vulnerable to climate change due to its sensitivity to water availability which is often restricted. Africa has less than 9% of the world's renewable freshwater resources, half of which are concentrated in just six African countries (UNESCO, 2019). Some cities in Mozambique, Zimbabwe and Ghana already experienced water shortages in 2019 (IEA, 2019a). Water scarcity means that electricity generation using hydro often needs to compete with other uses of water. Competition for water between energy, residential and productive uses are expected to be accentuated in some locations, given the increased risk of water stress due to changing and erratic precipitation patterns.

Moreover, public officials and utilities in the majority of African countries, particularly those in rural areas, have low levels of adaptive capacity; some of them are already experiencing difficulties in coping with the current level of climate variability (IPCC, 2014a). For example, an expert mission of the World Meteorological Organization (WMO) to Mozambique after cyclone Idai identified the limited capacities of key central and local government authorities to respond to emergencies as one of its major weaknesses (WMO, 2019a). Managing the adverse impacts of climate change may become more challenging with the increasing variability of climate patterns and more frequent extreme weather events. A lack of appropriate regulatory regimes, low levels of planning and the absence of disaster risk reduction strategies could exacerbate vulnerability to climate impacts in African countries (IPCC, 2014a). Several studies point to the importance of improving access to quality climate data, analysis and knowledge to reduce vulnerability (IPCC, 2012; WMO, 2019b).

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Chapter 3 Climate impacts on African hydropower

What is climate impact?

Climate impacts are the actual consequences of climate change. The changes in long-term climate trends and extreme weather events can directly affect all stages of the energy value chain of the electricity system, which includes generation, transmission and distribution, and demand.

Box 3.1 Climate impacts on the energy value chain of electricity system: The case of Cyclone Idai

Tropical Cyclone Idai had devastating impacts on Africa in 2019. It was one of the strongest known cyclones on the east coast of Africa, hitting Mozambique, Madagascar, Malawi and Zimbabwe with strong winds, severe flooding and destructive landfall. Over 900 people died due to the storm, which was the greatest loss of life in a southern hemisphere tropical cyclone in the last 100 years (WMO, 2020).

Many climate experts believe that Tropical Cyclone Idai was intensified by climate change. Warmer air and sea-surface temperatures made more energy available for cyclones and more rain was released (BBC, 2019; The Telegraph, 2019). An El Niño drought, exacerbated by climate change, had continued for months before Idai hit, making the earth unable to absorb water quickly and susceptible to flash flooding. (Oxfam International, 2019). Rising sea levels intensified the impact of storm surges on coastal regions, raising the probability of inland flooding in low-lying cities. For instance, Beira, a coastal city of Mozambique, was severely devastated by Idai (WMO, 2019; The Telegraph, 2019).

Entire parts of the electrical energy value chain, including hydropower generation, were also affected by Tropical Cyclone Idai on several levels:

- Generation: Due to flooding and excessive debris, two major hydropower plants in Malawi were damaged and went offline, reducing Malawi's hydropower capacity by more than 80% (Centre for Disaster Philanthropy, 2019; The Watchers, 2019). It caused widespread disruptions in electricity supply for several days (ReliefWeb, 2019).

- Transmission and distribution: The transmission lines from Mozambique to South Africa were damaged by the cyclone, and created a loss of 1 100 MW of power. It forced Eskom, South Africa's electricity utility, to implement load-shedding to prevent putting more demand on the grid. At the height of the crisis, South Africans had their power interrupted twelve times in a four-day period (CFR, 2019).
- Demand: Due to the interrupted electricity supply from the central grids after Tropical Cyclone Idai, electricity demand patterns in South Africa were markedly changed. Demand for diesel jumped as the disruption resulted in the use of back-up generators (CFR, 2019).

The number of intense tropical cyclones at the level of Idai is likely to increase in the future while the total number of tropical cyclones will decline (WMO, 2019). In 2019 in the South Indian Ocean basin 13 cyclones out of 18 reached hurricane intensity, equalling the largest number on record (WMO, 2020). The projected increase in frequency of high-intensity tropical cyclones requires African countries to be prepared for future climate impacts on their electricity systems.

Sources: WMO (2019), WMO (2020); BBC (2019), The Telegraph (2019), Oxfam International (2019), Centre for Disaster Philanthropy (2019), The Watchers (2019), CFR (2019), ReliefWeb (2019).

Hydropower plants which generally have a long lifespan, ranging from 50 to 100 years, are likely to be impacted by climate change (ADB, 2013; Ebinger and Vergara, 2011; IHA, 2019; Burillo, 2018; WMO, 2017; US EIA, 2019). Rising temperatures will affect hydropower generation by increasing evaporation losses. Changes in precipitation will also alter potential, generation output, peak level and seasonal variations of hydropower. Increasingly erratic precipitation patterns such as the increasing number of dry days may arouse concerns over interrupted hydropower generation due to water shortages. Extreme weather events such as cyclones, floods, and land slides also damage hydropower assets and disrupt electricity supply. For instance, an increased sediment load after floods or landslides caused by storms can reduce the efficiency of hydropower generation and abrade turbines.

How to assess climate impacts

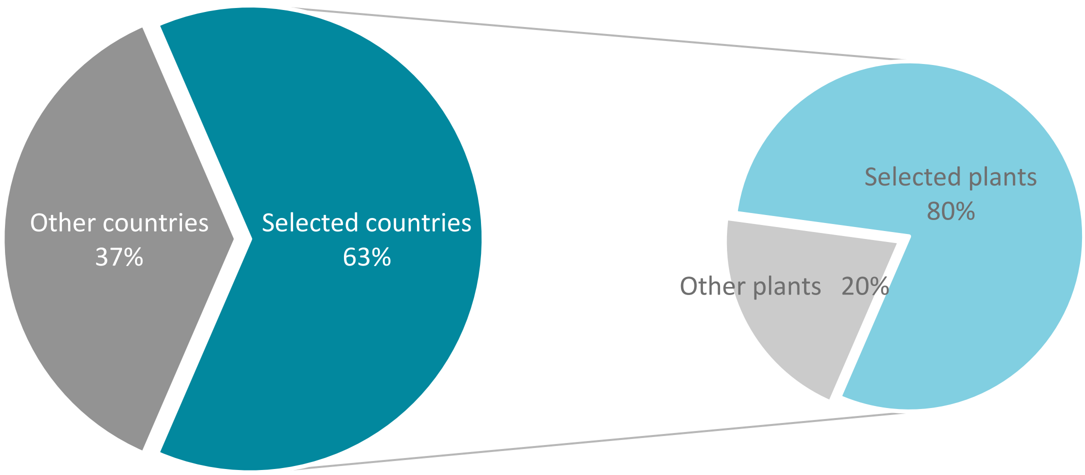
An assessment of future climate impacts is often challenging due to the complexity of the climate system and the range of models which often provide different results. For Africa, it is often compounded by a lack of historical observation data to verify those models. To address this, an assessment based on a thorough analysis of various models and data sources, and a comparison across these modeling outcomes, is needed.

This section shows results from an assessment of climate impacts on African hydropower generation. It involves estimating future annual and monthly capacity factors for 64 hydropower plants in 13 African countries between 2020 and 2099, and comparing the projected results with the values of the baseline period from 2010 to 2019.

The geographical scope of the assessment covers Nile basin countries (Egypt, Ethiopia, Kenya, Sudan and Uganda), Congo and Zambezi basin countries (the Democratic Republic of Congo, Malawi, Mozambique, Tanzania, Zambia and Zimbabwe), a North African country (Morocco) and a West African country (Ghana). The total installed hydropower capacity of the selected countries is over 21 000 MW, accounting for about 63% of the total installed hydropower capacity in Africa (over 36 000 MW) (International Hydropower & Dams, 2019).

The assessment covers over 18 000 MW of installed hydropower capacity in total, accounting for 80% of the total installed hydropower capacity of the 13 African countries, and around 50% of the entire continent. The full list of the assessed hydropower plants can be found in the Annex.

Figure 3.1 Share of selected plants in African hydropower in terms of installed capacity



The total installed capacity of selected hydropower plants accounts for half of the total installed capacity of African hydropower.

To derive annual and monthly capacity factors per hydropower plant, the assessment developed a high-resolution global discharge map that combines monthly run-off data derived from 40 different ensembles of five General Circulation Models (GCM), four Global Hydrological Models (GHM), two Representative Concentration Pathways (RCP) (see Annex), a high-resolution (15″ × 15″) area accumulation and drainage direction map from the HydroSHEDS project (ISIMIP Database; Gernaat et al., 2017; Lehner et al., 2008), and a low-resolution (0.5˚ x 0.5 ˚) map of monthly run-off.

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

The assessment examined as many combinations of models as possible to enhance the reliability of results and minimise potential distortions by outliers. Since outliers are difficult to avoid due to the different assumptions within each model and the embedded uncertainty of climate and hydrological systems, the results present average annual and monthly capacity factors by aggregating and comparing outcomes from various GCMs, GHMs and RCPs.

Two scenarios: Below 2°C and Around 3°C

The report assesses potential climate impacts using two different scenarios that lead to two different global average temperature outcomes: **Below 2°C** and **Around 3°C**. By comparing these two scenarios the report aims to present how greenhouse gas (GHG) concentrations are likely to impact hydropower capacity in Africa.

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

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

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

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

Table 3.1 Overview of the scenarios: Below 2°C and Around 3°C

Scenario	Below 2°C	Around 3°C
Representative Concentration Pathway	RCP 2.6	RCP 6.0
Targeted radiative forcing in the year 2100	2.6 W/m²	6.0 W/m²
CO_2-equivalent concentrations (ppm)	430-480	720-1000
Global temperature change	1.6(±0.4)°C	2.8(±0.5)°C
Likelihood of staying below a specific temperature level over the 21st century	Likely to stay below 2°C	More unlikely than likely to stay below 3°C

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

Key results of the impact assessment

Africa, where today more than 600 million people are deprived of electricity, is expecting to add 20 million people to the electricity network every year from now to 2030. In addition, the fast-growing urban population and accelerated economic growth are expected to boost electricity demand. Sub-Saharan Africa (excluding South Africa) in particular is likely to see the fastest growth in electricity demand of any region worldwide, at an annual rate of 6.5% on average (IEA, 2019a). Large-scale deployment of renewable energy is considered to be a cost-effective path to meet the soaring demand for electricity while mitigating emissions from electricity generation.

Hydropower, which currently comprises the majority of installed renewable capacity in Africa, is expected to remain one of the largest renewable sources of electricity. In a scenario that assumes the fulfilment of climate and sustainable development goals, hydropower grows even further to more than 23% of electricity generation by 2040 in Africa, accounting for one-third of total electricity generation from renewables

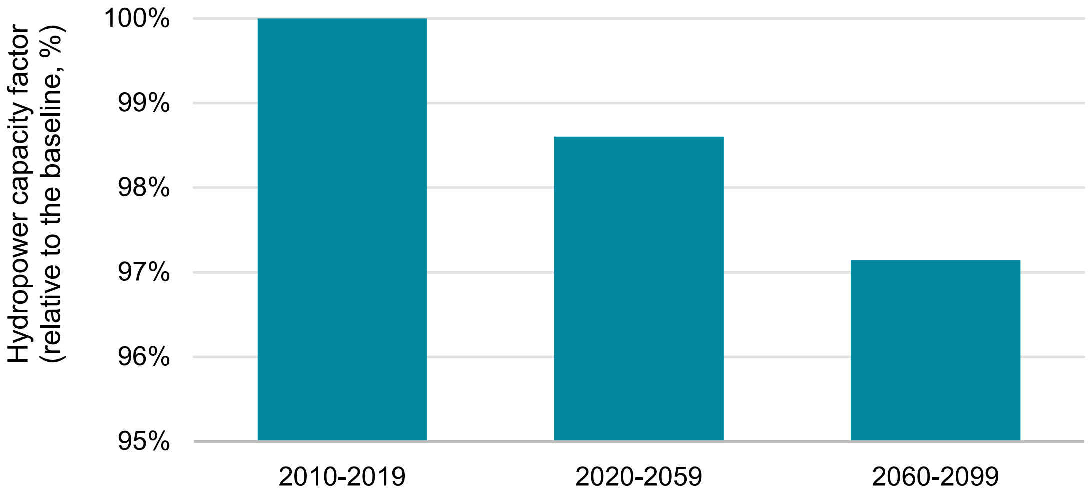
(IEA, 2019a). Given the increasing role of hydropower in Africa, the impacts of climate change on the future hydropower capacity factor need to be assessed in advance to ensure climate resilience of the electricity system.

The regional mean of hydropower capacity factor is projected to decrease in both scenarios

From now until the end of the century, the mean hydropower capacity factor of selected hydropower plants will decrease due to climate change in both climate scenarios, when other conditions remain unchanged.

The mean capacity factor over the period from 2020 to 2059 is likely to decrease by more than 1% compared to the baseline level of 2010-19. The decrease in hydropower capacity factor is projected to continue in the latter 40 years of the century. Between 2060 and 2099, the mean hydropower capacity factor is projected to fall by around 3% compared to the baseline level of 2010-19 in both scenarios. The projected decrease in hydropower generation from the selected African hydropower plants during 2020-99 is expected to be around 130 TWh, equivalent to the total annual hydropower generation in Africa in 2017 (IEA 2019a).

Figure 3.2 Average hydropower capacity factor of selected plants during 2020-99 relative to the baseline level of 2010-19



For the remainder of the 21st century, climate change is likely to decrease the average hydropower capacity factor of selected hydropower plants.

The decline in capacity factors is mainly driven by two elements: decreasing levels of peak monthly capacity during the wettest months, and a further decline in water flow during the driest months in a majority of the selected plants. Under both climate scenarios, peak monthly capacity levels of the baseline period will no longer be reached in most of the selected countries from 2060 onwards. Moreover, in the Democratic Republic of Congo, Malawi, Morocco, Mozambique, Zambia and Zimbabwe, lower water levels during the driest months may further decrease hydropower capacity factors.

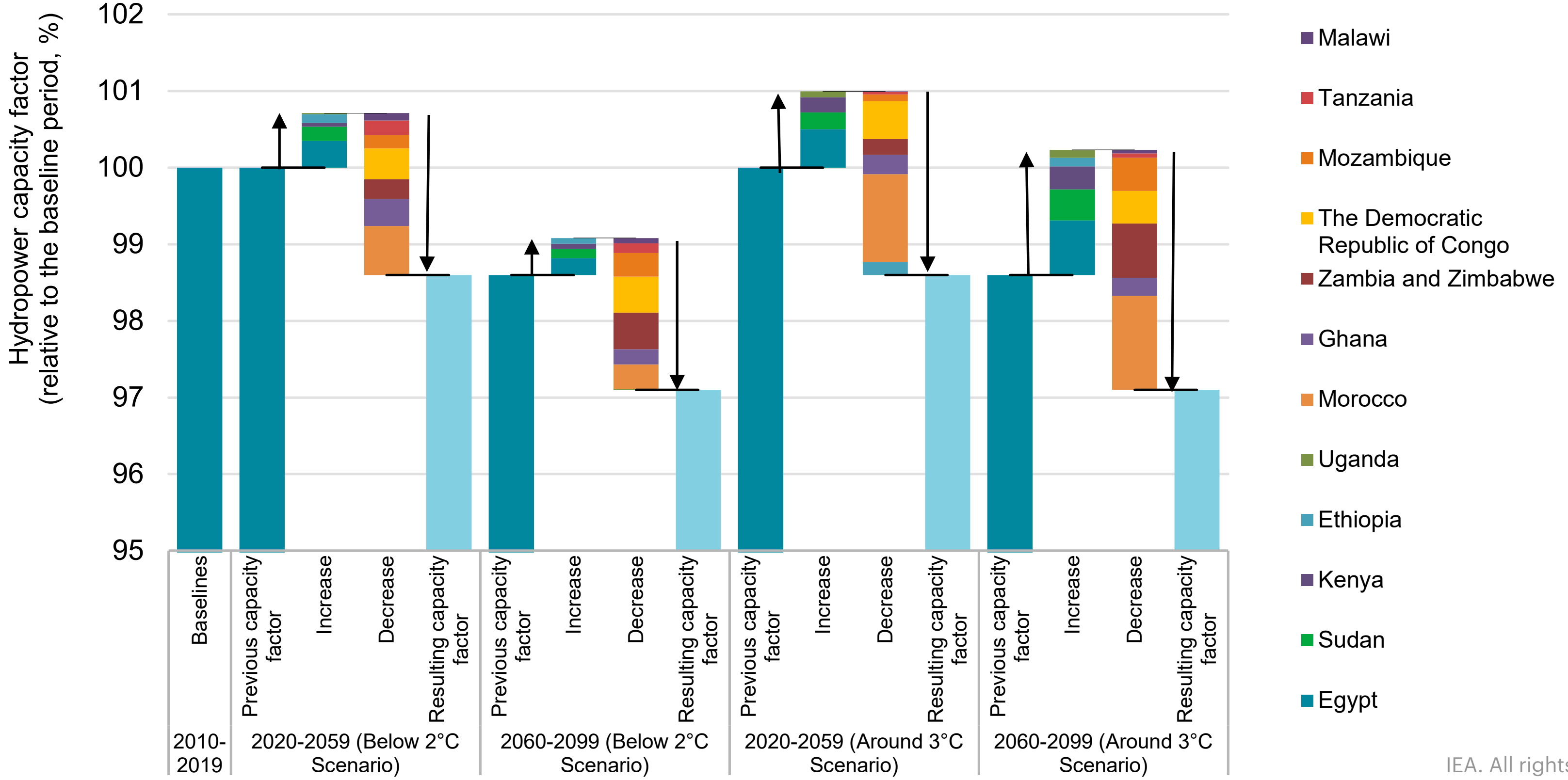
However, the projected decrease in the regional mean does not capture all aspects of climate impact

The projected decrease in the regional mean hydropower capacity factor may generate false impressions regarding future climate impacts on African hydropower. For instance, the projected 3% decrease in 2060-99 compared to the baseline period may seem to be negligible at first glance, given that non-climate factors could have same or even higher impacts. Furthermore, this may prompt the conclusion that different levels of greenhouse gas (GHG) concentrations will not have decisive impacts on future hydropower capacity factors.

However, country-specific data show that climate change will have significant impacts on most African countries, although the patterns of change may vary from one country to the other. For example, the hydropower capacity factors in Morocco, Zambia, Zimbabwe, the Democratic Republic of Congo and Mozambique are projected to decline considerably, while the decrease would be offset by an increase in the hydropower capacity factors of the Nile basin countries, notably Egypt, Sudan and Kenya.

The graph with fractions by country also shows that these climate impacts will be largely affected by the level of GHG concentration. Between 2060 and 2099, for example, the decrease of the hydropower capacity factor in Morocco, Zambia and Zimbabwe in the Around 3°C scenario is projected to be 50% more than in the Below 2°C scenario. The larger decrease in these countries offsets the higher increase from the Nile basin countries under the Around 3°C scenario. This will eventually generate the same level of decline of approximately 3% in the regional mean hydropower capacity factor in both scenarios.

Figure 3.3 Comparison of changes in hydropower capacity factor during 2020-99 relative to the baseline period in both scenarios

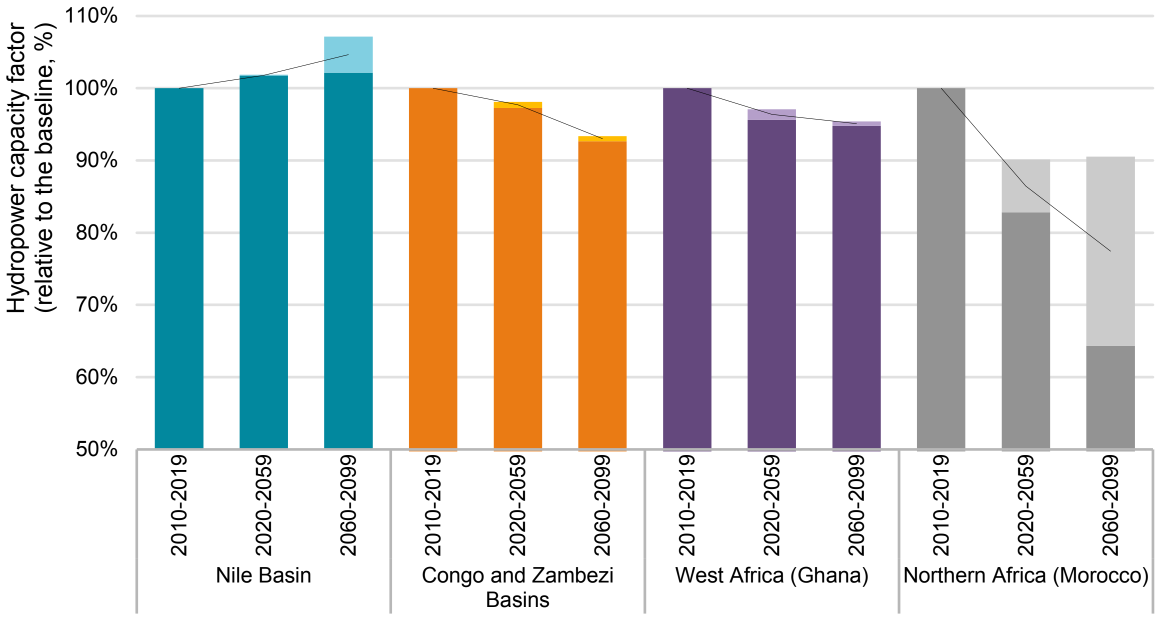


Country-specific data show that climate change will have different impacts on each country and are largely affected by GHG concentration pathways.

Climate impacts on hydropower generation will be spread unevenly across the continent

The decline in the regional mean hydropower capacity factor means that the overall hydropower generation in Africa is likely to decrease. However, the impacts of climate change will be spread unevenly across the continent. For instance, Morocco in North Africa is likely to experience the largest drop in its hydropower capacity factor during the rest of the century, while East African countries around the Nile basin are likely to see an increase, benefiting from more frequent heavy rainfall.

Figure 3.4 Changes in hydropower capacity factor by African subregion



Note: Areas that are lightly coloured indicate the gap between the projections of the Below 2°C scenario and the Around 3°C scenario

The impacts of climate change are likely to be unevenly distributed across the continent, widening the gap in hydropower capacity factors between African subregions.

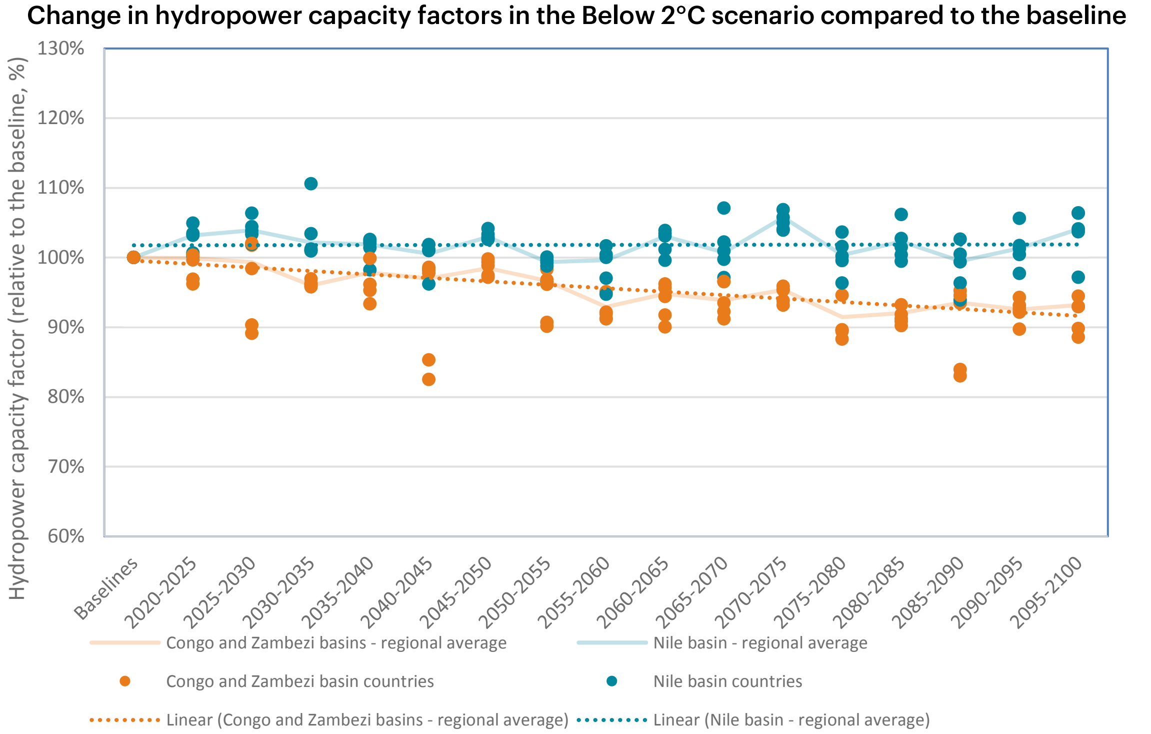
The projected decrease in the capacity factor in the Congo and Zambezi Basins is alarming, given the significant role of hydropower in this subregion. Some countries already have difficulties in coping with the current level of dryness. For instance, the power supply in Zambia, where more than 80% of electricity comes from hydro (IEA, 2019b), has been significantly affected by declining water availability due to a shorter rainy season and more frequent droughts (Onishi, 2016). In February 2016, the water level of the Kariba Dam, one of the biggest electricity sources for Zambia and Zimbabwe, dropped to near-record lows, 12%, prompting blackouts, power rationing, and a slow-down of economic development in some places (IHA, 2017). The disruption occurred again in August 2019, and the Kariba station needed to cut output and impose daily blackouts (Bloomberg, 2019). The projected changes in rainfall patterns can severely threaten the electricity security of Zambia and Zimbabwe, given their heavy reliance on electricity supply from the Kariba station.

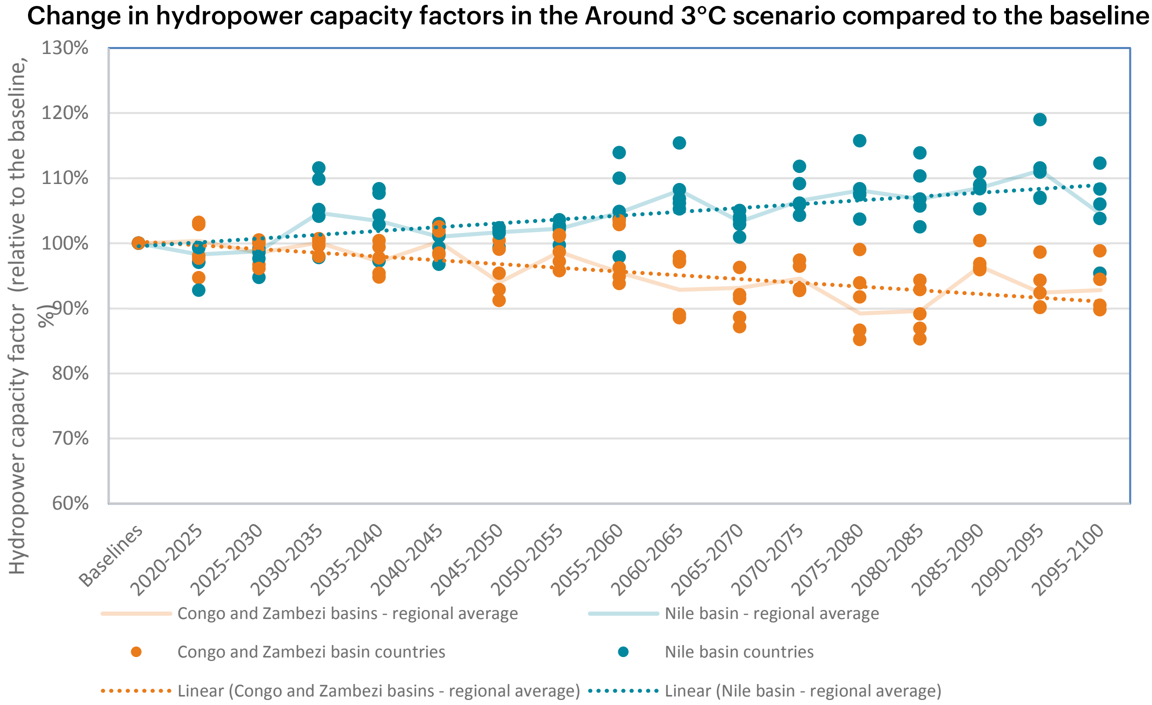
The spatial variations in hydropower capacity factors are likely to be starker with higher GHG concentrations

In the Below 2°C scenario, Central and Southern African countries around the Congo and Zambezi basin are likely to see decreases of 3% on average in hydropower capacity factors from 2020-59. On the other hand, East African countries around the Nile basin such as Egypt, Ethiopia, Kenya, Sudan and Uganda, are projected to experience mild increases of over 1.5% during the same period on average. During the last 40 years of the century (2060-99), countries in the Congo and Zambezi river basin are likely to see a continued decrease in the hydropower capacity factor to over 6.5%, while the Nile basin countries experience a further increase of over 2%. The spatial variations in hydropower capacity factors at a country level could be even larger, with a decrease of 10% in Morocco and Malawi, and an increase of almost 3% in Kenya.

In the Around 3°C scenario, the Congo and Zambezi basin countries could see a more significant decrease of over 7% on average during 2060-99, while Nile basin countries are likely to see an increase of more than 7%. For instance, the hydropower capacity factors in Mozambique, Zambia and Zimbabwe are likely to fall by over 9% during 2060-99, while those of Kenya and Uganda increase by over 12% and 7% respectively.

Figure 3.5 Comparison of changes in hydropower capacity factors for the Congo and Zambezi basins and the Nile basin under low and high GHG concentration scenarios





Note: Each dot represents the relative value of the projected average hydropower capacity factor of selected plants in each country every five years.

A higher GHG concentration is likely to accentuate differences in hydropower output between subregions.

The projected geographical variations in hydropower capacity factors underline the importance of developing a tailored approach for each country based on the best available scientific assessments of climate impact. Indeed, the two subregions, the Congo and Zambezi river basin and the Nile basin, are attracting much of the focus for future hydropower development. In the coming decades, 13 GW and 28 GW of additional hydropower capacity is envisioned for the Zambezi basin and the Nile basin, respectively (Trace, 2019). For the reliable operation of these new hydropower plants, countries in the Congo and Zambezi river basins need to consider long-term measures to address the gradual but negative impact of climate change. Meanwhile, East African countries need to consider measures to manage the projected increase in heavy rainfall along with plans to exploit the potential increase in generation.

Increasing variability in hydropower capacity factors will be exacerbated with higher GHG concentrations

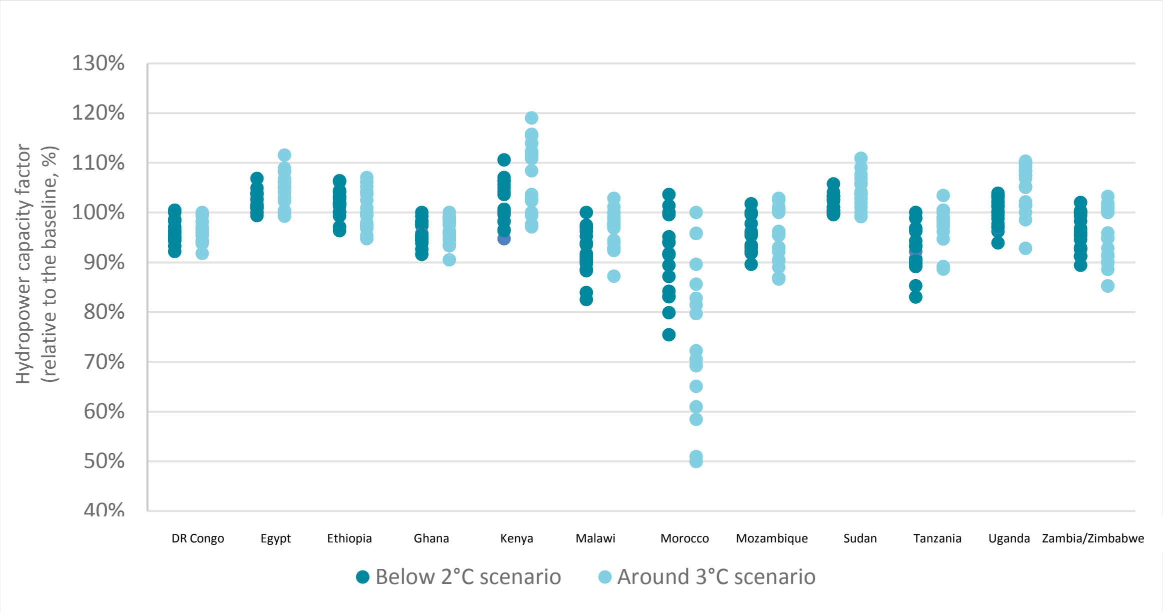
One of the biggest challenges caused by climate change is the increased year-to-year variability in hydropower capacity factors. Increasing anomalies in climate patterns and more frequent extreme weather events are likely to make the capacity factors of African hydropower fluctuate more. In particular, most of the selected hydropower plants (30 out of 32) in Egypt, Ethiopia, Ghana, Morocco and Sudan are likely to experience an increasing magnitude of fluctuation in their capacity factors for the remainder of this century in both scenarios. In particular, during the latter 40 years of this century, these hydropower plants are projected to see a higher variability in capacity factors. The escalating variability in hydropower capacity factors and output can significantly damage reliable electricity supply in these countries.

Moreover, if global GHG concentration is not regulated effectively, the increasing variability will become a serious concern for electricity security. Under the Around 3°C scenario, the variability in hydropower capacity factors is likely to be more accentuated. Of the plants analysed, 85% present stronger fluctuations in hydropower capacity factors under the Around 3°C scenario than the Below 2°C scenario.

In particular, Morocco, Mozambique and Zambia are likely to see an increase of over 50% in inter-annual variability under the Around 3°C scenario, compared to the level of the Below 2°C scenario. Given the significant share of hydro in electricity generation in Mozambique and Zambia, the projected increase in variability with higher GHG concentrations may pose a considerable challenge to electricity supply in these countries.

Even the Nile Basin countries (notably, Egypt, Ethiopia, Kenya, Sudan and Uganda), are also likely to face an increase in inter-annual variability under the Around 3°C scenario. Although the Nile Basin countries may benefit from a changing climate in terms of annual hydropower generation output, they will be unable to avoid the adverse impacts from increased inter-annual variability under the Around 3°C scenario.

Figure 3.6 Variability of hydropower capacity factors in the Below 2°C and Around 3°C scenarios for 2020-99



Note: Each dot represents the relative value of the projected average hydropower capacity factor of the selected plants in each country every five years.

Increased GHG concentrations are likely to intensify variability in hydropower capacity factors.

The increasing variability in hydropower capacity factors demands immediate actions to ensure reliable electricity supply

Many African countries such as the Democratic Republic of Congo, Ethiopia, Ghana, Mozambique and Tanzania are already experiencing frequent electricity outages due to poor maintenance regimes and aging infrastructure. In 2018, therefore, 40 TWh of electricity was generated from back-up generation capacity in sub-Saharan Africa (IEA, 2019a). However, most of the current back-up generators in Africa are relying on diesel fuel, which would contribute to a further increase in GHG emissions. To meet the climate and sustainable development goals while ensuring reliable electricity supply, African countries need to ensure access to other low-carbon back-up options.

Expanded interconnections can be a low-carbon option to address the increasing variability in hydropower generation. An interconnected network provides access to diverse and complementary markets. A country where hydropower generation drops or soars unexpectedly due to the increasing variability, may consider electricity import or export through an interconnected network. By allowing trades among countries, expanded interconnections can contribute to addressing the issues resulted from increasing spatial variations in climate impacts.

In Africa, most countries are already participating in regional power pools. For instance, in Ethiopia, which is a member of the Eastern Africa Power Pool (EAPP), cross-border interconnections with neighbouring countries are rapidly expanding, making Ethiopia a power hub for East Africa. Given the immense untapped potential and the projected increase in hydropower output in Ethiopia, hydropower is likely to take a greater share of future traded electricity in East Africa over the rest of this century.

Diversification of renewable energy sources in the electricity mix can also help to maintain reliable and sustainable electricity services. For instance, Morocco, which may well see a considerable increase in variability in hydropower capacity factors, has committed to diversifying its renewable energy sources. The government announced a target in 2015 to increase renewable generation capacity to 52% of the total installed power capacity by 2030, led by a significant increase in installed capacities of solar and wind. With the initiative of the government, the share of wind significantly increased from 3% in 2010 to 9% in 2017 while the share of hydropower in electricity generation fell rapidly from 15% to 5% for the same period (IEA, 2019b). The efforts to diversify renewable energy sources while lowering reliance on hydropower in Morocco are expected to reduce the vulnerability of the power sector to future climate impacts.

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Chapter 4 Measures to enhance the resilience of African hydropower

What is climate resilience?

Climate resilience refers to the capacity to anticipate, absorb, accommodate and recover from the stress and changes caused by climate change (IEA, 2016; IPCC, 2012). It is associated with three key dimensions: robustness, resourcefulness and recovery (IEA, 2016).

- **Robustness** is the ability of an energy system to withstand long-term and gradual changes in climate patterns and continue its operation. For instance, thermal power plants that use water from recirculation for cooling are considered more resilient to a gradual increase of water temperature than others that use external sources such as rivers, lakes or oceans.
- **Resourcefulness** is the ability to manage operations during immediate shocks such as extreme weather events. For example, a hydropower plant with a flood control reservoir is likely to be more resilient to floods than others.
- **Recovery** relates to the ability to restore the system's function after an interruption resulting from climate impacts. For example, a more resilient power system with a well-coordinated contingency plan is likely to recover from the shock caused by climate impacts faster than others.

Multiple benefits of enhancing climate resilience

The enhanced climate resilience of African hydropower can bring multiple benefits. Resilient hydropower systems can support uninterrupted electricity supply which is essential for delivering Sustainable Development Goals (SDGs) in Africa. Although Africa has made strong progress on electricity access in past decades, the continent still needs to add 20 million people to the electricity network every year from now to 2030. In addition, the urbanisation and economic development of Africa will increase demand for reliable, affordable and quality electricity supply. Hydropower is a cost-effective option to meet the increasing demand while limiting emissions from the energy sector. Building climate resilient hydropower systems will help the continent meet its development and climate goals.

In addition, resilient hydropower stations can minimise losses and save costs from climate impacts. In most parts of Africa, investment in resilience measures, such as enhancing reservoirs and improving generation efficiency, could help utilities save costs for recovery and reduce losses from the underutilisation of hydropower (World Bank, 2015). For governments and communities, resilient hydropower systems can minimise the socio-economic costs incurred by climate change. For instance, a resilient hydropower will support a fast recovery from extreme weather events, bolstering the continuous provision of public services with an uninterrupted electricity supply after the shocks.

Resilient hydropower can also provide adaptation benefits, limiting climate impacts on water resources. The projected impacts of climate change may reduce accessibility to water resources and escalate spatial and seasonal variations in water availability. It can pose a significant challenge to many African countries which already suffer from water shortage. Resilient hydropower with a reservoir capacity can act as a storage buffer against climate change, providing reliable water supply for irrigation, potable water supply and flood control (Berga, 2016).

Measures to enhance resilience

Enhancing the resilience of the hydropower plants in Africa is important to ensure a reliable electricity supply in the face of increasing climate impacts. However, there is no one-size-fits-all solution to enhance the resilience of hydropower plants because of the wide range of patterns and magnitude of potential climate impacts. **A tailored combination of resilience measures based on a systematic assessment of climate risk and impact** will help countries and operators increase the resilience of their systems.

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

Table 4.1 Examples of possible soft and hard measures for the resilience of African hydropower

Soft measures	Hard measures
Strategies and regulations for resilience • Plan a national energy mix based on the assessment of potential climate impacts • 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 • 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	**Upstream management** • Manage a catchment (e.g. forestation) • Build smaller dams upstream
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	

Source: IHA (2019), Hydropower Sector Climate Resilience Guide; WBCSD (2014), Building a Resilient Power Sector; IEA (2016), Energy, Climate Change and the Environment: 2016 Insights, (Report, November 2016).

The implementation of resilience measures can help African hydropower plants reduce (though not fully eliminate) the risk of climate-related disruptions (OECD,

2018) and withstand long-term changes in climate patterns. The aim is to allow plants to continue operating ("robustness"), to manage operations during the disruptions caused by extreme weather events ("resourcefulness"), and for plants to recover function after disruptions ("recovery").

Examples of soft measures

Soft measures can be adopted and implemented by both governments and utilities. Governments can play a central role in enhancing resilience by introducing strategies and appropriate regulations. Based on a scientific and comprehensive assessment of climate risk and impact, governments could, if necessary, actively plan for an energy mix to improve the resilience of the electricity system. This could entail the development of certain energy sources that are less vulnerable to climate change. For instance, countries in the Congo and Zambezi river basins that are reliant on hydropower could consider diversifying their renewable energy sources given the projected increase in climate impacts on their hydropower capacity.

Governments can also encourage utilities to pay more attention to climate resilience by creating a regulatory framework that incentivises the implementation of resilience measures (OECD, 2018). 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 restriction of land development around vulnerable catchment areas can also reduce the probability of serious damage from climate hazards.

Utilities and project developers can enhance the resilience of new hydropower plants by taking into account the potential impact of climate change when they design and plan hydropower plants. For existing hydropower, utilities can adapt to climate change by revising operating regimes in a manner that responds to projected climate impacts. For instance, utilities can integrate a climate resilience monitoring process into operation and maintenance plans. It will help utilities regularly collect information on future climate risks and assign clear responsibilities.

In addition, stronger and more co-ordinated emergency response measures can reduce the time for recovery 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 the emergency preparedness of businesses and households by improving institutional co-ordination and information dissemination.

Examples of hard measures

Most hard measures are related to physical system hardening and upstream management. Enhancement of reservoir capacity, increased dam height, modification of turbines and redesign of spillways can help manage erratic patterns of water flow. For instance, the Qairokkum hydropower plant in Tajikistan is implementing a full rehabilitation project to enhance resilience to the projected increase in hydrological variability by modifying turbines and spillways (Green Climate Fund, 2015).

In addition, an enlarged reservoir may help hydropower plants reduce their vulnerability to floods by limiting overflow. An augmented level of water storage reservoirs can reduce the adverse impacts of droughts. Redesigning of canals or tunnels can also contribute to better management of the variability of water levels by adapting to changed discharge patterns.

In countries that are 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.

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

Major barriers to implementing resilience measures in Africa

However, there are still major barriers to implementing measures to enhance the resilience of African hydropower:

There is a significant lack of reliable and accessible information about climate risks and impacts on hydropower in Africa. Many countries have limited observational data on climate and hydrology. Even if a country has meteorological and hydrological data, public access to the information could be limited. Therefore, models based on the available data often present conflicting or even misleading outcomes. For instance, there are still debates among international experts on the future precipitation patterns in southern Africa and the Sahara (IPCC, 2014). It is difficult to choose the most effective set of resilience measures without accurate data and information about potential climate impacts on hydropower plants (EEA, 2019).

There are few incentives for decision makers to invest in enhancing the climate resilience of hydropower plants. The benefits of investment in climate resilience measures on hydropower plants are likely to be seen only after several years or even decades, while the capital cost of implementing the measures is incurred immediately (OECD, 2018). Furthermore, the benefits of resilience tend to be spread across the value chain, while the immediate cost is likely to be imposed on service providers. These can make decision makers hesitant to initiate or implement resilience measures on hydropower plants, despite their longer-term benefits.

Unfavourable regulatory frameworks could discourage the implementation of climate resilience measures. The absence of climate resilience objectives in energy masterplans may send a misleading signal to developers and service providers, leading them to overlook climate resilience in the design, operation and maintenance process.

Some African countries still lacks the capacity to anticipate and cope with climate impacts. For instance, climate prediction and early warning systems are often constrained in Africa due to the lack of capacity (Ogallo and Oludhe, 2009). Limited understanding of the devastating impacts of climate variability and extreme weather events may hinder timely decision-making for the adoption and implementation of resilience measures.

Policy recommendations for African hydropower

Governments need to play a central role in overcoming the existing barriers to implementing resilience measures. Without support from governments, private actors may have a limited incentive to implement resilience measures. However, if hydropower systems remain vulnerable to climate impacts, it will eventually bring higher costs to society, while electricity service providers would bear only a fraction of the entire socio-economic costs. Thus, governments need to send strong signals to the private sector to encourage their investment in building climate resilience.

Governments can provide technical support by commissioning research and making available quality data and information on climate change. Governments can also offer financial support for resilient hydropower projects. Adoption of policies, regulations and guidelines to mainstream climate resilience considerations into the entire process of hydropower projects will encourage operators to focus on climate risks and impacts. Capacity-building activities supported by governments will facilitate the implementation of resilience measures.

- **Recommendation 1: Ensure that a systematic and comprehensive assessment of climate risk and impact is available to all relevant stakeholders.** Such an assessment is the first step towards climate resilience and should be organised systematically using scientific methodologies and established guidelines. Some governments, international organisations and academia have already introduced a few comprehensive methodologies to identify and assess climate risks to enhance the resilience of hydropower. Moreover, the assessment should be as comprehensive as possible. It is highly recommended for countries that have limited access to observed data, to utilise all available data sources and adopt various climate models so that the different results can be compared. A credible assessment of climate risk and impact will significantly reduce the cost of implementing resilience measures. According to a recent study, a project to build a resilient infrastructure without appropriate data on climate hazards and exposure will cost ten times more than a project which has sufficient information on climate risks (World Bank, 2019).

Box 4.1 Guidelines, standards and tools for climate resilience of energy systems

There are several guidelines, standards and tools devoted to helping public and private entities to assess climate change risks on energy systems and to develop strategies and measures to enhance their resilience. These include:

- *The Hydropower Sector Climate Resilience Guide*, developed by the International Hydropower Association, provides a comprehensive methodology to identify, assess and manage climate risks to enhance the resilience of hydropower plants (IHA, 2019).
- The U.S. Climate Resilience Toolkit was launched in November 2014 to help institutions to find and use tools, information and expertise to enhance climate resilience. Energy is included as one of the ten topics of the Toolkit, with a particular focus on climate impacts on energy security (NOAA, 2014).
- The Department of the Environment and Energy of the Australian Government developed a framework called Climate Compass in August 2018. It was designed to help public officers to manage climate risks to policies, programmes and asset management (CSIRO, 2018).

Sources: IHA (2019), Hydropower Sector Climate Resilience Guide; NOAA (2014), U.S. Climate Resilience Toolkit; CSIRO (2018), Climate Compass A Climate Risk Management Framework for Commonwealth Agencies.

- **Recommendation 2: Create the right incentives for electricity providers to align their interests with investments that are beneficial to the public.** An adequate level of rewards and penalties based on the assessment of social and economic costs will encourage service providers to go beyond the minimum mandatory standards, seek cost-effective solutions, and invest in climate resilience measures (World Bank, 2019). Governments with limited financial resources could consider working with multilateral development banks or other support programmes of international organisations.

Box 4.2 Climate resilience financial support initiatives: EBRD's Climate Resilience Bond

International financial institutions have started creating programmes to support investments in climate-resilient projects. One notable example is the recent creation of the Climate Resilience Bond of the European Bank for Reconstruction and Development (EBRD), launched in September 2019 (EBRD, 2019). This AAA-security, 5-year bond is the first ever to be entirely dedicated to financing climate resilience. It has raised USD 700 million at issuance, with demand from around 40 investors in 15 countries. Its proceeds will be used to finance (e.g. provide loans to) existing and new climate resilience projects within EBRD's Climate Resilience Portfolio. These include investments in climate-resilient infrastructure (e.g. climate-resilient electricity generation, transmission and distribution), investments in climate-resilient business and commercial operations, and investments in climate-resilient agricultural and ecological systems.

All the financed projects need to be consistent with the Green Bond Principles (International Capital Market Association, 2018) and the Climate Resilience Principles, published by the Climate Bonds Initiative in September 2019 (Climate Bonds Initiative, 2019). These principles prescribe a process to identify and assess climate change vulnerabilities, to mitigate the associated climate risks, and to establish the monitoring and evaluation system needed to appraise the climate resilience performance of the asset.

Sources: EBRD (2019), 1.625% US$700 Million 5-Year Climate Resilience Bond Due 27 September 2024; International Capital Market Association (2018), Green Bond Principles; Climate Bonds Initiative (2019), Climate Resilience Principles.

- **Recommendation 3: Integrate climate resilience into national energy plans and regulations.** Governments can send a strong signal to service providers and developers by mainstreaming climate resilience in the entire process of hydropower planning and operation. For instance, governments can consider including resilience standards into construction codes and asking for a regular climate risk assessment in the operation and maintenance rules. They can also facilitate further deployment of resilience measures by removing or adjusting conflicting regulations. For example, decision makers can streamline the process of granting environmental permits for certain resilience projects so that the required structural changes for climate resilience can be implemented more easily.

- **Recommendation 4: Build capacity of both public and private sector stakeholders**. Even where data and information are available, and supportive regulations and incentives are in place, their appropriate use and implementation require skills that are not always available (World Bank, 2019). Governments can accelerate the implementation of resilience measures by supporting capacity-building for risk and impact assessments, forecasting and early-warning, emergency response, and recovery in public and private sectors. This will provide African hydropower plants with more accurate information on anticipated climate hazards and quickly restore their functions after damages.

Box 4.3 Capacity-building services for climate resilience: The African Risk Capacity (ARC) Capacity Building Programme

The African Risk Capacity (ARC) is a specialised agency of the African Union. It is comprised of the African Risk Capacity Agency and the ARC Insurance Company Limited. It was established to help African governments improve their capacities to better plan, prepare and respond to extreme weather events and natural disasters.

The ARC Capacity Building Programme, one of the ARC's services, aims to prepare African countries for effective disaster risk management through the introduction of tools and processes that enhance response to natural disasters. In this programme, technical experts of African governments are trained on how to define the country's climate risk profile using the ARC's software, *Africa RiskView*, and get advisory support in developing a contingency plan.

Source: African Risk Capacity (2017), *Capacity Building Programme Brochure*.

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Annex: Methodology

Scope

The study presented in this report assessed the climate impacts on 64 hydropower plants in 13 African countries between 2020 and 2099, comparing the results with the values of the baseline period from 2010 to 2019.

The geographical scope of the assessment covers Nile basin countries (Egypt, Ethiopia, Kenya, Sudan and Uganda), Congo and Zambezi basin countries (the Democratic Republic of Congo, Malawi, Mozambique, Tanzania, Zambia and Zimbabwe), a North African country (Morocco) and a West African country (Ghana). The assessment includes over 18 000 MW of installed hydropower capacity in total, accounting for 80% of the total installed hydropower capacity of the 13 African countries, and around 50% of the entire region. About 83% of selected hydropower plants are impoundment facilities with reservoirs. The other 17% are mostly diversion (run-of-river) facilities and one pumped hydropower storage. Each hydropower plant assesed 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).

Table A.1 List of selected hydropower plants by country

Country	Hydropower plant
The Democratic Republic of Congo	Inga I and II, Koni, Nseke, Nzilo, Ruzizi I and II, Zongo I and II
Egypt	Aswan High and Low, Esna, Naga Hamady
Ethiopia	Awash II and III, Fincha, Koka, Melka Wakena, Tana-Beles, Tekezé, Tis Abay I and II
Ghana	Akosombo, Bui, Kpong
Kenya	Gitaru, Kamburu, Kiambere, Kindaruma, Masinga, Sondu Miriu, Tana, Turkwel
Malawi	Kapichira, Nkula Falls, Tedzani
Morocco	Afourer, Al Massira, Bin El Ouidane, Imfout, Mansour Ed Dahbi, Moulay Youssef, Al Wahda, Allal El Fassi, Idriss I, Oued El Makhazine

Country	Hydropower plant
Mozambique	Cahora Bassa
Sudan	Jebel Aulia, El-Girba, Merowe, Roseires, Sennar, Setit and Upper Atabara
Tanzania	Hale, Kidatu, Lower Kihansi, Mtera, Nyumba ya Mungu, Pagani Falls
Uganda	Kiira, Nalubaale
Zambia / Zimbabwe	Itezhi-Tezhi, Kafue Gorge, Kariba, Victoria Falls

Note: Zambia and Zimbabwe are presented as one given their co-ownership of the Kariba hydropower plant. Due to the limited availability of information on some African hydropower plants (particularly small or recently constructed ones), the assessment does not fully cover all hydropower plants located in selected countries.

Models and data

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

The discharge maps were used to extract the design discharge and design load factors per hydropower plant (Gernaat, 2019). By ordering the discharge of a selected hydropower plant from the lowest to the highest month of discharge, a flow duration curve was generated. The value of the fourth-highest discharge month is called the design discharge and determines turbine capacity. The capacity factor is, by design, 100% for the four wettest months and less than 100% for the remaining eight drier months. Further information on the selected models and methodology is described below in this Annex. The assessment examined 40 different combinations of GCM, GHM and RCP to ensure the reliability of results and minimise potential distortions by outliers. The results of the assessment present the mean annual and monthly capacity factors of these various ensembles.

Table A.2 Overview of the GCMs, GHMs and RCPs considered in the assessment

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

General Circulation Models (GCM)

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

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

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

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

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

Global Hydrological Models (GHM)

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

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

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

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

Representative Concentration Pathways (RCP)

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

This report analyses climate impacts on African hydropower based on two RCPs: RCP 2.6 and RCP 6.0.

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

The Around 3°C scenario follows the trajectory of the RCP 6.0 which assumes a radiative 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.

Table A.3 Overview of the scenarios: Below 2°C and Around 3°C

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

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

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Abbreviations and acronyms

ARC	African Risk Capacity
CDKN	Climate and Development Knowledge Network
CO_2	carbon dioxide
CSIRO	Commonwealth Scientific and Industrial Research Organisation
EAPP	Eastern Africa Power Pool
EBRD	European Bank for Reconstruction and Development
ECC	Environment and Climate Change
EEA	European Environment Agency
GCM	General Circulation Models
GHG	greenhouse gas
GHM	Global Hydrological Models
IHA	International Hydropower Association
IPCC	Intergovernmental Panel on Climate Change
IPSL	Institute Pierre Simon Laplace
OECD	Organisation for Economic Co-operation and Development
OLADE	Latin America Energy Organization (*Organización Latinoamericana de Energía*)
PV	photovoltaics
RCP	Representative Concentration Pathway
SDG	Sustainable Development Goals
SDS	Sustainable Development Scenario
STEPS	Stated Policies Scenario
UEGCL	Uganda Electricity Generation Company Limited
WBCSD	World Business Council for Sustainable Development
WMO	World Meteorological Organization

Units of measure

bbl	barrel
bbl/d	barrels per day
bcm	billion cubic metres
bcm/yr	billion cubic metres per year
cm/s	centimetres per second
gCO_2	gramme of carbon dioxide
gCO_2/kWh	grammes of carbon dioxide per kilowatt hour
GJ	gigajoule

Gt/yr	gigatonnes per year
$GtCO_2$	gigatonne of carbon dioxide
$GtCO_2/yr$	gigatonnes of carbon dioxide per year
GW	gigawatt
GWh	gigawatt hour
MW	megawatt
TWh	terawatt hour
W/m^2	Watt per square metre

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The IEA examines the full spectrum of energy issues including oil, gas and coal supply and demand, renewable energy technologies, electricity markets, energy efficiency, access to energy, demand side management and much more. Through its work, the IEA advocates policies that will enhance the reliability, affordability and sustainability of energy in its 30 member countries, 8 association countries and beyond.

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