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Impacts of expected climate change on hydropower generation in Rwanda

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ABSTRACT

Climate change has significantly threatened power supply systems around the world, and will continue to do so especially in countries where the share of hydropower in the total electricity supply mix is high. This study assessed impacts of climate change on the future Rwanda's hydropower generation and provided information necessary to make appropriate decisions that would reduce the vulnerability of the country's power supply and enhance the viability of new investments. To account for all hydrologic processes occurring within the studied area, the Water Evaluation and Planning system model (WEAP) was used. Impacts on hydropower were assessed for two Representative Concentration Pathways (RCP): RCP4.5 and RCP8.5; with climate data from two climate models: HadGem2-ES and MIROC-ESM-CHEM. Compared to the designed production, changes in hydropower generation are projected to range between -13% and +8% for the 2020 to 2039 period, -22% and -9% for the 2040-2059 period, -24% to +3% for the 2060 to 2079 period and from -29% to +12% for the 2080 to 2099 period. Given these generation changes and the high dependence of Rwanda's power supply on hydropower, it was concluded that climate change will compromise the country's ability to meet the national power demand unless earlier measures are taken.

Keywords: Climate change, climate models, hydrologic model, hydropower, RCP.

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INTRODUCTION

By 2050, Rwanda seeks to achieve a green based economy when energy needs will be met by low carbon indigenous resources (Government of Rwanda, 2015, 2011). This will not only terminate the country's dependence on imported fossil fuels for its power generation, it will also reduce its contribution to the global climate change. Before 2003, the electricity supply in Rwanda was 100% dependent on hydropower (REG Ltd, 2014). Since this year, however, water resources have declined which caused losses in hydropower generation; and climate change is reported to be the main cause (Ministry of Natural Resources, 2006; Rwanda Environment Management Authority, 2011). To cover the power generation deficits, rented emergency diesel generators have been introduced, and ensure an affordable tariff, the Government has subsidised the electricity sector through paying part of the capacity charges for the rented diesel generators, and exempting fuels for power generation from paying import duties. In 2005 only, for example, these emergency generators costed the Government 1.84% of the country's Gross Domestic Product (GDP) (Eberhard et al., 2008).

To address these electricity supply constraints in a sustainable manner, investments in power generation from renewable energy sources, especially hydropower, have been intensified. This was done through direct investments and subsidies by the Government and its development partners, and the establishment of institutional, legal and regulatory frameworks to facilitate and attract the private participation in the energy sector (Uhorakeye, 2011). Similar to the past, hydropower is expected to represent a significant share in the long-term power supply mix of Rwanda (REG Ltd, 2015). However, due to the expected climate change, the existing and planned hydropower plants will operate under climatic conditions different from those they were designed to operate under, which may affect the country's power supply (Ebinger and Vergara, 2011). This study assessed potential impacts of climate change on hydropower generation in Rwanda in order to provide decision and policy-makers, hydropower plant operators and developers with relevant information necessary to make appropriate decisions. Such decisions would result into actions and measures that reduce the vulnerability of the country's power supply to climate change impacts, and enhance the opportunity of power producers to recover their investments and the viability of new investments.

Weather, climate and recent observed changes within the climate system

Weather reflects, for a specific time, the state of the atmosphere in terms of relevant quantities such as precipitations, temperature and humidity while climate refers to the statistical description in terms of mean and variability of the same quantities over a long-time period (typically 30 years) (IPCC, 2007). The earth's weather and climate are determined by the distribution of- and the balance between the incoming solar energy to the earth and the outgoing radiant energy from it (Trenberth et al., 2007). From the total incoming solar radiation (about 341.3 W/m^2), nearly a third of it is reflected back to space while the remaining portion is absorbed by the atmosphere and the earth's surface (Trenberth et al., 2007). During the reflection process, the outgoing radiations pass through the atmosphere (since they are short waves) and spread back into space, whereas the portion absorbed by the earth is radiated back in form of heat (long waves). Due to the presence of natural Greenhouse Gases (GHGs) in the atmosphere, a part of the radiated heat is kept in the atmosphere which maintains the earth's temperature at a comfortable level for the life (IPCC, 2007). Climate change occurs when the net difference between the incoming and outgoing energy, known as Radiative Forcing (RF) and expressed in W/m^2, is disturbed. A positive value of RF has a warming effect while a negative value represents a cooling effect. The net global RF has been rising in such a way that its levels were 0.57 W/m^2 in 1950, 1.25 W/m^2 in 1980 and 2.29 W/m^2 in 2011 relative to the 1750 value (Myhre et al., 2013). While the increase in the global mean temperature over the 1880 to 2012 period ranges between 0.65 and 1.06°C, there have been very little precipitation changes although the regions that experienced heavy rains have increased more than those where rains have decreased (Legates and McCabe, 1999).

Projected changes within the climate system

The climate is estimated based on information on possible future atmospheric GHG concentrations and other pollutants to which climate is sensitive. Because of uncertainties in estimating pollution, scenarios are used to cover a range of possible future emission trajectories (IPCC, 2000). There has been a series of globally accepted emission scenarios developed under the umbrella of the Intergovernmental Panel on Climate Change (IPCC). These scenarios include the 1990 IPCC Scenario A (SA90) used in the IPCC First Assessment Report (FAR), the 1992 IPCC Scenarios (IS92) used in the IPCC Second Assessment Report (SAR), the Special Report on Emissions Scenarios (SRES) used in the IPCC Third Assessment Report (TAR) and in the IPCC Fourth Assessment Report (AR4), and the Representative Concentration Pathways (RCPs) used in the IPCC Fifth Assessment Report (AR5) (IPCC, 2013). The future climate discussed in this study is based on RCPs since they are the latest generation of scenarios that provide input to climate models. There are four RCPs: RCP2.5, RCP4.5, RCP6.0 and RCP8.5. Under RCP2.6 pathway, the RF levels are expected to reach 3.1 W/m^2 by mid-century, and returns to 2.6 W/m^2 by 2100. The RCP4.5 pathway is a stabilisation scenario where the total RF is stabilised to 4.5 W/m^2 after 2100, while under RCP6.0 pathway the total RF would be stabilised to 6.0 W/m^2 after 2100 without overshoot. The last pathway is RCP8.5 which is characterised by increasing GHG emissions leading to 8.5 W/m^2 in 2100 (Wayne, 2013). Based on the RCPs, it is projected that the global mean temperature will continue to rise throughout the 21st century. Relative to the 1850 to 1900 average, the temperature changes by the end of the century is projected to exceed 1.5°C for RCP4.5, and 2°C for RCP6.0 and RCP8.5. Concerning precipitations, no significant changes are expected, except for the case of RCP8.5 where the annual mean precipitations are projected increase for the equatorial Pacific Ocean and in many mid-latitude wet regions while a decrease is projected for many mid-latitude and subtropical dry regions (IPCC, 2013).

Hydropower generation challenges in Rwanda

Generally, the designs for hydropower generation capacities are based on historical daily and seasonal climatic patterns. The existing and planned hydropower plants in Rwanda have been also designed in the same way using climate data covering the 1971 to 1990 period (SMEC, 2010; CNEE, 2012). However, due to expected changes in precipitations and temperature, these power generation facilities will operate under climatic conditions different from those they were designed to operate under. This may not only compromise the ability of the electricity supply system to meet the demand, but also the opportunity of power producers to recover their investments as well as the viability of new investments (Ebinger and Vergara, 2011). In addition, the projected increase in the mean temperature and changes in precipitations may reduce water resources and increase the competition between hydropower and other water users such as the agriculture and public water supply (Wilbanks et al., 2007; Feeley et al., 2007). This is justified, for instance, by the fact that the agricultural sector in Rwanda had depended on natural rain-fed until 2010 when a national Irrigation Master Plan (IMP) was developed. It was planned under the IMP that the surface (runoff, rivers and lakes) and underground water resources will be exploited in order to increase food security and reduce the sector's vulnerability to climate change (Malesu et al., 2010). Moreover, the daily water consumption in rural areas in Rwanda (where about 80% of the country's population live) was 8.15 litres per capita in 2010; and under the country's Water Strategic Plan 2011 to 2015, it was planned to increase this consumption to 20 L by 2015 (Ministry of Natural Resources, 2011) which may affect hydropower generation as well.

Although by 2016 no study had been conducted to investigate impacts of the expected climate change on hydropower generation in the country, there is a number of related studies in the region that justify the need of a similar study for Rwanda. Hamududu (2012) analysed the trends in power generation for the central and southern African regions towards the end of the 21st century. He found that hydropower generation may decrease by 7 to 34% in the southern region and increase by 6 to 18% in the central region. Yamba et al. (2011) assessed implications of climate change and climate variability on hydropower generation in the Zambezi River Basin, and concluded that power generation from the existing and planned hydropower plants may increase for the 2010 to 2016 period and then decrease towards 2070. Harrison and Whittington (2002) analysed the viability of the Batoka Gorge (between Zambia and Zimbabwe) hydropower scheme to climate change and projected between 10 and 35.5% reductions in annual flow levels at Victoria Falls which would cause 6.1 to 21.4% losses in the annual electricity production. Beyene et al. (2010) investigated potential impacts of climate change on the hydrology and water resources of the Nile River basin and concluded that water flows at the Nile River will increase for the 2010 to 2039 period, and decline for the 2040 to 2099 period; and that the power generation would follow the same trends.

MATERIALS AND METHODS

Need of a hydrological model and its set-up

Since hydropower generation depends on both hydrologic processes occurring within a given catchment and the amount of water withdrawn from the same catchment, a hydrological model was necessary to account for all these factors. In this regard, the Water Evaluation and Planning system (WEAP) model was used. The WEAP model allows the computation of water balance (evapotranspiration, surface and subsurface run-off, irrigation and other water needs) and hydropower generation within the area under an investigation (Sieber and Purkey, 2011). To qualify for climate change impacts assessment, a hydrological model must be adjusted to the site-specific conditions and this is done through the model calibration and validation. The calibration deals with adjusting the model input parameters until it produces acceptable outputs as compared to observed (historical) data for the same condition (Moriasi et al., 2007). Validation on the other hand deals with running the model using parameters determined during the calibration process (Doherty, 2004; Refsgaard, 1997). A performance test is then conducted on the calibration and validation outputs in order to accept or reject the predictability of the model (Gupta et al., 1999; Legates and McCabe, 1999; Moriasi et al., 2007; Nash and Sutcliffe, 1970). This study used the WEAP model calibrated, validated, and tested under the study "Modelling electricity supply options for Rwanda in the face of climate change" by Uhorakeye (2016). This model was calibrated and validated for the catchment of which the outlet point is located at the Ruliba Stream Gauging Station shown in Figure 1. This catchment covers an area of 8,316 km^2 (about a third of the country's area).

Assessment of the past and expected climates

To assess recent changes in Rwanda's climate, an analysis of daily precipitation and temperature data recorded from 1961 to 2010 was conducted. The data used for this purpose are the WFD and the WFDEI. WFD stands for Water and Global Change (WATCH) Forcing Data and cover the 1958 to 2001 period (Weedon et al., 2011). WFDEI on the other hand means WATCH Forcing Data methodology applied to ERA-Interim data; and these data cover the 1979 to 2012 period (Weedon et al., 2014). For the overlap between the two datasets (that is, the period from 1979 to 2001), the WFDEI data were considered. The WFD and WFDEI data in NetCDF format and at 0.5 × 0.5-degree (about 55 × 55 km) spatial resolution were downloaded free of charge from the website of the International Institute for Applied Systems Analysis[1]. Since the WFD and WFDEI data cover the entire planet, Climate Data Operator (CDO) (Schulzweida, 2014) and the Geographic Information System (GIS) tools were used to extract and process data that overlays the study area. For the analysis of the past climate, only precipitations and temperature were assessed as they are the main drivers of changes in hydropower generation. Trends in annual total time series

[1] ftp://rfdata:forceDATA@ftp.iiasa.ac.at

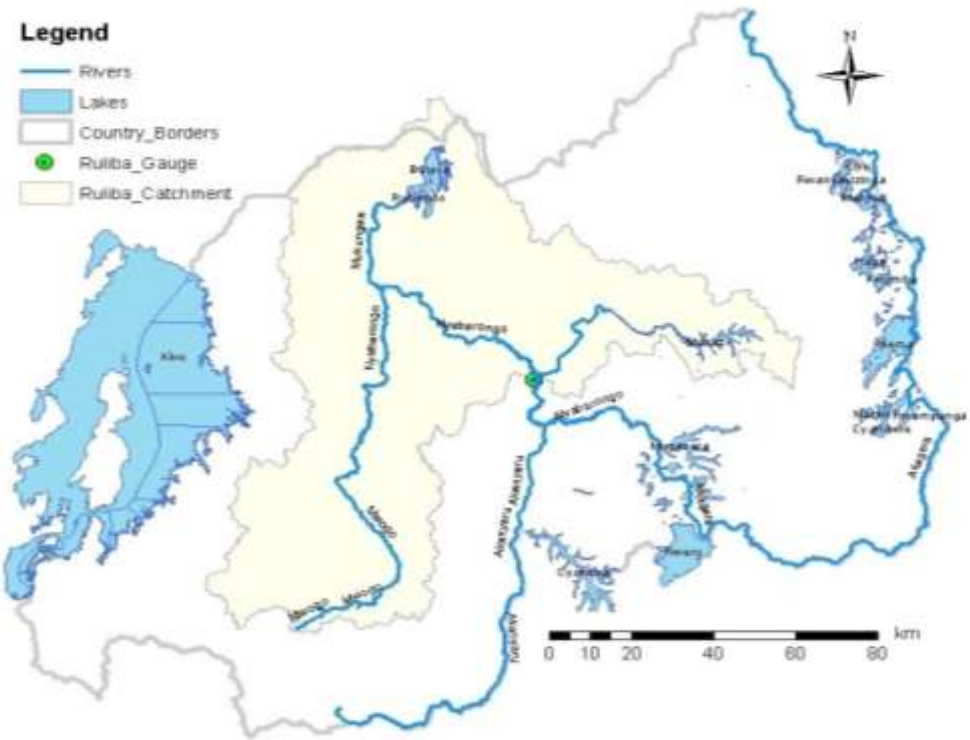

Figure 1. Study area location.

were assessed for precipitations while the mean annual values were analysed for the temperature.

As for the future climate, it was assessed by comparing projected precipitations and temperature with their corresponding average values of the 1961 to 1990 period. The comparison was conducted on four periods of 20-years each from 2020 to 2099. Percentage changes were calculated for annual precipitations while absolute changes were investigated for the annual mean temperature. The expected climate and its impacts on hydropower generation was assessed for RCP4.5 and RCP8.5 since these two pathways represent the worst (RCP8.5) and intermediate (RCP4.5) cases of the evolution of the future climate. The data used to assess the future climate was developed under the first Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) by Potsdam Institute for Climate Impact Research (PIK). ISI-MIP data was developed by interpolating, in space, the corresponding models in order to match the WFD grids (that is, 0.5 × 0.5 degree), and then statistically removing biases using WFD data (Hempel et al., 2013). Daily ISI-MIP precipitation and temperature data in NetCDF format and covering the whole world were downloaded free of charge from the website of the Earth System Grid Federation[2]. Like in the case of the past climate, CDO was also used to extract the data that exactly covers the area of interest, as well as to aggregate and average the daily time step data into monthly and yearly quantities. Out of the five climate models under the ISI-MIP data, the best two of them in producing historical stream discharges at the Ruliba stream gauging station were selected to be used for climate change impact analysis in this study. These models are HadGem2-ES from the Met Office Hadley Centre (UK) and MIROC-ESM-CHEM from the University of Tokyo and National Institute for Environmental Studies (Japan).

Assessing impacts on hydropower generation

To assess impacts of climate change on hydropower, the study area (Figure 1) was subdivided into sub-catchments. The pour points for these sub-catchments were placed at the location of each hydropower dam for dam-based power plants and at the intake point for run-off river based power plants. The computation of hydropower generation requires many more details about the design and operation of each power plant; however, it was not possible to acquire data for all the existing and planned power plants within the studied catchment. This was due to the complexity of the system and the fact that most of the mini- and micro-hydropower resources were still under feasibility studies at the time of data collection. Therefore 8 (4 run-off and 4 dam-based) power plants for

[2] esg.pik-potsdam.de/esgf-web-fe

which enough information for the simulation was available were analysed and the impacts were extrapolated to the rest of power plants. This means that the whole catchment was subdivided into 8 sub-catchments corresponding to the assessed power generation plants. The boundaries and surface area for each sub-catchment were derived on the basis of drainage modelling by means of a 30 × 30 m Digital Elevation Model downloaded free of charge from the website of the Japanese Earth Resources Satellite Data Analysis Center[3].

To compute the water balance in WEAP, relative humidity and wind speed data are also required in addition to precipitation and temperature data discussed in the previous section. These data were also extracted from the ISI-MIP data; and Thiessen polygon method was used to determine the quantity of each the above climate parameters for the whole catchment and its sub-catchments. This method assumes that the climate value at any point in the catchment is the same as that at the nearest measuring station; and therefore, a weight is assigned to each station based on the area that is closest to it. Details on water withdrawal by the main water users (mainly domestic use and irrigation) in each sub-catchment were also included in the model and assigned supply priorities. It was assumed that, in case of water scarcity, the residential sector will be supplied first, then the agricultural sector second and the hydropower industry the last. The number of people who extract water from each sub-catchment was computed using the Tabulate Intersection functionality provided in GIS based on the administrative map of sectors and the population distribution per sector obtained from the National Institute of Statistics of Rwanda (NISR). The per capita water needs were set to 8.15 per day in 2012 and increased to 20 L by 2015 (Ministry of Natural Resources, 2011) and to 50 L by 2050 (Brown and Matlock, 2011). Regarding the irrigation, the WEAP model provides an option to set conditions of when to start and stop irrigation by instructing the model to start irrigation when soil moisture falls below a predefined level called Lower Irrigation Threshold (LIT), and to cease it when soil moisture reaches a predefined level called Upper Irrigation Threshold (UIT) (Sieber and Purkey, 2011). In this study, both the LIT and UIT values were set at the Management Allowable Deficit (MAD) point which is a soil moisture value below which agricultural yield starts to decline (Sieber and Purkey, 2011; CNEE, 2012). Recommended MAD values for the crops cultivated in the study area were extracted from Peters et al. (2013) and USDA and MSU (1990). The irrigated area per each sub-catchment was also computed in ArcGIS based on the 2012 land cover map obtained from the Land Husbandry Water harvesting and Hillside Irrigation project (LWH). The year 2012 was chosen as the base year because a national population census, which provided most of the information necessary to run the WEAP model, was conducted in this year.

To quantify impacts of climate change on hydropower, energy that would have been produced by the existing and planned plants during the 1971 to 1990 period was compared with the projected generation. This period was chosen because most of these power plants were designed using climate data covering this period as mentioned in the previous section. Since during the 1971 to 1990 period both HadGem2-ES and MIROC-ESM models simulated more energy than the historical production, the bias correction technique was used to remove the discrepancies between historical and simulated time series. The bias correction method deals with determining a transfer function that relates simulated and measured or recorded data (Ho et al., 2012; Hempel et al., 2013). In this study multiplicative correction factors on monthly power generation time series were determined. Under this method, each time-step of the time series is multiplied by a constant factor, which conserves the trends observed in the original time series whilst removing the discrepancies (Hempel et al., 2013). The correction factor C_i for each month was calculated according to Equation 1 where $E_{i,hist}$ represents historical power production for month i and $E_{i,sim,ref}$ is the simulated power generation for month i during the reference period.

$$C_i = \frac{\sum_{i=1}^{n=20} E_{i,hist}}{\sum_{i=1}^{n=20} E_{i,sim,ref}} \quad (1)$$

After determining the correction factors, Equation 2 was used to remove discrepancies from simulated hydropower generation time series. In Equation 2 $E_{i,Sim,adj}$ represents the adjusted value of the simulated generation $E_{i,sim}$ for month i.

$$\sum_{i=1}^{n=20} E_{i,sim,adj} = C_i \cdot E_{i,sim} \quad (2)$$

In the WEAP model hydropower generation is computed based on the amount of water passing through the turbine during time (t) and the working head according to Equation 3.

$$E(t) = Q_{Tr}(t) \cdot g \cdot \eta \cdot h \cdot p_f \cdot t \quad (3)$$

where:

$E(t)$ Energy (MWh) generation during time t (hours)

$Q_{Tr}(t)$ Volume of water (m^3) through turbine

[3] gdem.ersdac.jspacesystems.or.jp

during time t

g	Gravitational acceleration, ($m \cdot s^{-2}$)
η	Overall generating efficiency, (%)
h	Working head, (m)
p_f	Plant factor, (%)

In Equation 3, the working head is fixed for run-off river-based power plants whereas it varies with the reservoir's level for dam-based power plants. Since the turbine operates between two points: the maximum turbine flow (Q_{Tmax}) and the minimum turbine flow (Q_{Tmin}), Equation 4 is used to control the generation and maintain it within allowable limits:

$$Q_{Turb} = \begin{cases} 0 & \text{if } Q(t) < Q_{T\min} \\ Q(t) & \text{if } Q_{T\min} \leq Q(t) < Q_{T\max} \\ Q_{T\max} & \text{if } Q(t) > Q_{T\max} \end{cases} \quad (4)$$

The Minimum Draw-down Level (MDDL), Full Reservoir Level (FRL), Tail Water Level (TWL) in metres above the sea level (m.a.s.l) as well as other parameters required to compute hydropower generation for the 8 considered power plants are presented in Table 1. It is important to mention that the active volumes for Mukungwa 1 and Ntaruka were not available from the specified sources in Table 1; they were estimated by the Author using the surface volume function of the ArcGIS tool. In addition, the plant factor and efficiency of Nyabarongo 1 were applied to the remaining three dam-based power plants as there was no information for each single plant about these quantities.

After simulating the future monthly hydropower generations, biases were removed and the obtained time series were aggregated to form annual total generations and then compared with the 1971 to 1990 average generation. In addition, exceedance probability for historical and projected generations were computed according to Equation 5 where P is the exceedance probability, m is the ranking from the highest to the lowest of total annual hydropower generation and n is the total number of years in the period:

$$P = \frac{m}{n+1} \quad (5)$$

To assess the effects of the expected climate change on hydropower plants located in the study area but not included in the simulations as well as those hydropower plants located outside the study area, identified power generation changes for the analysed power plants were extrapolated to the rest of the country. To achieve this, the percentage changes between the designed and simulated energy generations for each year from 2012 to 2099 and for each model and scenario were determined. Then, computed changes were applied to the annual total hydropower energy generation at the national level.

RESULTS AND DISCUSSION

Observed climate

The analysis of precipitation records for the 1961 to 2010 period revealed an annual total average of about 1260 mm. As it can be seen in Figure 2, there are no observable trends in annual total precipitations. However, the inter-annual variations increased in such a way that the deficits and excesses were increasingly escalating. The highest observed precipitation deficits were 17.5% recorded 1993. As for excesses, the highest precipitations were records in 1965 and were 21.52% higher than the annual total mean value. It was also found that the deficit and excess precipitations appeared at almost regular intervals (4 to 7 years) and they correspond with El Niño and La Niña episodes. Unlike the situation of precipitations where there is no significant difference between the annual records, there is a clear increasing trend in temperature records as it can be seen in Figure 3. The average rate of increase in annual mean temperature between 1961 and 2010 is 0.032°C per year which corresponds to an overall increase of 1.6°C.

Projected climate

The projected changes in annual total precipitations can be visualised in Figure 4 for RCP4.5, and in Figure 5 for RCP8.5. Under RCP4.5 pathway, the medians of changes in annual total precipitations are all negative for each analysed period from 2020 to 2079 which means that precipitation deficits are expected to last at least during half of the period. In addition, deficits are projected to be more considerable than excess precipitations (Figure 4). However, towards the end of the century, both HadGem2-ES and MIROC-ESM models project excess precipitations.

Like in the case of the past climate, there is no significant trend in the projected annual precipitations under RCP4.5 pathway. The average of percentage change in annual total precipitations varies from -4.11 to -1.48% for HadGem2ES and -5.81 to +3.21% for MIROC-ESM models. These trends in annual total precipitations are, however, smaller compared to the inter-annual variability which are projected to range from -23.83 to +22.91% for HadGem2-ES and -24.48 to +29.20% for MIROC-ESM models.

As for the RCP8.5 pathway, it is expected that excess precipitations will be recorded for at least 10 years for the between 2020 and 2039 while at least 10 years of precipitation deficits are expected for the 2040 to 2059 period. For the period from 2060 to 2099, excess precipitations are projected under MIROC-ESM while deficits are expected for HadGem2-ES models (Figure 5). There is an increasing trend in annual total precipitation for the MIROC-ESM model but no significant trend in the HadGem2-ES projections. Under this pathway, changes

Table 1. Basic data of simulated hydropower plants.

ID	Plant name	Type	MDDL (m.a.s.l)	FRL (m.a.s.l)	TWL (m.a.s.l)	Head (m)	Volume (×10⁶ m^3)	Q_{Turb} (m^3s^{-1})	p_f (%)	η (%)	Source
1	Mukungwa 1	Dam	1756	1760.5	1644	-	106	14	95	89.2	EWSA (1984)
2	Ntaruka	Dam	1859.7	1864	1762	-	198	12	95	89.2	RECO (2013)
3	Nyabarongo 1	Dam	1495	1499	1432	-	13.37	54.75	95	89.2	SMEC (2014)
4	Nyabarongo 2	Dam	1389.9	1409	1369	-	307	80.2	95	89.2	CNEE (2012)
5	Mukungwa 2	Run-off	-	-	-	32	-	10.7	95	88	Hydropower International Ltd (2006a)
6	Rugezi	Run-off	-	-	-	135	-	2.3	95	88	Hydropower International Ltd (2006b)
7	Rukarara 1	Run-off	-	-	-	137	-	9.0	95	88	Eco Power Limited (2006)
8	Rukarara 2	Run-off	-	-	-	42.4	-	5.6	95	88	SHER (2009)

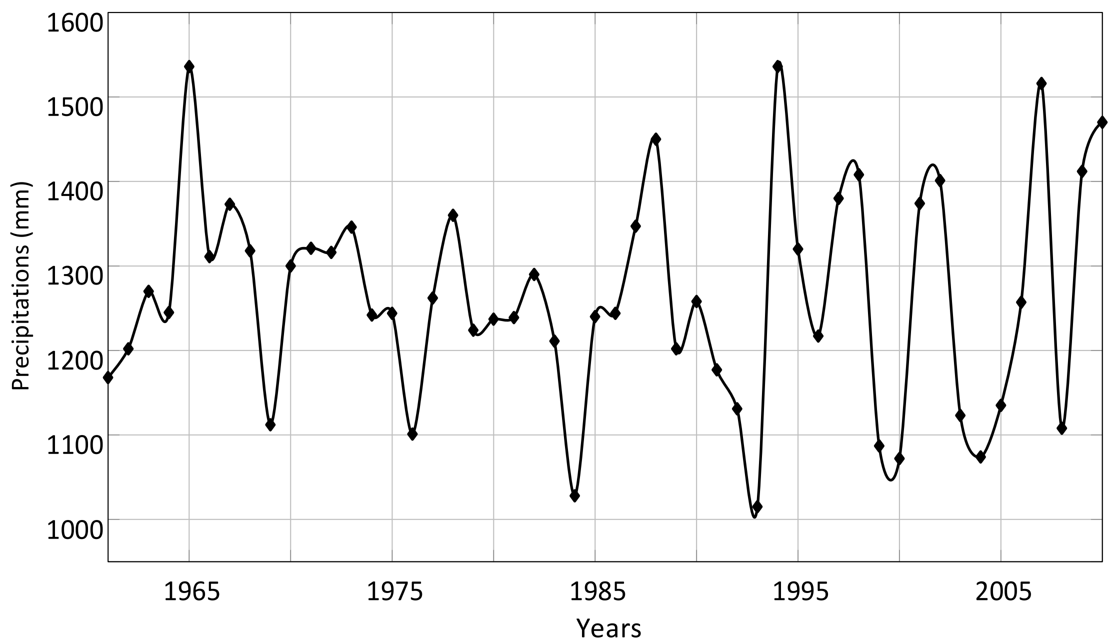

Figure 2. Recorded annual precipitations for the 1961-2010 period.

in annual total precipitations are projected to vary from -5.55 to +2.40% for the HadGem2-ES and -4.77 to +28.53% for the MIROC-ESM models. Inter-annual variations are projected to range from -32.94 to +24.50% for the HadGem2-ES and -19.25 to +50.21% for the MIROC-ESM models.

Contrary to precipitation projections where positive and negative anomalies are expected, trends in annual mean temperatures are expected

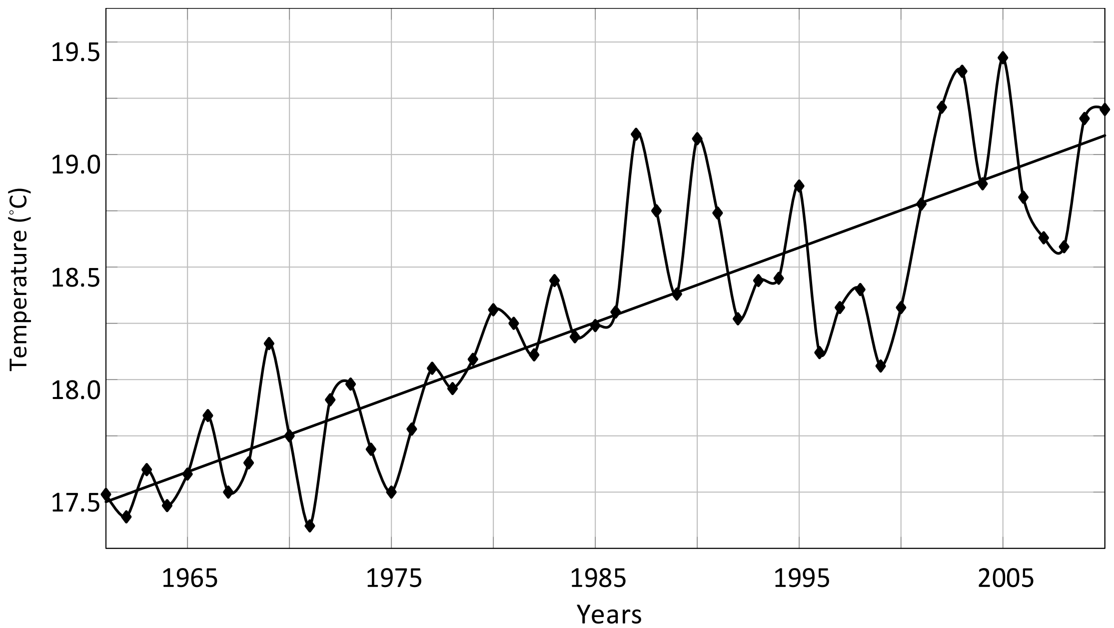

Figure 3. Recorded annual mean temperature for the 1961-2010 period.

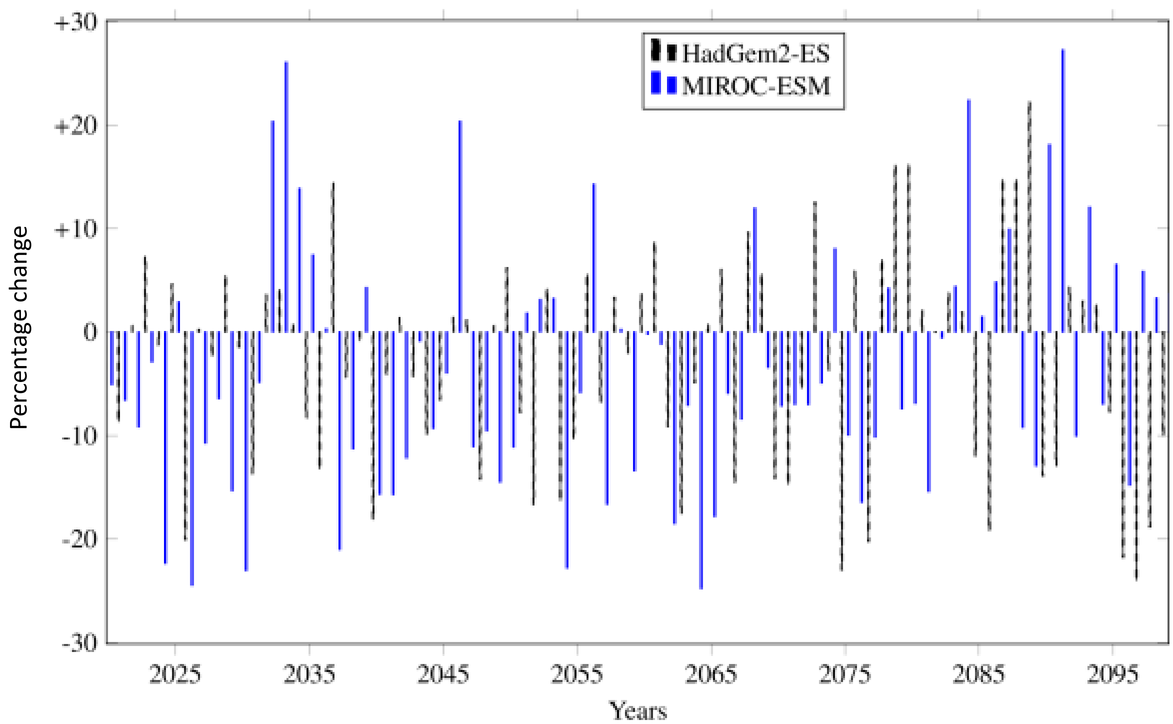

Figure 4. Precipitation anomalies (RCP4.5) relative to the 1961-1990 average.

to be positive under both RCP4.5 and RCP8.5 pathways and both HadGem2-ES and MIROC-ESM models. The increase in temperature is expected to be much faster under RCP8.5 than under RCP4.5 pathways (Figure 6). The analysis of annual mean temperature time series under RCP4.5 pathway revealed an average increase rate of 0.032°C per year (or 0.32°C per decade) for the HadGem2-ES model and 0.021°C per year (or 0.21°C per decade) for the MIROC-ESM model. Under this scenario, it is projected that the average temperature for the 2080 to 2099 period will be 2.19°C (MIROC-ESM) to 3.7°C (HadGem2-ES) higher than the 1961 to 1990

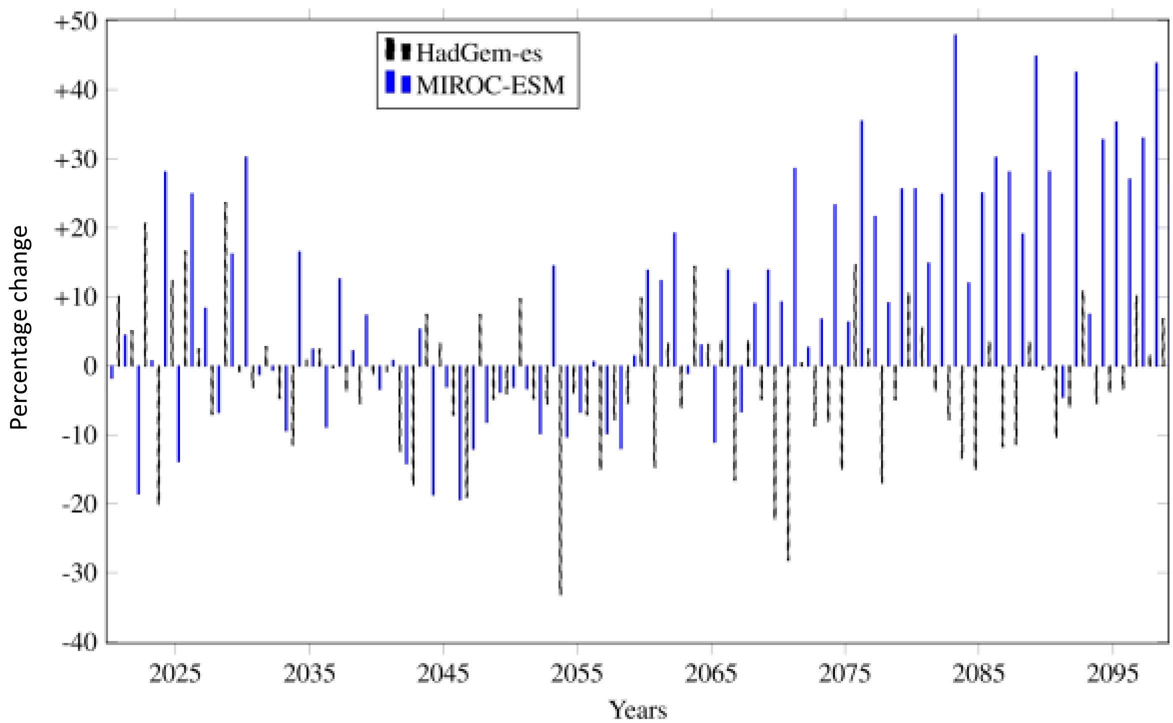

Figure 5. Precipitation anomalies (RCP8.5) relative to the 1961-1990 average.

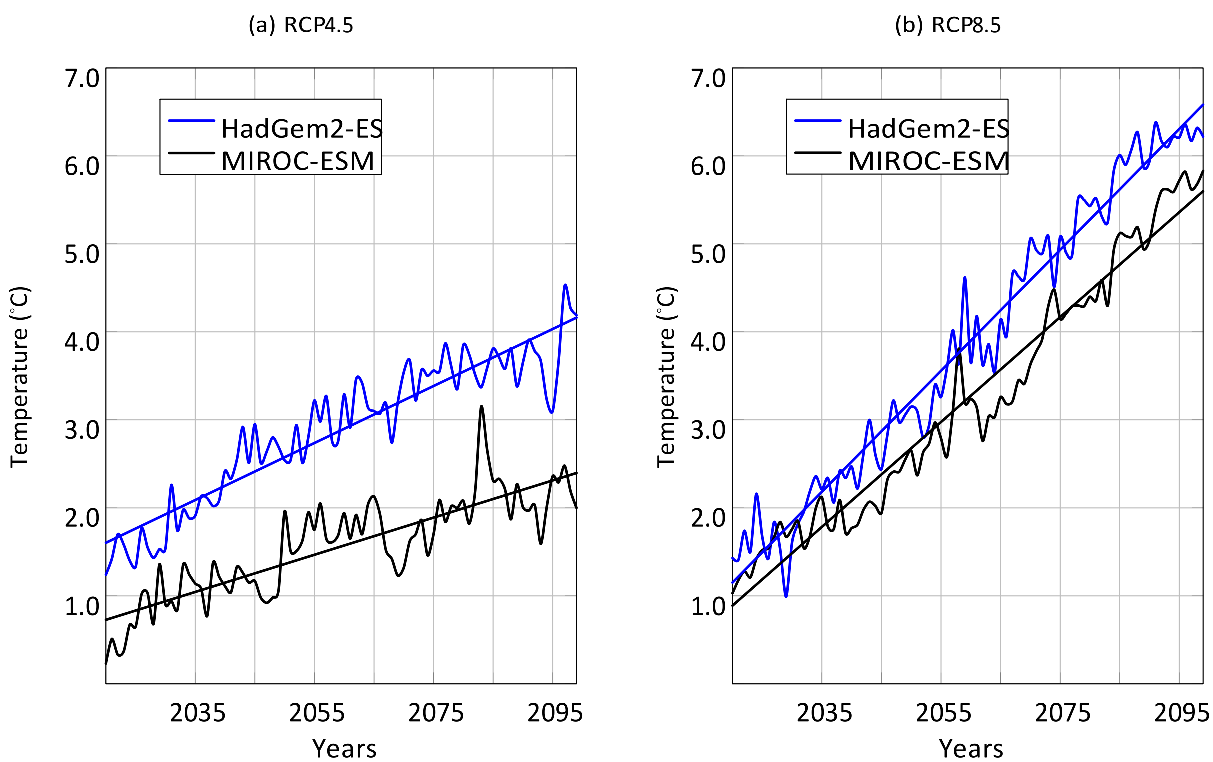

Figure 6. Temperature anomalies for the 2020-2099 period relative to 1961-1990 average.

average. As for the RCP8.5 pathway, an increase rate of 0.069°C per year (or 0.69°C per decade) is expected for HadGem2-ES model and 0.06°C per year (or 0.6°C per decade) for MIROC-ESM. By 2100, the temperature change relative to the reference period is projected to range between 5.19°C (MIROC-ESM) and 5.98°C (HadGem2-ES).

Similar to the past climate, the projected temperature changes in Rwanda are much higher than the global average. Relative to the 1986 to 2005 average, the global annual mean temperature change for the 2081 to 2100 period is expected to range from 1.1 to 2.6°C for the RCP4.5 pathway and 2.6 to 4.8°C for RCP8.5 pathway (IPCC, 2013). These changes are smaller than those simulated under this study that range between 2.19 and 3.72°C for the RCP4.5 pathway and between 5.19 and 5.98°C for RCP8.5 pathway.

Impacts on hydropower generation

As described in the methodological section, impacts of climate change on hydropower generation were assessed by comparing the projected power production with what would have been produced if the power plants were operated between 1971 and 1990. Over this period, the simulated annual mean power generation obtained by running the WEAP model using historical climate data is 448 GWh with a standard deviation of 40 GWh. As for the HadGem2-ES and MIROC-ESM models, their simulated means over the same period are 497.65 GWh and 496.00 GWh respectively, equivalent to about 10.7% more energy production than the historical generation. However, their standard deviations are diverse: 41.6 GWh in case of HadGem2-ES and 66.5 GWh for MIROC-ESM. After the bias correction, the annual mean power generations become 445 GWh for both models while the standard deviations become 38 GWh for the HadGem2-ES model and 60 GWh for the MIROC-ESM model. After the bias correction, the annual mean power generations become 445 GWh for both models while the standard deviations are 38 GWh for HadGem2-ES and 60 GWh for the MIROC-ESM. Although the distribution of annual power generation for the MIROC-ESM mode is more spread out compared to the simulations for the HadGem2-ES model, the performed bias correction resulted in a good model fitting in terms of mean since the designed annual power generation is 445 GWh.

With regard to the future production, the power generation exceedance probabilities for every 20-year period between 2020 and 2099 can be visualized in Figures 7 to 10.

Period 2020-2039

The probability that the power generation will be greater than or equal to the designed production is about 40% for HadGem2-ES and 34.5% for MIROC-ESM models (Figure 7) in case the evolution of the future climate follows the RCP4.5 pathway. The analysis of the simulated cumulative power productions over this period revealed reductions in power generation equivalent to 3.2% for the HadGem2-ES and 6.6% for MIROC-ESM

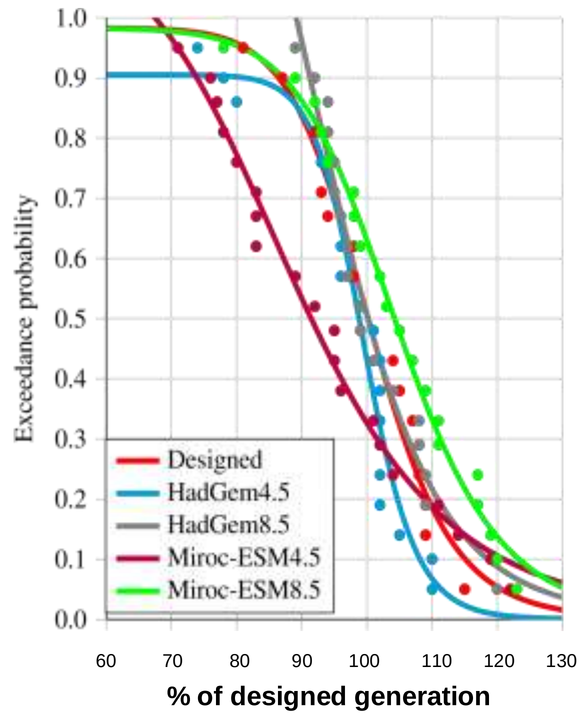

Figure 7. Generation curve for the 2020-2039 period.

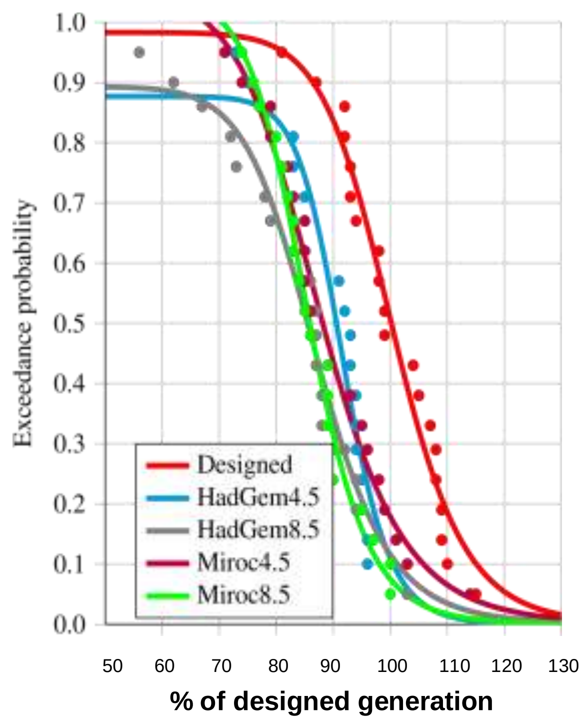

Figure 8. Generation curve for the 2040-2059 period.

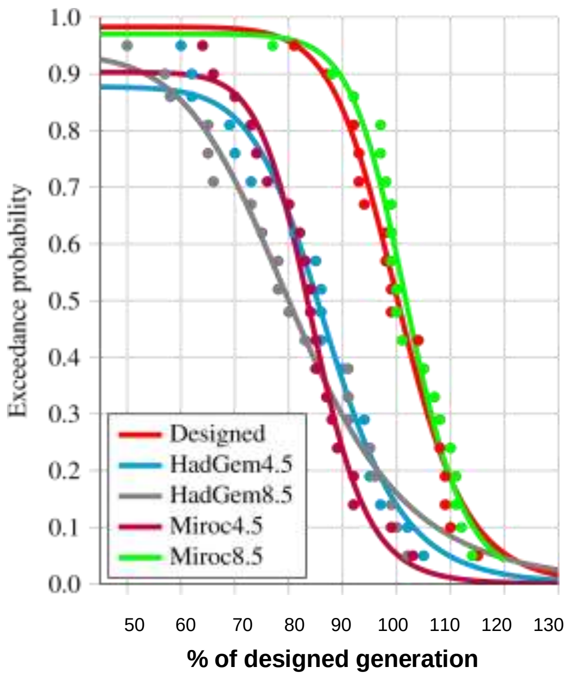

Figure 9. Generation curve for the 2060-2079 period.

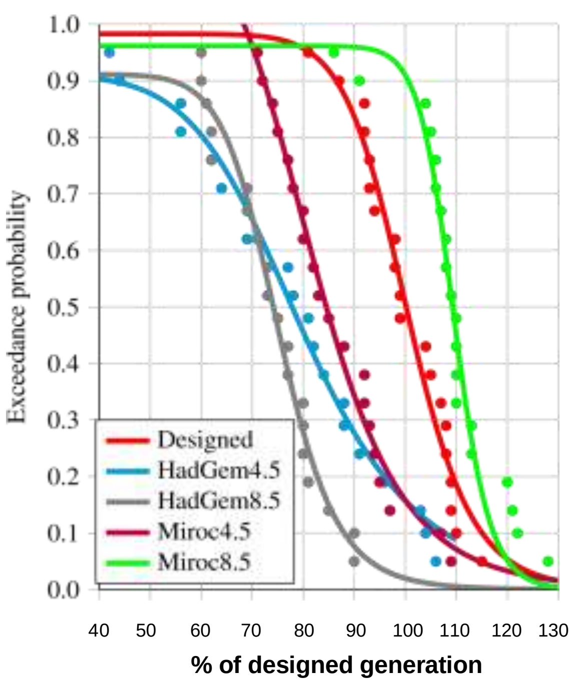

Figure 10. Generation curve for the 2080-2099 period.

models relative to the production during the reference period. The annual power generations are distributed in such a way that the means and standard deviations (in brackets) are 434 (42) GWh and 418 (66) GWh for the HadGem2-ES and MIROC-ESM models respectively. This shows how the dispersion around the mean of the power production is conserved for the HadGem2-ES model and increased for the case of the MIROC-ESM model relative to the reference period. Peaks in power production as well as very pronounced deficits are projected to be more frequent for MIROC-ESM than for HadGem2-ES. As for RCP8.5, the probability that the generated power will be above the designed energy is approximately 50% for the HadGem2-ES model and 60% for the MIROC-ESM model as it can be seen in Figure 7. The increases in power generation of 2.2% for the HadGem2-ES model and 4.1% for the MIROC-ESM model are expected. Under this pathway, the 20-year annual means and standard deviations are 458 (41) GWh for the HadGem2-ES model and 466 (51) GWh for the MIROC-ESM model.

Period 2040-2059

The analysis of the projected generation revealed that this period will be characterised by more generation deficits than any of the assessed periods. During this period, the probability of generating the designed energy is less than 20% for both models and under both pathways (Figure 8). The 20-year annual mean power productions under the RCP4.5 pathway are 375 GWh for the HadGem2-ES model and 387 GWh for the MIROC-ESM models. The corresponding standard deviations are 33 GWh for the HadG-em2-ES model and 46 GWh for the MIROC-ESM model. The power generations for the HadG-em2-ES model range from 250 GWh to 462 GWh while they range between 330 GWh and 448 GWh for the MIROC-ESM model. The cumulative energy production is projected to decline by 10% relative to the generation during the reference period. With regard to the simulations under the RCP8.5 pathway, losses in cumulative energy generation of 6.4% for the HadGem2-ES model and 13.6% for the MIROC-ESM model are expected.

Period 2060-2079

Over these two decades, the probability to generate the designed energy is less than 15% for the HadGem2-ES model under both RCP4.5 and RCP8.5 pathways, and the MIROC-ESM model under the RCP4.5 pathway as it can be deduced from Figure 9. For the MIROC-ESM model under RCP8.5 pathway, the percentage of time during which projected power generation will exceed the designed energy is about 60% as shown in the same figure.

Under RCP4.5 pathway, the 20-year annual mean power generations are projected to be 374 GWh for the HadGem2-ES model and 370 GWh for the MIROC-ESM model. As for RCP8.5 pathway, it is projected that an average of 356 GWh for the HadGem2-ES model and

453 GWh for the MIROC-ESM model can be produced annually. The analysis of the cumulated generation over this period revealed deficits equivalent to 16.6 and 20.4% for the HadGem2-ES model under RCP4.5 and RCP8.5 respectively, and 17.3% for the MIROC-ESM under RCP4.5. As for the MIROCESM model under RCP8.5, an increase in the cumulative power generation of 1.1% is expected.

Period 2080-2099

Similar to the previous period, it is projected that the two last decades of the century will be characterised by loss in power generation except for the case of the MIROC-ESM model under RCP8.5. For the HadGem2-ES model under RCP4.5 and RCP8.5, and MIROC-ESM under RCP4.5, the probability to generate power greater than or equal to the designed energy is projected to be less than 20%; while it is more than 90% for the MIROC-ESM model under RCP8.5. The annual mean production under the RCP4.5 pathway is 345 GWh for the HadGem2-ES model and 386 GWh for the MIROC-ESM. As for RCP8.5, the means are 330 GWh for the HadGem2-ES model and 490 GWh for the MIROC-ESM model. Over this period, the deficits are anticipated to reach 23% for the HadGem2-ES under RCP4.5, 26.3% for the HadGem2-ES model under RCP8.5 and 13.8% for the MIROC-ESM model under RCP4.5. As for the MIROC-ESM model under RCP8.5, an increase in the cumulative power generation of 9.3% is expected.

Impacts at the national level

As discussed in the methodological section, the assessment of climate change effects on hydropower generation at the national level was done by extrapolating identified annual power generation changes of the analysed power plants to hydropower plants located in the studied area but not simulated in this study as well as the effects on power plants located outside the study area assuming similar conditions of operation. It was found, under the RCP4.5 pathway, that changes in power generation will range between -4,240 GWh and +744 GWh (or -13% to +3%) for the 2020-2039 period. As for the RCP8.5 pathway, it is projected that power generation change will vary between -853 GWh and +2,482 GWh (or -3% to +8%). Negative generation means loss in energy generated and positive values refer to excess generation with reference to the designed energy generation. The period from 2040 to 2059 is projected to be characterised by losses in power generation under both RCP4.5 and RCP8.5 pathway. Relative to the cumulative designed energy generation, losses are projected to vary between 9% and 15% (between 2,773 GWh and 5,790 GWh) under the RCP4.5 pathway, and between 12% and 22% (3,668 GWh and 8,154 GWh) under the RCP8.5 pathway. Between 2060 and 2079, changes in cumulative generation are projected to range from -8,971 GWh to -4,092 GWh (24% to -14%) under the RCP4.5 pathway, and -8,550 GWh to +770 GWh (or -22% to +3%) for the RCP8.5 pathway. For the last 20-year period of the century, it is projected under RCP4.5 that hydropower generation change will vary between -29% (-10,896 GWh) and -12% (-3,259 GWh). As for RCP8.5, changes in power generation are projected to range from -27% (-10,339 GWh) to +12% (+3,460 GWh).

CONCLUSION

The aim of this study was to assess impacts of climate change on hydropower generation in Rwanda in order to provide decision- and policy- makers, hydropower plant operators and developers as well as Rwanda's power utility with relevant information necessary to make appropriate decisions that would reduce the vulnerability of the country's power supply to the impacts of climate change, and enhance the opportunity of power producers to recover their investments and the viability of new investments.

The evolution of the future climate of Rwanda under RCP4.5 and RCP8.5 pathway was assessed for two climate models: HadGem2-ES and MIROC-ESM. The analysis of precipitations under both RCP4.5 and RCP8.5 pathways and for both HadGem2-ES and MIROC-ESM climate models indicated considerable reductions in annual precipitations for the period 2030 to 2060 especially. In addition, inter-annual variations in total annual precipitations are expected to dominate the future climate where changes are expected to reach 50%. As for the temperature changes, it is projected that warming in Rwanda will be much more than the projected average global warming. For the study area, temperature changes relative to the 1961 to 1990 average are projected to range between from 2.19 to 3.72°C for the RCP4.5 pathway and 5.19 to 5.98°C for the RCP8.5 pathway. However, changes in the projected global average temperature range from 1.1 to 2.6°C for the RCP4.5 pathway and 2.6 to 4.8°C for the RCP8.5 pathway (IPCC, 2013).

These changes in precipitations and temperature combined with the increasing water demand are expected to lower the amount of water available for hydropower generation. Relative to the designed hydropower generation, it is projected, under RCP4.5, that changes in cumulative power generation would range between -13 and +3% for the 2020 to 2039 period, from -15 to -9% for the period from 2040 to 2059, between -24 and -14% for the 2060 to 2079 period and from -29 to -12% for the 2080 to 2099 period. Regarding hydropower generation under RCP8.5, it is expected that hydropower generation changes between 2020 and 2039 would vary between -13 and +3%. Between 2040 and 2059 changes in hydropower generation are expected to range from -3 to +15. Between 2060 and 2079, it is projected that change in hydropower generation would range between -22 and +3% while changes for the last 20 year of the century would vary between -27 and +12% for the lsat 20 years of the century.

Based on the results from this study, it is evident that climate change will compromise the ability of Rwanda's electricity supply system to meet the national power demand since hydropower is expected to dominate the future electricity supply of the country. However, the expected power supply challenges can be attenuated if the identified vulnerabilities are early integrated into the planning and operation of the electricity supply system. This can be achieved, for example, by cascading more run-off power plants and building reservoir storages on the Nybarongo River which flows over 350 km before it drains into the Akagera River at Lake Rweru in the south-eastern Rwanda.

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