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Assessment of a climate-resilient and low-carbon power supply scenario for Rwanda

Théoneste Uhorakeye[1] and Bernd Möller

Department of Energy and Environmental Management (EEM-SESAM), Interdisciplinary Institute for Environmental, Social, and Human Studies, Europa-Universität Flensburg, Munketoft 3b, 24937 Flensburg, Germany

ABSTRACT

Renewable energy sources are playing a key role in the transition to a low-carbon based economy while maintaining cost and environmental effectiveness. However, climate change threatens this opportunity especially in countries like Rwanda where more than half of the total supplied electricity in the country comes from hydropower. This study assesses the evolution of Rwanda's electricity demand towards 2050 and suggests a power supply scenario that considers impacts of climate change on the country's hydropower generation. The study findings indicate that to meet the projected demand under the Business As Usual (BAU), more than 20% of electricity requirements would come from imported more polluting fossil fuels. Under the suggested alternative scenario, however, no fossil fuels will be needed by 2050. Furthermore, the average emissions for the 2012-2050 period are estimated at 116 gCO_2eq/kWh for the alternative scenario and 203 gCO_2eq/kWh for the BAU scenario. Based on the findings of the study, it is concluded that the developed alternative scenario is resilient since it meets the projected demand when impacts of climate change are accounted for. Moreover, the scenario ensures the security of the country's electricity supply because it only relies on domestic energy resources. Furthermore, the suggested scenario positions the country to a low-carbon development pathway compared to the existing power supply plans.

Keywords:

Bottom up;
Climate change;
Energy planning;
Long-range Energy Alternatives Planning system;
Representative Concentration Pathways
Top down;

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1. Introduction

Climate change has negatively affected electricity supply systems around the world, and will continue to do so, especially in countries like Rwanda where the share of hydropower in the total electricity supply mix is high. For such power supply systems, an energy planning approach that considers potential impacts of climate change is necessary. This study assesses the evolution of Rwanda's electricity demand towards 2050 and suggested a power supply scenario to meet the projected power demand by considering impacts of climate change on the country's hydropower generation. This section provides general information on Rwanda, the country's electricity demand and supply, and an overview on climate change impacts on hydropower generation on the African Continent in general and in Rwanda in particular.

1.1. General information on Rwanda

Rwanda is one of the countries with the highest population growths and population densities on the African continent. In 2012, for example, the total population of the country was about 10.5 million inhabitants with an average population growth rate

[1] Corresponding author: e-mail: tuhorakeye@yahoo.fr

of 2.6%, and a population density of 415 inhabitants/km^2 [1]. Between 2002 and 2012, the life expectancy has risen from 51.2 to 64.4 years while the number of people living under the poverty line has declined from 58.9% to 44.9% over the same period [1]. It is projected that Rwanda's population will vary between 15.4 and 16.9 million by 2032 [2], and will exceed 21 million by 2050 [3]. Due to the expected rapid increase in the country's population, it can be expected that more and more energy will be required to meet the growing demand.

In terms of economy, Rwanda's income is mainly based on services, agriculture, and industry. The service sector dominates the country's economy in such a way that for the 2008–2012 period, for example, its share to the Gross Domestic Product (GDP) varied between 51.1% and 52.8% [4]. According to the same source, the agricultural sector contributed 32.0% to 33.9%, while the industrial sector contributed 14.4% to 16.3%. In terms of per capita, the GDP (at current market prices) has increased from US$ 207 in 2000 [5] to US$ 720 in 2016 [6]. The average GDP growth rate (at constant 2011 prices) for the 2010–2015 period was 7% [6]; and existing scenarios predict a GDP growth rate of 8% by 2032, and most of the increase are expected to come from the industrial and service sectors [19, 20]. The expected country's expansion in economy will likely result in an increased total energy needs, especially electricity.

1.2. Rwanda's electricity demand and supply

Rwanda is one of the countries with the lowest access to electricity and the lowest per capita power consumption in the world. In 2014, for example, Rwanda was ranked among 15 least electrified countries with an access rate of 19.8% [7]. By December 2016, the access rate to electricity was 30% [8] while the average per capita power consumption was 42 kWh in 2014 [9]. The reasons of such low electricity access and consumption include the lack of investments in the power generation and considerable technical (transmission and distribution) and non-technical (illegal connection) losses. An analysis of energy data collected from Rwanda Energy Group (REG) reveals that the total electricity losses for the 2000–2013 period, for example, varied between 17% and 33%.

The minimum power demand has increased from 18.5 MW in 2003 to 42.9 MW in 2013 while the maximum peak power demand has increased from 43.0 MW to 87.9 MW over the same period [10]. The maximum peak demand was projected to reach 470 MW in 2018 [9], however, during a visit to Rwanda Energy Group in February 2018, it was noticed that the installed capacity was 210 MW.

Although the country faces power supply challenges, Rwanda is endowed with different types of energy resources, most of these resources, however, remain untapped. The country's electricity (potential and exploited) resources comprise:

- Hydropower, where more than 330 potential sites totalling over 350 MW have been identified [11], and only 90 MW were installed by 2016 [12];
- Solar energy, which varies with the country's topography and increases from the West (3.5 kWh/m^2 per day) towards the East (6.0 kWh/m^2 per day) [13], and only 8.75 MW were connected to the national grid by 2016 [12];
- Geothermal energy, where estimates predicted between 150 and 320 MW [14], and the assessment of this resource was still underway in 2017;
- Peat reserves, where 155 million tons of dry peat were estimated [15], and the first peat fired power plant was still under construction in 2017;
- Methane gas, which is dissolved in deep waters of the Kivu Lake where up to 350 MW of electricity (share of Rwanda) can be produced [16], and about 30 MW of methane fired power plants were in operation in 2017 [12];
- Wind energy, where preliminary estimates revealed an annual mean wind speed varying between 2.43 and 5.16 m/s [17];
- Municipal waste, which represents a promising potential given the increasing lifestyle in urban areas, where there are considerable amounts of post-consumption waste such as organic waste, paper, cardboard and wood that can be used to generate electricity.

1.3. Effects of climate change on hydropower generation

Generally, the designs for hydropower generation capacities are based on historical daily and seasonal climatic patterns. However, due to expected changes in precipitation and temperature, many power generation facilities will operate under climatic conditions different from those they were designed to operate under. As demonstrated in the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), the global mean temperature will continue to rise throughout the 21st century whereas precipitation will increase in some regions, decrease in some others while others will experience no significant change [18]. This may not only compromise the ability of electricity supply systems to meet average and peak demands it might hamper the opportunity of power producers to recover their investments as well as the viability of new investments [19], [20].

In Africa, a number of studies have assessed impacts of climate change on the future hydropower generation on the continent. Hamududu and Killingtveit [21] analysed the trends in power generation for the central and southern African regions and found that, towards the end of the 21st century, hydropower generation may decrease by 7% to 34% in the southern African and increase by 6% to 18% in the central African regions. Yamba et al. [22] 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 would increase for the 2010–2016 period, and then decline towards 2070.

Harrison and Whittington [23] assessed the viability of the Batoka Gorge hydropower scheme to climate change. They found that annual flow levels at Victoria Falls will decline between 10% and 35.5%, which would cause reductions in annual electricity production between 6.1% and 21.4%. Beyene et al. [24] assessed the potential impacts of climate change on the hydrology and water resources of the Nile River basin and concluded that stream flow at the Nile River will increase for the 2010-2039 period and decline for the 2040-2099 period; and that the power generation would follow the stream flow's trends.

In Rwanda, climate change is reported to have disrupted hydropower generation during the last decade. Until 2003, all the electricity supplied in the country was 100% dependent on hydropower [12]. Since 2004, however, water resources have declined especially in the Burera and Ruhondo lakes (from which about 90% of the total electricity came from) which caused more than 60% losses in hydropower generation [25]. To temporarily respond to this situation, emergency diesel generators have been introduced, and to ensure an affordable tariff, the Government was obliged to subsidise the electricity sector through paying part of the capacity charges for rented generators as well as exempting fossil fuels for power generation from paying import duties. The costs of running these emergency generators, in 2005 for example, were estimated to be 1.84% of the country's GDP [26]. Despite these subsidies, however, the electricity tariff has continuously risen where the tariff for the residential sector between 2005 and 2012, for example, has increased by more than 60% [27].

Like in the past, hydropower generation is expected to represent a significant share in the total power supply mix of the country for the medium- and long-term. It is projected under the "Electricity Master Plan 2008–2025" [28] and the "Rwanda electricity development plan 2013–2032" [29] that more than 50% of the total power supply mix of the country over these two period will come from hydropower.

Although these plans did not consider climate change, Uhorakeye and Möller [30] demonstrated that climate change impacts will negatively affect hydropower generation in Rwanda. In their study, the authors analysed the future climate of Rwanda under two Representative Concentration Pathways (RCP): RCP4.5 and RCP8.5; and they found that there will be considerable reductions in annual precipitation especially for the period 2030 to 2060. Their analysis also revealed that changes in temperature relative to the 1961 to 1990 average will range between +2.19 to +3.72°C for RCP4.5, and +5.19 to +5.98°C for RCP8.5. Relative to the designed power generation, the resulting changes in hydropower generation were estimated to range between –13% and +8% for the 2020 to 2039 period, and –22% and –9% for the 2040–2059 period.

Given these considerable losses and the expected high share of hydropower generation in the future country's power supply mix, it is necessary to develop power supply plans that incorporate impacts of climate change in order to reduce or mitigate negative impacts on the overall electricity subsector; and this is the aim of the present study.

2. Methodology

This section discusses the methodology used to project the evolution of Rwanda's electricity demand and the way the demand could be met by considering impacts of climate change on the country's hydropower generation. This section starts with describing the energy model used in this study, and goes on with the approaches used to analyse the future electricity demand and supply. The section concludes with highlighting ways in which power generation costs and associated emissions are estimated.

2.1. Energy modelling tool

The complexity of energy systems requires appropriate data management and handling in terms of systematic preparation and aggregation of temporal and spatial energy processes, energy flows, capacity extensions, costs, waste heat recovery, energy storage systems, etc. Thanks to the advancement in computational technology, energy models allow to represent mathematically these complex energy systems, which facilitates their conceptualization and analysis [31–33]. Highly relevant for most developing economies is the inclusion of growth in population and per capita domestic product, as the future electricity demand is highly sensitive to both.

In this study, the Long-range Energy Alternatives Planning system (LEAP) model is used. LEAP is not a model for a specific energy system, but a tool that can be used to build simple to complex energy systems. The model supports a wide range of modelling approaches for both the demand and the supply [34]. On the demand side, LEAP supports bottom up, top down, and hybrid modelling methodologies. On the supply side, the model provides flexible and transparent accounting, simulation, and optimization methodologies to model power generation and capacity expansion planning. For calculations, LEAP provides two conceptual levels: the first level comprises LEAP's built-in expressions while the second level allows modellers to specify multi-variable models or enter spreadsheets and expressions. Most of LEAP's calculations occur on an annual time-step, but also seasonal, monthly, daily and hourly time-steps are supported, and the time horizon can extend for an unlimited number of years (typically between 20 and 50).

LEAP has been used for over 70 peer-reviewed journal papers including the modelling sustainable long-term electricity supply-demand in Africa [35], assessment of renewable energy and energy efficiency plans in Thailand's industrial sector [36], projections of energy use and carbon emissions for Bangkok [37], future scenarios and trends of energy demand in Colombia using Long-range Energy Alternative Planning [38], industrial sector's energy demand projections and analysis of Nepal for sustainable national energy planning process of the Country [39], energy efficiency and CO_2 mitigation potential of the Turkish iron and steel industry using the LEAP (long-range energy alternatives planning) system [40], and implication of CO_2 capture technologies options in electricity generation in Korea [41].

2.2. Electricity demand analysis

An analysis of the electricity consumption is assessed by grouping the power demand into two categories: the residential and non-residential sectors. The residential sector comprises households while the non-residential sector groups together the agricultural, the industrial, and the service sectors. The sectors comprising the non-residential sector are grouped together because of the lack of disaggregated information on electricity consumption by each of them.

A bottom up approach is used to analyse the evolution of the power demand by the residential sector. This method is chosen in order to take into considerations the main drivers of the sector; namely the access to electricity, the effects of equipment saturation, the population growth, and improvements in efficiencies of household appliances. The year 2012 is used as base year because a national population census, which provided considerable amount of information necessary to undertake this study, was conducted in that year. The average base year (2012) power consumption per an electrified household is estimated based on Eq. (1) where E_{Av} represents the average annual electricity consumption of an electrified household (in kWh), P_i is the rated power of appliance i (in kW), n_i is the average number of appliance i per household, h_i is the usage time of appliance i (hour/day), and 365 is the number of days in a year. The data used in Eq. (1) were extracted from the Fourth Population and Housing Census [1], and from the Economic Data Collection and Demand Forecast study [28].

$$E_{Av} = 365 \cdot \sum_{i=1}^{n} P_i \cdot n_i \cdot h_i \cdot p_{e,i} \tag{1}$$

To project the population towards 2050, assumptions used in three existing projection scenarios for the 2013–2032 period by the National Institute of Statistics Rwanda (NISR) are adopted. According to these projections, the population growth rate by 2032 will be 1.63% for the low scenario, 1.89% for the medium scenario, and 2.18% for the high scenario from 2.31% in

2013 [2]. For the period beyond 2032, the trends observed in the NISR's projections are maintained, which leads to growth rates of 1.45% for the low scenario, 1.71% for the medium scenario, and 2.00% for the high scenario. Similarly, the assumption by NISR that the number of persons per households would decline from 4.3 in 2012 to 3.1 in 2032 is adopted. For the period beyond 2032, this study assumes that there will be very little decline in the household size so that it will be 3 persons per household in 2050.

The number of households with access to electricity is estimated based on the existing two electrification pathways: the likely and ambitious scenarios. The likely scenario anticipates that 35% of the country's households would have access to electricity by the end of 2017 [9] and 71% by 2032 [29]. The ambitious scenario predicts that 48% of the country's households would have access to electricity by the end of 2017 [9] and 78% by 2032 [29]. Given observed difficulties and challenges in the implementation of different power generation and transmission projects during the last years, only the very likely electrification scenario is considered in this study.

For the period 2033–2050, this study assumes that the remaining non-electrified households will be those located very far away from the national electricity grid so that a 100% electrification would be achieved in 2050. It is important to mention here that a 100% electrification rate in 2050 does not mean that all households will have access to electricity in 2050. There are different initiatives whereby households located far away from the national grid are being supported to access electricity through off-grid solutions. This electrification scheme is not simulated in this study. The assumed 100% electrification means that all households would be connected to the national grid by 2050. On the other hand, it is assumed that all household appliances will consume 15% less than the consumption in 2012 thanks to the improvement in energy efficiency. Furthermore, an assumption that most of these appliances will saturate towards 2050 is adopted.

As for the power consumption by the non-residential sector, the top down approach is chosen because the bottom up approach requires more details on the end use electricity equipment which was not possible to acquire for the whole sector. To analyse the evolution of the power consumption by the non-residential sector, the relationship between the past electricity consumption and the GDP of this sector is determined using the regression method of ordinary least squares. This method allows to determine the slope a and intercept b of Eq. (2) that fits best data [42]. In the context of this study, y represents the non-residential sector's energy consumption and x is the sector's GDP.

$$y = ax + b \tag{2}$$

Eq. (3) and Eq. (4) is used to respectively determine coefficients a and b of the line represented by Eq. (2). In these two equations, x_i is the total GDP for year i while y_i is the power consumed by the non-residential sector in producing the total GDP for year i. The energy data used to determine the relationship was obtained from REG while the GDP data was extracted from Rwanda Statistical Yearbooks 2009 and 2013 [1] [43].

$$a = \frac{n \cdot \sum_{i=1}^{n} x_i y_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{n \cdot \sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i \right)^2} \tag{3}$$

$$b = \frac{n \cdot \sum_{i=1}^{n} x_i^2 - \sum_{i=1}^{n} y_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} x_i y_i}{n \cdot \sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i \right)^2} \tag{4}$$

Eq. (5) represents the determined logarithmic relationship between the non-residential electricity consumption and the national GDP. To check the goodness of fit, Pearson's correlation coefficient is determined. This coefficient is found to be +0.99 which indicates a very high positive correlation between the electricity demand and the GDP.

$$\log(y) = 1.256\log(x) - 2.78 \tag{5}$$

For the future power consumption of this sector, three electricity demand scenarios are developed based on different GDP growth rates. These scenarios are (i) the *high scenario* which envisages Rwanda as a fast-developing economy where the GDP growth would slightly decline from 8.0% in 2012 to 6.0% in 2050, (ii) the *medium scenario* which anticipates a moderate economic development so that the GDP growth rate would decrease from 8.0% in 2012 to 4.5% in 2050, and

(iii) the *low scenario* where the economy would grow slowly so that the GDP growth rate would decrease from 8.0% in 2012 to 3.0% in 2050.

The total national electricity demand is determined by combining the residential and non-residential sectors' demands, and since this combination leads to nine different scenarios, only three representative scenarios are analysed. These scenarios are called in this study the "very low scenario" which comprises the low scenarios of each sector, the "very likely scenario" which includes the medium scenarios of the residential and non-residential sectors, and the "very high scenario" which incorporate the very high scenarios of both sectors.

The peak power requirements, $P_{req,i}$ (in MW), for each year between 2012 and 2050 are calculated according to Eq. (6) where $E_{req,i}$ is the electricity requirements (in MWh), L_F is the load factor while 8764 is the number of hours in a year.

$$P_{req,\,i} = \frac{E_{req,\,i}}{8764 \cdot L_F} \tag{6}$$

The electricity requirements $E_{req,i}$ in Eq. (6) is the sum of the total simulated electricity demand and the transmission and distribution losses. In this study, it is assumed that the transmission and distribution losses will decline from their 2012 level of 21% to 10% by 2020 and then be maintained at this level during the rest of the simulation period. The 2013 load factor used to calculate the peak power requirements was also obtained from REG.

2.3. Power supply analysis

To meet the estimated electricity demand described in the previous section, a Business-As-Usual (BAU) and an alternative power supply scenarios are developed. Each of these two scenarios includes three sub-scenarios: a sub-scenario which does not consider impacts of climate change on hydropower generation, and scenarios that considers impacts of climate change. Climate change is assessed under two Representative Concentration Pathways (RCPs): RCP4.5 and RCP8.5. RCP4.5 is a stabilization scenario where the total Radiative Forcing (RF) is stabilized to 4.5 W/m^2 after 2100 while RCP8.5 is characterized by increasing Greenhouse Gas (GHG) emissions leading to a RF of 8.5 W/m^2 in 2100 [44].

The development of the BAU scenario is based on the country's existing power generation plans. Since these plans extend up to 2025 only, the generation capacity beyond this year is gradually increased (within the country's potential limits) to match the demand. According to these plans, nearly 32% (over 400 MW) of the electricity requirements by 2025 would be covered by imports from Ethiopia and Kenya [45] However, these countries may prioritize to satisfy domestic power demands first before exporting to other countries since electrification rates in these two countries are also low: 45% for Ethiopia and 65% for Kenya [8]. To consider these effects, electricity imports are excluded from the analysis of the future power supply.

For hydropower generation, it is assumed that the installed capacity would increase from the planned 254 MW by 2025 to the national (so far) proven capacity of about 350 MW by 2050. Similarly, the capacities for methane and geothermal-based power generations are set to increase up to their maximum estimated capacities (350 MW and 340 MW respectively) by 2050. Based on recent development in solar power generation which envisages 39.75 MW by 2025 [28], it is assumed that a cumulative capacity of 100 MW solar power can be achieved by 2050. As for peat-based power generation, a capacity of 300 MW is used in the simulation. It is assumed that the demand that cannot be met by the above power generation technologies will be covered by power generation from imported fossil fuels.

To analyse the evolution of Rwanda's power supply under climate change (under RCP4.5 and RCP8.5), monthly time series of hydropower generation from the study "Impacts of expected climate change on hydropower generation in Rwanda" by Uhorakeye and Möller [30] (described in the introduction section) are used.

The development of the alternative power supply scenario is guided by principles such us the scenario's ability to allow the country to terminate its dependency on imported fossil fuels for its power supply and meet the growing demand with domestic resources despite the emerging climatic conditions. To achieve this, five measures are explored as described below.

- *Improvement of efficiency of household appliances*: under the BAU scenario, it is assumed that the efficiency of household appliances will increase by 15% by 2050, and that these improvements would be voluntarily achieved by consumers. Under the alternative scenario, it is assumed that the Government will intervene by introducing import standards so that old and non-efficient appliances would not be allowed to enter into the country. It is assumed that this measure would lead to 10% consumption reductions compared to the BAU scenario.

- *Intensive exploitation of the Nyabarongo River*: this river draws its waters from the northern, southern and western parts of Rwanda and then flows over 350 km before it drains into the Akagera River at Lake Rweru in the south-eastern Rwanda. This study suggested cascading more run of river power plants and building reservoir storages on this river which would lead to 140 MW more.
- *More use of solar energy*: it is assumed under this scenario that the installed capacity of solar power plants would increase from 0.25 MW in 2012 to 8.75 MW in 2015 and 500 MW in 2050 (compared to 100 MW for the case of the BAU scenario).
- *Introduction of wind energy*: based on the results from an assessment of wind energy resources in Rwanda by De Volder [17], this study assumes that up to 250 MW wind power plants can be installed by 2050.
- *Municipal waste*: the use of municipal waste as a source of electricity is considered for Kigali, the capital city of Rwanda where data was available. In 2012, for example, 400 tons of solid waste per day (of which 75% of it were organic and paper matters) were collected [46]. Since the population of Kigali is expected to increase from about one million inhabitants in 2012 [47] to 3.5 million by 2040 [48], available waste for power generation would also increase from 300 tons to about 940 tons per day over the same period. Given a net heat content of 14 GJ per metric ton [34] and an electrical efficiency of 35% [49], and assuming an availability factor of 80%, the 300 tons would be enough to supply a 21 MW power plant, and the 940 tons of waste in 2040 would be equivalent to about 66 MW capacity.

For the simulation in LEAP, the generating technologies are assigned dispatching priorities according to specified orders. Once power plants with high priorities achieve their maximum operating capacity, plants with the next order are dispatched until they also reach their capacity limits and so on. In this study, the first priority is assigned to solar, wind, and run-of-river-based hydroelectric power plants. The second priority is assigned to dam-based hydropower plants, the third priority to methane and geothermal power plants, the fourth priority to peat-based power plants, and the fifth priority to diesel fired power plants.

2.4. Estimation of power generation costs and emissions

- *Capital costs*: investment costs per megawatt for all technologies other than solar, wind, and waste-to-power are estimated based on information from two studies: one by the African Development Bank (AfDB) [50], and another by Fichtner and decon [51]. To estimate the capital costs for solar-based power plants in the base year, the unit capital cost for the existing Rwamagana Solar power station (8.5 MW) is used. For the future development, it is assumed that investment costs would fall by 25% by 2020, 45% by 2030 and 65% by 2050 relative to the costs in 2012 according to estimates by the International Energy Agency (IEA) [52]. As for wind, since no power plant from this technology had been installed yet in the country by 2017, international average data are used. To consider factors such as transport of wind power generation components as well as the cost of technology transfer, a factor of 10% is added to the international data. Consequently, an average of US$ 2,000/kW is taken as the global average investment costs; and for Rwanda the cost would be 10% higher (i.e. US$ 2,200/kW). According to IEA [53], the average investment cost of wind energy is projected to decline by 25% on land, and 45% off-shore by 2050. Being a landlocked country, a reduction of 25% by 2050 is applied for Rwanda. Concerning municipal waste-to-power, its investment cost is estimated based on information from the Confederation of European Waste-to-Energy Plants [54].
- *Operation and maintenance costs*: the fixed Operation and Maintenance (O&M) costs for different technologies are obtained from AfDB [50], Fichtner and decon [51], and IEA [55]. The variable O&M costs for hydropower, geothermal, solar and wind technologies are assumed to be zero according to IEA [55]. The variable O&M costs for waste-to-power are also set to zero since households and institutions pay a fee for waste collection. It is assumed that the variable O&M costs will be offset by the paid collection fee. As for diesel fired power plants, the projection of oil prices by IEA [56] are adopted.

As for emissions from the electricity generation, they are calculated internally in LEAP which is achieved by linking the electricity producing technologies to the model technology and environmental database. This database includes default emission factors suggested by the Intergovernmental Panel on Climate Change (IPCC) for use in climate change mitigation analyses [34]. In this study three Greenhouse Gas (GHG) emitting fuels namely diesel, methane gas and peat are linked to IPCC Tier 1 Default Emission Factors. Under Tier 1 approach, GHG emissions from stationary combustions are calculated by multiplying the consumed fuel by the default emission factor [57].

3. Results

This section presents the simulation results of the evolution of Rwanda's electricity demand and supply under both the BAU and the suggested alternative scenarios. Furthermore, it discusses the estimated generation costs and emissions from power generation. The section concludes by highlighting required adjustments in policy and institutional frameworks to implement the suggested power supply scenario successfully.

3.1. Projected electricity demand

By 2050, the total annual power consumption in Rwanda is projected to be 6,546 GWh under the very low scenario, 8,100 GWh for the very likely scenario, and 10,240 GWh for the very high scenario, from 380 GWh in 2012. Like in the past, the residential sector will continue to dominate the national demand for electricity except for the 2041-2050 decade when the non-residential sector will take a lead. The projected total power demand as well as the shares of the residential (Res.) and the Non-residential (Nonres.) sectors are presented in Table 1.

In terms of power generation requirements (including transmission losses), about 7,270 GWh will be required by 2050 for the very low scenario, 9,000 GWh for the very likely scenario, and 11,380 GWh for the very high scenario, from 480 GWh in 2012. The evolution of the electricity generation requirements between 2012 and 2050 are shown in Figure 1 (left). It is important to highlight that these electricity requirements may exceed the simulated power presented in this section if losses are not reduced to the assumed values. It was, for example, planned to reduce technical losses from 20% in 2007 to 15% by 2012 [58]. On the contrary however, losses have risen over this period and reached 21% in 2012 and 22% in 2013.

As for the installed capacity requirements (assuming a reserve margin of 20%), about 1,480 MW will be needed in 2050 for the very low scenario, 1,830 MW for the very likely scenario, and 2,310 MW for the very high scenario. The evolution of the requirements in installed peak capacity between 2012 and 2050 is also presented in Figure 1 (right).

3.2. Projected impacts of climate change on Rwanda's hydropower

Figure 2 shows hydropower generation anomalies for the 2012–2050 period. This figure is constructed based on hydropower generation time series developed by Uhorakeye and Möller [30] in their study described in the introduction section.

As it can be noticed in Figure 2, there is no significant difference between the designed and the simulated hydropower generations for the period 2012–2021. Over this period, the cumulative hydropower generation anomalies are about +3 GWh for both RCP4.5 and RCP8.5. Between 2022 and 2031, deficits equivalent to

Table 1: Projected electricity demand per scenario and per sector

	Very low			Very likely			Very high		
Year	Total (GWh)	Res. (%)	Nonres. (%)	Total (GWh)	Res. (%)	Nonres. (%)	Total (GWh)	Res. (%)	Nonres. (%)
2012	380	51.32	48.68	380	51.32	48.68	380	51.32	48.68
2015	537	55.26	44.74	538	55.24	44.76	540	55.18	44.82
2020	923	58.19	41.81	934	57.93	42.07	943	57.59	42.41
2025	1,487	60.07	39.93	1,529	59.34	40.66	1,568	58.50	41.50
2030	2,272	61.41	38.59	2,387	59.96	40.04	2,504	58.42	41.58
2035	3,185	61.04	38.96	3,445	58.60	41.40	3,730	56.08	43.92
2040	4,161	59.57	40.43	4,675	55.79	44.21	5,276	51.95	48.05
2045	5,289	58.69	41.31	6,215	53.23	46.77	7,385	47.76	52.24
2050	6,546	58.48	41.52	8,100	51.01	48.99	10,240	43.63	56.37

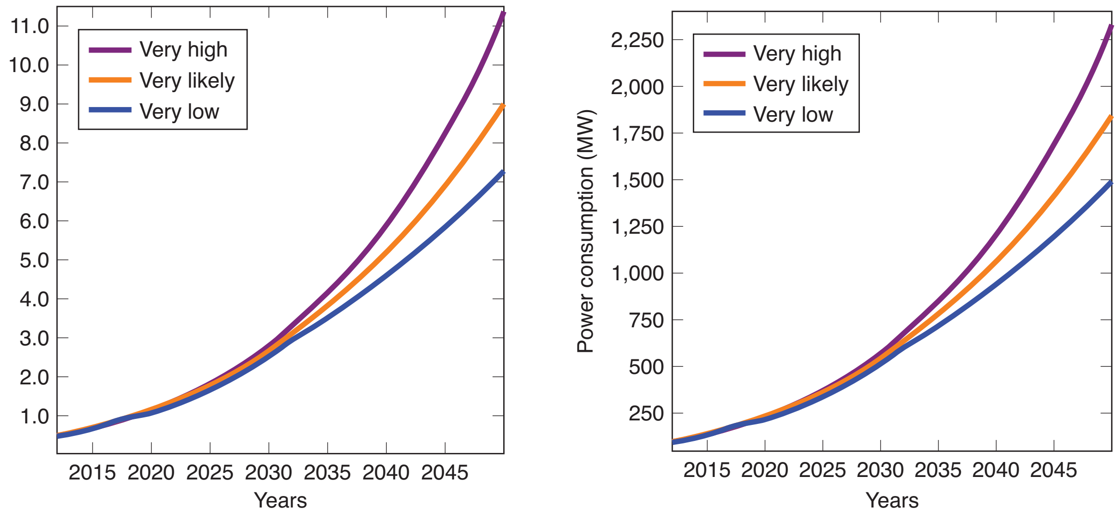

Figure 1: Electricity generation (left) and peak power (right) requirements

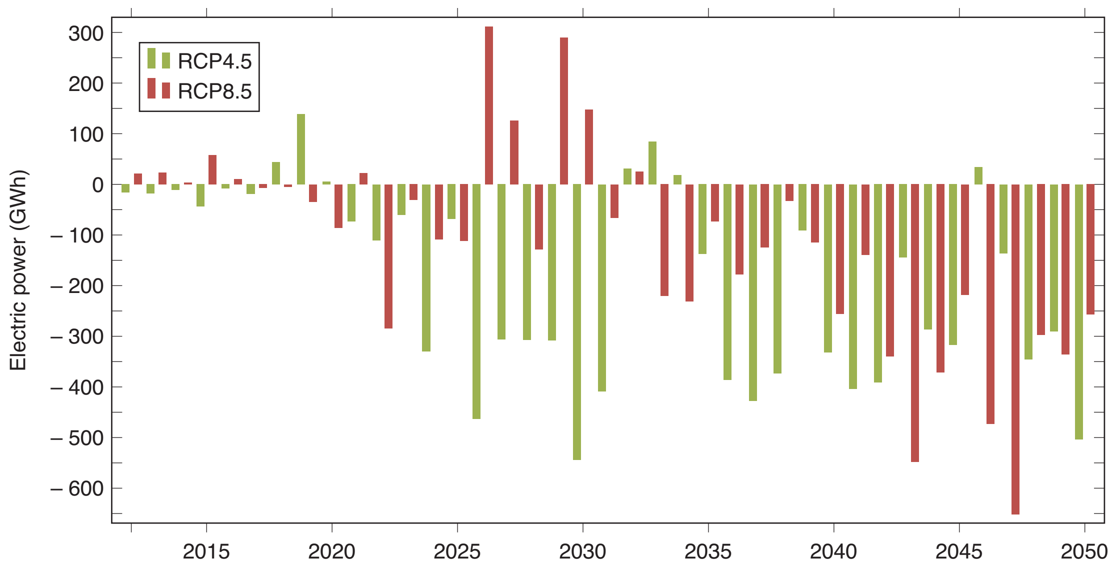

Figure 2: Hydropower generation anomalies between 2012 and 2050

about 3000 GWh are expected under RCP4.5 while RCP8.5 presents surplus of about 150 GWh. As for the 2032–2050 period, almost all the years over this period will record deficits in power generation. For the whole period, more 7,200 GWh deficits are expected for RCP4.5 and 4,659 GWh for RCP8.5.

3.3. BAU power supply without climate change considerations

The analysis of the BAU power supply scenario revealed that the national energy resources will be sufficient to meet the power demand projected under the very low and very likely electricity demand scenarios. Consequently, the analysis of the power supply concentrated only on electricity supply scenarios that meet the projected demand under the very high scenario.

As described in the methodology section, the BAU power supply under no climate change considerations assumed that hydropower plants will continue to produce their designed energy throughout the simulation period. Under this assumption, it was found that the share of hydropower to the total power supply mix will increase from 55.6% (of 480 GWh) in 2012 to 77.7% (of 1,740 GWh) in 2025, and then decline to 17% (11,380 GWh) in 2050. The simulation results reveals that power generations from hydropower, solar, methane, and geothermal will meet the whole demand until 2040. After this year, power generations from peat and diesel will be needed: peat will represent 18.5% and diesel 16.5% of the total electricity needs in 2050. The distribution of the generation between different technologies under the BAU scenario are shown in Figure 3 (a) while the total power supply and the percentage shares of the used technologies are presented in Table 2.

As for the alternative power supply scenario without climate change considerations, it is projected that 10,700 GWh will need to be generated in 2050, from 480 GWh in 2012. The reduction in the power demand of about 6% compared to the BAU scenario is due to the assumed improvements in efficiency of household appliances. Under this scenario, no electricity generation from diesel power plant will be needed until 2050. In addition, the share of power generation from peat will decline from 18.5% (under the BAU scenario) to about 9.0%. The distribution of the power generation between different technologies under the alternative scenario are shown in Figure 3 (b) while the corresponding total power supply requirements and the percentage shares of different technologies are presented in Table 2.

3.3. Power supply under RCP4.5

For the BAU power supply under the RCP4.5 pathway, the shares of different technologies to the total power supply mix will oscillate following the variations in hydropower generation. The share of hydropower generation is projected to increase from 55.6% (of 480 GWh) in 2012 to 73.9% (of 1,740 GWh) in 2025 (against 77.7% under no climate change consideration scenario), and then decline to 12.6% (of 11,380 GWh) in 2050 (against 17% under the no climate change consideration scenario). The power generation distribution between different technologies under the BAU scenario are shown in Figure 4 (a).

In 2050, more power generation from diesel will be required under this power supply scenario (20.9%) compared to the case of no climate change considerations (16.5%). The total power supply requirements and the percentage shares of different technologies under the BAU power supply scenario evolving under RCP4.5 are presented in Table 3.

Concerning the alternative power supply scenario evolving under the same RCP4.5, no electricity generation from diesel-based power plants will be needed for the whole simulation period. However, the share of peat in 2050 will represent 16.4% (against 9.0% under no climate change consideration), and this is due to considerable losses in hydropower generation caused by climate change. The distribution of the power generation between different technologies under this scenario are shown in Figure 4 (b) while the corresponding power supply requirements and the percentage shares are presented in Table 3.

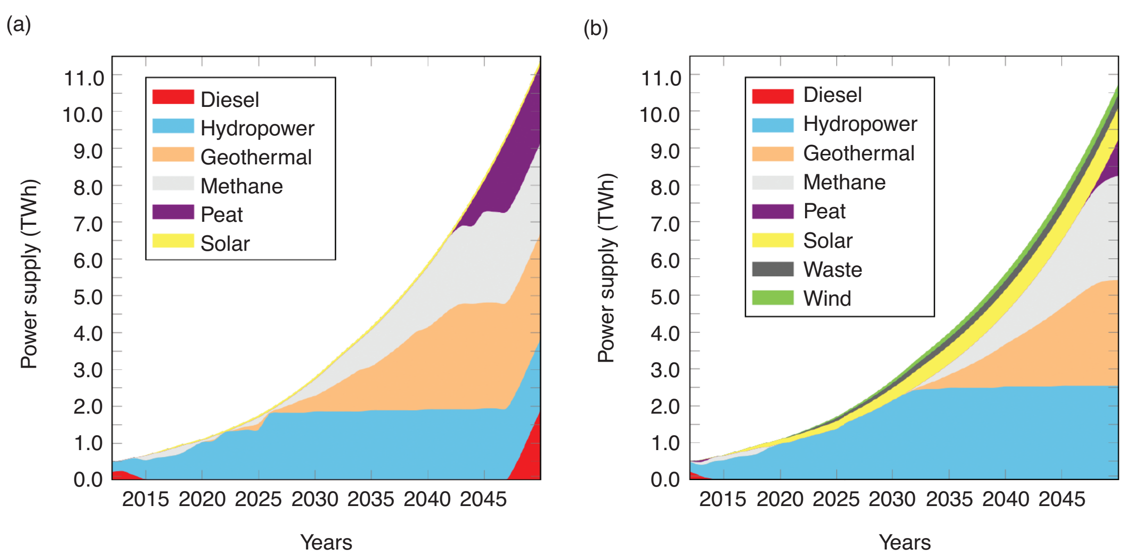

Figure 3: Electricity supply by resource under no climate change considerations

Table 2: Shares of different technologies under no climate change considerations

Scenario	Technology	2012	2020	2030	2040	2050
	Diesel (%)	42.48	0.00	0.00	0.00	16.48
	Hydropower (%)	55.61	92.30	66.36	32.51	17.01
	Geothermal (%)	0.00	0.30	15.20	37.92	25.20
BAU	Methane (%)	1.85	3.84	15.84	27.88	21.62
	Peat (%)	0.00	0.00	0.00	0.00	18.53
	Solar (%)	0.06	3.56	2.60	1.69	1.16
	Total (TWh)	0.48	1.10	2.78	5.86	11.38
	Diesel (%)	42.48	0.00	0.00	0.00	0.00
	Hydropower (%)	55.61	88.59	79.40	44.98	23.70
	Geothermal (%)	0.00	0.00	0.00	20.69	26.78
	Methane (%)	1.85	0.00	0.00	15.06	26.42
Alternative	Peat (%)	0.00	0.00	0.00	0.00	8.96
	Solar (%)	0.06	11.41	12.51	11.34	8.21
	Waste (%)	0.00	0.00	5.02	4.54	3.28
	Wind (%)	0.00	0.00	3.07	3.39	2.65
	Total (TWh)	0.48	1.08	2.68	5.57	10.70

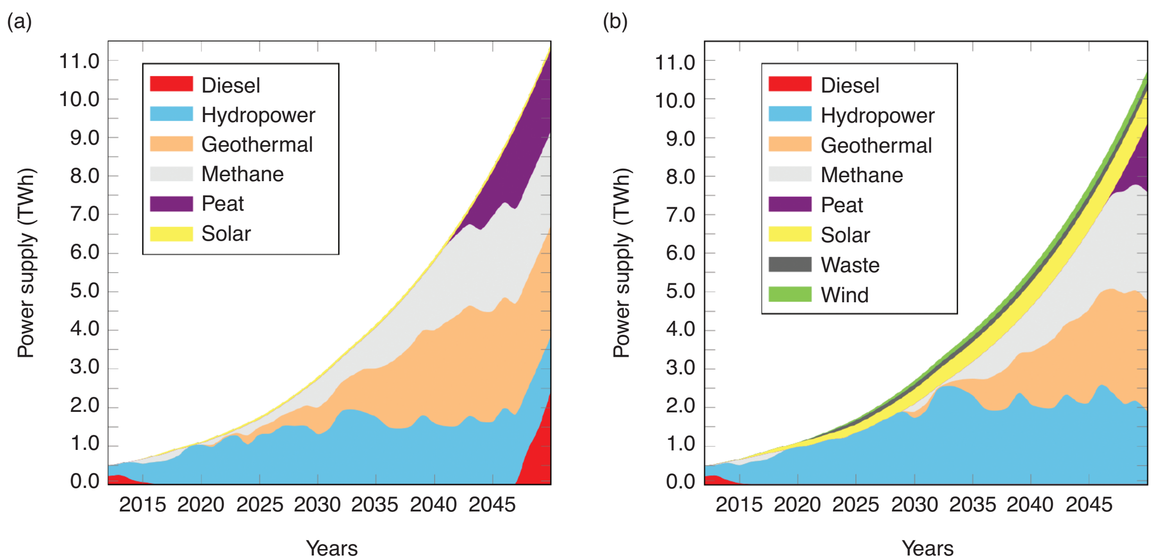

Figure 4: Electricity supply by resource under RCP4.5

3.4. Power supply under RCP8.5

Under RCP8.5, the contribution of different technologies to the total power supply mix will follow variations in hydropower generations like in the previous section. For the BAU scenario when the climate evolution follows RC8.5, the share of hydropower will increase from 55.6% (of 480 GWh) in 2012 to 71.3% (of 1,740 GWh) in 2025 (against 77.7% under no climate change considerations), and then decline to 14.8% (of 11,380 GWh) (against 17% under the no climate change consideration) in 2050. The distribution of the power generation between different technologies under the BAU scenario are shown in Figure 5 (a) while the corresponding total power supply requirements and the percentage shares of different technologies are presented in Table 4.

The performance of the proposed alternative power supply scenario under RCP8.5 differs from that under RCP4.5 regarding the amount of available hydropower production which dictates the shares of the other energy technologies. Like in the case of RCP4.5, no diesel-based power generation will also be needed under the RCP8.5

Table 3: Distribution of the electricity supply by resource type under RCP4.5

Scenario	Technology	2012	2020	2030	2040	2050
BAU	Diesel (%)	42.48	0.00	0.00	0.00	20.91
	Hydropower (%)	55.61	92.69	46.77	26.86	12.59
	Geothermal (%)	0.00	0.27	24.80	41.18	25.20
	Methane (%)	1.85	3.48	25.83	30.27	21.61
	Peat (%)	0.00	0.00	0.00	0.00	18.53
	Solar (%)	0.06	3.56	2.60	1.69	1.16
	Total (TWh)	0.48	1.10	2.78	5.86	11.38
Alternative	Diesel (%)	42.48	0.00	0.00	0.00	0.00
	Hydropower (%)	55.61	89.18	64.13	37.14	17.51
	Geothermal (%)	0.00	0.00	6.04	24.44	26.78
	Methane (%)	1.85	0.00	7.24	20.67	26.41
	Peat (%)	0.00	0.00	0.00	0.00	16.47
	Solar (%)	0.06	10.82	14.36	11.34	8.21
	Waste (%)	0.00	0.00	4.71	3.03	1.97
	Wind (%)	0.00	0.00	3.52	3.39	2.65
	Total (TWh)	0.48	1.08	2.68	5.57	10.70

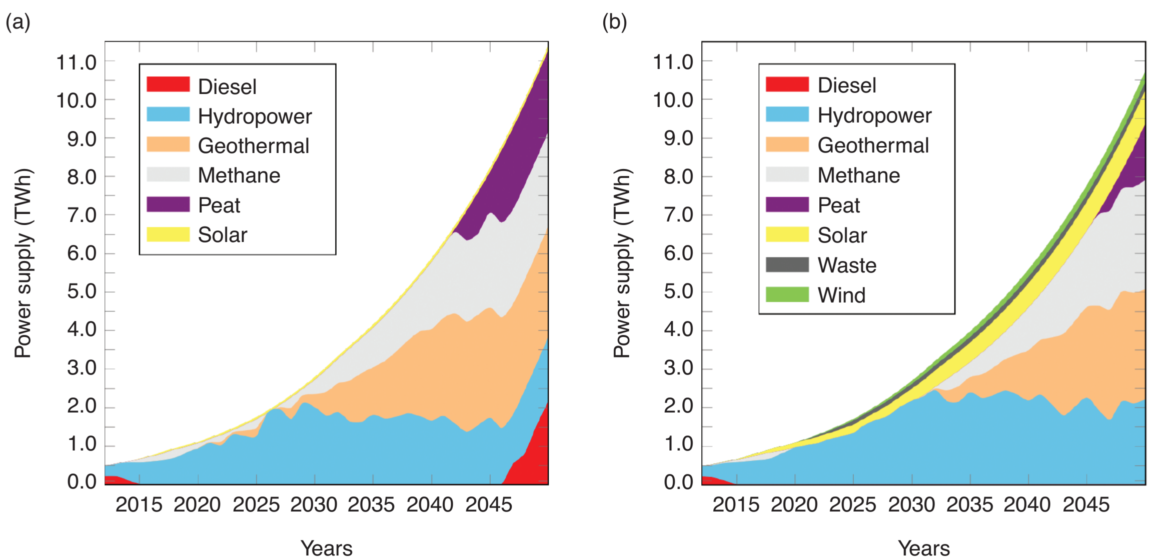

Figure 5: Electricity supply by resource under RCP8.5

scenario. The share of peat-based power generation will reach 13.4% in 2050 (against 16.5% under RCP4.5, and 9.0% under no climate change considerations). The power generation distribution between different technologies under the alternative scenario are shown in Figure 5 (b) while the corresponding total power supply requirements and the percentage shares of different technologies are presented in Table 4.

3.5. Emissions from power generation and generation costs

Under no climate change considerations, the average emissions for the 2012–2050 period are projected to be 101 gCO_2eq/kWh for the alternative scenario, and 183 gCO_2eq/kWh for the BAU scenario. Under the RCP4.5 power supply scenario, the average CO_2 emissions are 116 gCO_2eq/kWh for the alternative scenario, and 203 gCO_2eq for the BAU scenario. In case of RCP8.5, emissions are projected to be 104 gCO_2eq/kWh for the alternative scenario, and 192 gCO_2eq/kWh for the BAU scenario. Figure 6 (left) compares the projected average emissions for the 2012–2050 period. No-CC in this figure refers to "no climate change considerations".

Regarding power generation costs, the average unit costs between 2012 and 2050 for the BAU scenarios are

Table 4: Distribution of the electricity supply by resource type under RCP8.5

Scenario	Technology	2012	2020	2030	2040	2050
	Diesel (%)	42.48	0.00	0.00	0.00	18.74
	Hydropower (%)	55.61	84.61	71.60	28.16	14.75
	Geothermal (%)	0.00	0.86	12.64	40.42	25.20
BAU	Methane (%)	1.85	10.97	13.16	29.73	21.62
	Peat (%)	0.00	0.00	0.00	0.00	18.53
	Solar (%)	0.06	3.56	2.60	1.69	1.16
	Total (TWh)	0.48	1.1	2.78	5.86	11.38
	Diesel (%)	42.48	0.00	0.00	0.00	0.00
	Hydropower (%)	55.61	88.26	80.63	38.94	20.54
	Geothermal (%)	0.00	0.00	0.00	23.46	26.78
	Methane (%)	1.85	0.00	0.00	19.84	26.42
Alternative	Peat (%)	0.00	0.00	0.00	0.00	13.44
	Solar (%)	0.06	11.74	11.78	11.34	8.20
	Waste (%)	0.00	0.00	4.71	3.03	1.97
	Wind (%)	0.00	0.00	2.88	3.39	2.65
	Total (TWh)	0.48	1.08	2.68	5.57	10.7

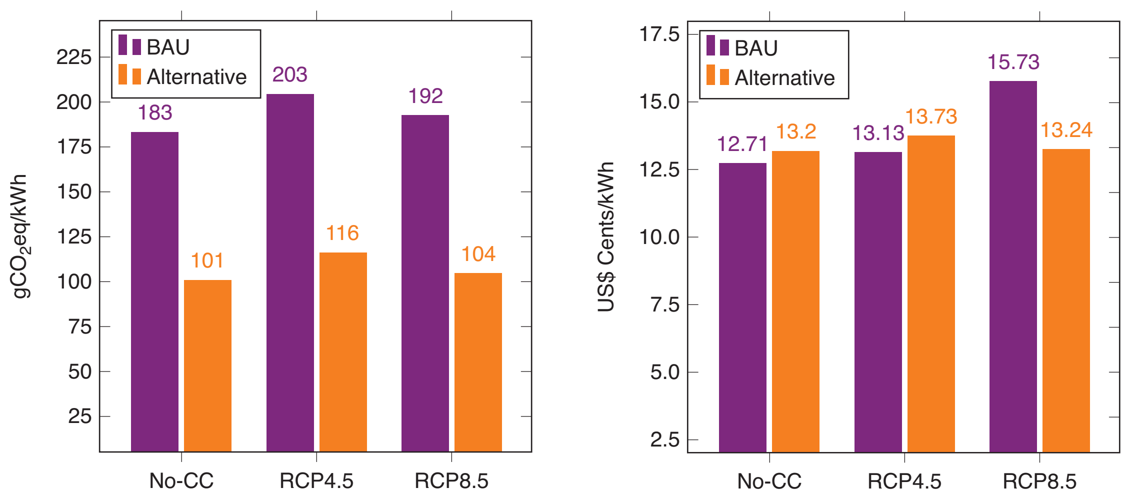

Figure 6: Average emissions and generation cost per kWh for the 2012–2050 period

projected to be 12.71 US¢/kWh under no climate change considerations, 13.13 US¢/kWh under RCP4.5, and 15.76 US¢/kWh under RCP8.5. As for the alternative scenario, the average unit generation costs are anticipated to be 13.20 US¢/kWh under no climate change considerations, 13.73 US¢/kWh under RCP4.5, and 13.24 US¢/kWh under RCP8.5. Figure 6 (right) compares the projected average power generation costs per kWh for the 2012–2050 period.

3.6. Policy and institutional frameworks

To successfully implement the suggested alternative power supply scenario, enabling policies as well as institutional frameworks must be in place. A policy that allows Independent Power Producers (IPPs) to cover the production costs and earn reasonable returns on their investments is required at the first place. In this regard, a Feed-In-Tariff (FIT) scheme for solar and wind technologies is necessary until these technologies mature. In addition to the FIT policy, other incentives such as the construction of access roads to the power plant sites and transmission lines connecting new plants to the national grid would also attract private investments.

FIT policy will not only increase the share of renewable energy in the country power supply mix, also through the implementation and operation of solar and wind projects, thousands of jobs will be created, especially in rural areas where more than 80% of the country's population live.

However, to operate these two technologies know how is required. Therefore, a training component should be given a priority in the deployment of solar and wind technologies in the country. In the past, the Government, in partnership with its development partners, has organized training courses on hydropower projects development and management. In the Author's knowledge this has considerably reduced the number of hydropower projects that failed shortly after their commissioning due to inadequate maintenance and management.

4. Conclusions

This study analysed the evolution of Rwanda's electricity demand and supply towards 2050. Since hydropower generation is expected to represent a considerable share in the country's total power supply mix, and given the expected vulnerability of this technology to the impacts of climate change, a planning approach that incorporates impacts of climate change on Rwanda's hydropower generation was necessary. Under the BAU power supply scenario, it was found that there will be deficits in hydropower generation of more 7,200 GWh under RCP4.5 and 4,659 GWh under RCP8.5. As consequence of these losses, more than 20% of electricity requirements in 2050 are expected to come from imported fossil fuels. Under the suggested alternative scenario, however, no imported fossil fuels would be needed by 2050. Also the average CO_2 emissions per kWh for the 2012–2050 period is 116.42 gCO_2eq for the alternative scenario against 203.24 gCO_2eq for the BAU scenario. The average generation cost per kWh between 2012 and 2050 varies between 12.71 and 15.76 US¢/kWh for the BAU scenario, and between 13.20 and 13.73 US¢/kWh for the alternative scenario.

These findings allow to conclude that the suggested scenario is resilient to climate change impacts as it meets the projected power demand when these impacts are accounted for. Furthermore, the scenario also ensures the security of the country's power supply because it re-lies only on domestic energy resources. Moreover, CO2 emissions per kWh under this scenario are about 40% lower than the emissions under the BAU scenario. To successfully implement this scenario, FIT scheme for solar and wind technologies are recommended until these technologies mature. In addition, short- and long-term training courses in these two technologies are also recommended since investors will be interested in investing in areas where they can find manpower with enough skills to operate and maintain installed technologies

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