Received: 15 February 2023 | Revised: 30 March 2023 | Accepted: 17 April 2023 | Published online: 24 April 2023

Green and Low-Carbon Economy
2023, Vol. 1(3) 138–146
DOI: 10.47852/bonviewGLCE3202762

RESEARCH ARTICLE

Understanding the Potential Impact of Climate Change on Hydropower Generation in Rwanda

Hakizimana Eustache[1,*], **Umaru Garba Wali**[2] and **Kayibanda Venant**[1]

[1]*Department of Mechanical and Energy Engineering, University of Rwanda, Rwanda*

[2]*Department of Civil, Environmental and Geomatics Engineering, University of Rwanda, Rwanda*

Abstract: The primary energy sources used in Rwanda include solar energy, methane gas, diesel and heavy oil generators, hydropower plants, and thermal power plants. Hydropower is a significant renewable low-carbon energy source and generates more than 45% of Rwanda's total electricity. It requires water to produce energy; therefore, any modifications to the natural hydrological cycle brought on by climate change have an impact and will continue to have an influence on the production of electricity. Hydropower is sorrow from an increase in extreme weather occurrences and erosion. Therefore, by altering flow (discharge) and head, climate change may have an effect on hydropower. The amount of sediment that is transferred to the reservoir lowers its capacity, and the dry season may result in less water in the reservoir, which has an impact on the hydroelectric power generation process. According to the study, changes in river flow have the greatest impact on how hydropower is affected by climate change. Droughts, seasonal and frequent floods, and greater variability due to climate change are the main contributors. The results show that climate change is likely to have a more pronounced impact on hydropower operations, with reductions in water availability due to climate change expected to result in reduced power generation. Additionally, existing dams will be located in areas at high risk of flooding due to climate change. In order to ensure electricity availability throughout the year, especially during the hot or dry seasons when discharges are often low, the required changes should be performed. These adjustments include using alternate backup sources and storage systems. Water consumers can be conserved and optimized through water resource management, drought resistance, flood protection, and conservation.

Keywords: hydropower plant, climate, environmental impacts

1. Introduction

Renewable energy comes from renewable or naturally supplementary resources. The main renewable energy technologies used in Rwanda for electricity generation are hydroelectric (water power and fluid power), solar (electricity and hot water), and biomass (heating and cooking). As far as greenhouse gas emissions go, they are all zero (wind, solar, and hydro), very low (geothermal), or neutral (biomass) during operation. As the most common source of renewable electricity which shown by the Figure 1 (Gaudard et al., 2013). Hydropower still generates a considerable share of the world's electricity (International Energy Agency, 2012). It strikes a balance between the quantity of CO2 absorbed during growth and emissions from neutral sources. However, the overall environmental impact of each source depends on the emissions it produces throughout its entire lifecycle, which also includes consequences related to the manufacturing of equipment and materials, installation, and land usage.

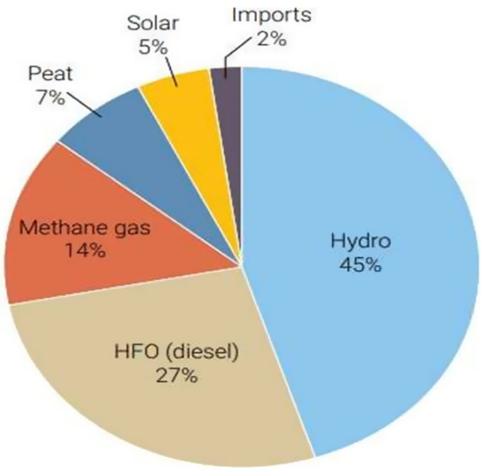
Conventional hydroelectric plants can be built on rivers without reservoirs (referred to as "drainage" units), or they can be built with reservoirs and used on demand. As water flows downstream, they direct it downward through pipes or other water intake structures in dams (pendent pipes). The flowing water turns the blades of the water turbines that generate electricity for the power station at the foot of the dam. The main environmental impact is the construction of reservoirs or dams to channel water to hydroelectric plants, which will change the ecosystem and physical characteristics of the river. Rwanda's electricity supply consists of domestic generation and imported electricity from power plants in neighboring countries and regional communities.

Rwanda's strategic plan aims to increase electrification penetration to 100% by 2024, with a focus on off-grid and on-grid solutions. Rwanda Energy Group (REG) is fully responsible for the development of energy resources and power supply in Rwanda. REG is a group of companies (Energy Utility Corporation Limited (EUCL) and Energy Development Corporation Limited) (Rwanda Energy Group, 2021). The group is strongly committed to supporting the objectives of University of Rwanda (UR), particularly in the areas of industry linkages and student placements to promote skills transfer and sustainable development; promote research development and support the dissemination of knowledge on indigenous energy; provide access to energy infrastructure, to promote research and provide access to state-of-the-art technologies; and strengthen collaboration between industry and academia in training local and regional renewable energy workforces.

Grid energy is only available in a small area, mostly in and around Kigali. The primary energy source for the majority of the

*Corresponding author: Hakizimana Eustache, Department of Mechanical and Energy Engineering, University of Rwanda, Rwanda. Email: haki2012eustache@gmail.com

Figure 1
Rwanda's current power generation mix



nation is firewood. Rwanda intends to increase its grid capacity (as shown in Figure 1) from 276 MW in 2022 to 556 MW in 2024 (MININFRA, 2018). It may also import more electricity from its neighbors. In order to guarantee that homes in off-grid areas have access to power or to aid with outages, it is also installing modest solar panels across the nation. By 2024, the government hopes to have power accessible to all citizens.

2. Country climate variation

The use of hydropower, a renewable energy source, is widespread around the world and is frequently viewed as having negative environmental and social effects at both the planning and implementation stages. Large, medium, and small hydropower facilities all have different environmental issues, and environmental degradation is a severe problem that varies according to the geographic, geological, and topographical factors in each country. Rainfall patterns and regional factors also have an impact on hydropower plants that use runoff to feed natural water into rivers. Climate change is also posing severe ecological challenges to these facilities (Gaudard et al., 2013, 2014, 2018).

Rwanda's high elevation results in a tropical and temperate climate. Without much variation, the yearly average temperature is between 16°C and 20°C. There was a lot of rain, yet there were some irregularities. Typically, the wind's velocity ranges from 1 to 3 m/s. Average temperatures in the highest elevations of the Congo-Nile ridge range from 15°C to 17°C, and rainfall is plentiful. In some locations, the temperature in the volcanic region might even go below 0°C. At modest heights, the yearly average rainfall is roughly 1000 mm, and the typical temperature ranges from 19 to 21°C. Rainfall is not so erratic as to regularly cause droughts. Temperatures are warmer in the lowlands (east and southeast), where extremes of more than 30°C are possible in February and July–August.

The southeast's Karama Plateau Station measured an absolute temperature of 32.8°C in September 1980. Calorie restrictions are stricter there than in other parts of the country. Additionally, this region receives just 700–970 mm of rainfall annually (Kseniia et al., 2015). The Convergent Tropical Zone is the primary synoptic characteristic scale structure regulating precipitation (ITCZ). This function is characterized by low pressure, maximum humidity, and wind concentration. It travels through Rwanda twice a year, establishing two rainy seasons: March to May and mid-September to mid-December. Northeasterly winds and humidity from the Indian Ocean and Lake Victoria moisture masses dominate the season from mid-September to December.

In the next dry season (which lasts from mid-December to late February), East Africa is invaded by significant amounts of dry, chilly air from the Arabian hinterland. However, Rwanda was able to keep some rainfall, thanks to Lake Victoria's moderating influence and the ethnic diversity of its population. Dry fronts between the southeast and southwest, which carry moisture from the South Atlantic to the Congo Basin, have an impact on Rwanda from March to May. The southeasterly air mass that reaches Rwanda during the dry season, which lasts from June to mid-September, dries up as it traverses the Tanzanian mainland from the air and diverts in the lower levels. Precipitation is not likely under these circumstances (Fan et al., 2020).

The country's climate has four seasons, two of which are wet and the other two are dry. Despite a few anomalies, the annual precipitation is generally evenly distributed, as can be seen in Figure 2b: The climatic classification map for Rwanda. While the northern and western regions (Musanze, Rubavu, Nyarugusu, and Gicumbi) experience heavy rainfall, which frequently causes erosion, flooding, and mountain landslides, the eastern and southeastern regions (Nyagatare, Kibuungo, Bugesera, and Kirehe) are more severely affected by a protracted drought.

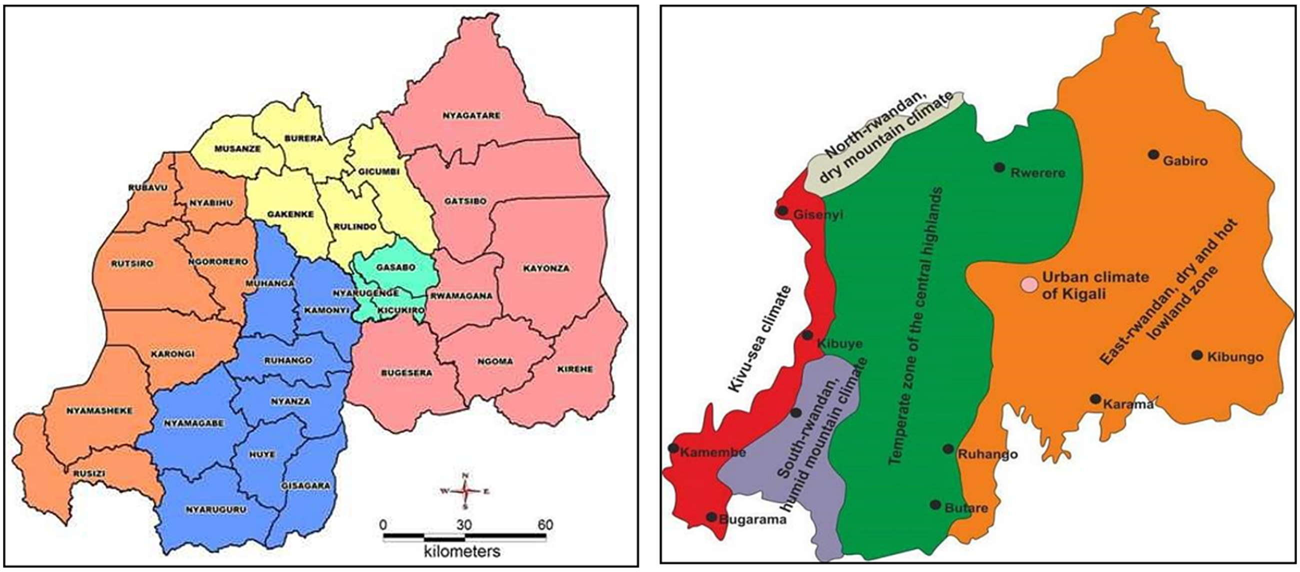
Extreme rainfall is becoming more common in Rwanda. The rainy season has grown shorter and more intense, particularly in the northern and western regions. Additionally, its temperature has increased by 1.4° C since 1970, above the global average, and is expected to increase by 2.0°C between 1970 and the 2030s (Rwanda Environment Management Authority, 2023). There are several natural water resources in Rwanda, including the Nile River, which rises in the highlands, roughly 101 lakes, and 860 swamps, which make up 16% of the nation's land area. However, the Eastern Province (see Figure 2a: Geographical description of Rwanda - based on provinces) is where the loss of water resources is most noticeable. Climate change is one of the factors contributing to this water shortage (Hamududu & Killingtveit 2012; Solaun and Cerda, 2017; Wagner, et al., 2016).

Long-term changes in temperature and weather patterns are referred to as climate change. Science has proven that human activity has increased the atmospheric concentration of greenhouse gases. Examples include using fossil fuels for transportation, deforestation, burning coal, oil, or gas for electricity production, poorly managed landfills, ruminants, and agricultural practices like overusing industrial fertilizers, among others. A rise in greenhouse gases causes a rise in global warming, which in turn causes a shift in the climate. Rwanda could serve as a role model for the use of climate data in energy planning given the nation's dedication to green growth and climate resilience. Future climate data should be taken into account when making strategic decisions in the energy sector, according to energy planners. Figure 3 shows the comparison of seasonal variations between storage and runoff hydropower plants. Rwanda is a landlocked country with a mild climate and relatively high rainfall. Climate change is expected to lead to higher temperatures, more rainfall and longer dry seasons. This presents different challenges for different regions: erosion in the mountains in the west of the country, severe flooding in parts of the north-central and south, and drought and desertification in the east and south-east (Ministry of Foreign Affairs, 2018).

3. Status of hydropower plants in Rwanda and data collection

The nation's 333 prospective micro-hydropower sites have been identified along Rwanda's major rivers. Micro and hydropower projects, as well as chances for East African partners

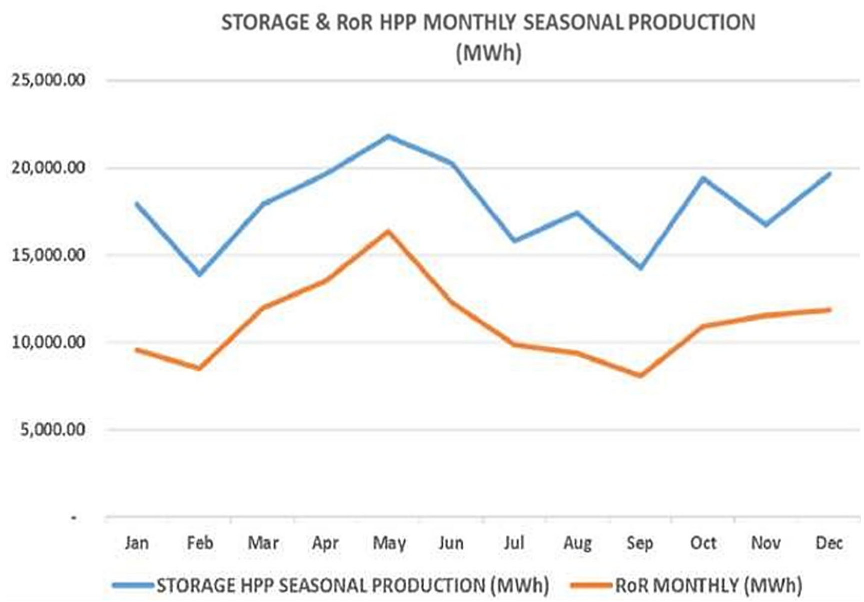
Figure 2
The climatic classification map for Rwanda



a: Geographical description of Rwanda - based on provinces

b: The climatic classification map for Rwanda

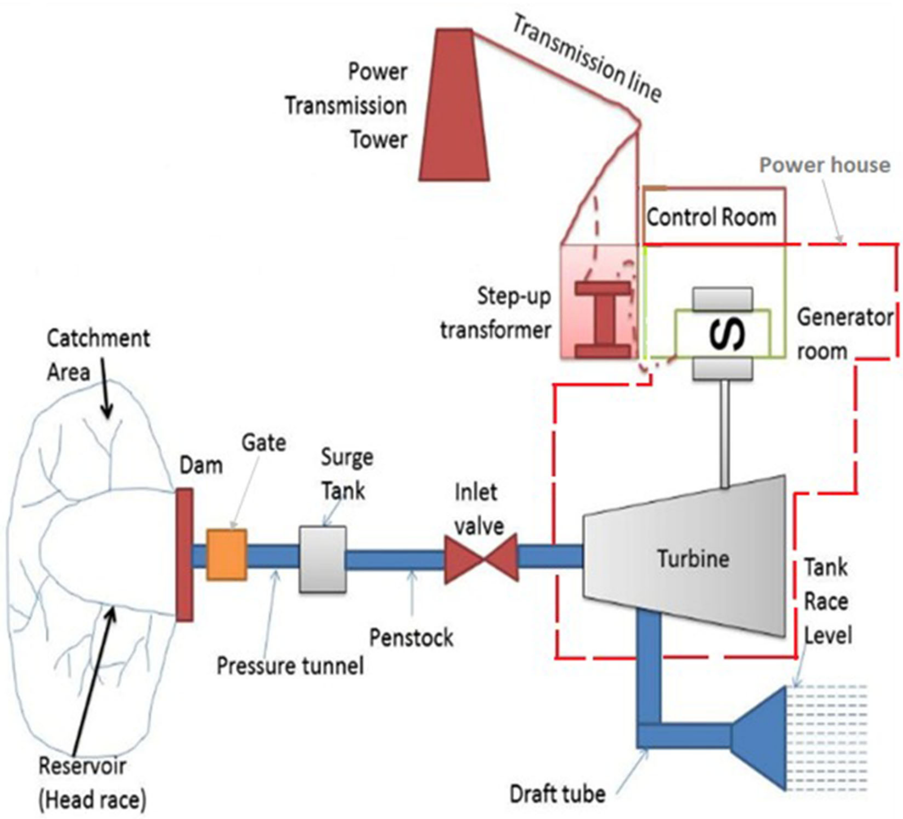
Figure 3
Hydropower plant seasonal variation



to collaborate on regional hydropower projects. The Democratic Republic of the Congo, Burundi, Rwanda, and Tanzania are all working together on a 145 MW hydropower project, and Tanzania, Burundi, and Rwanda are developing an 80 MW project. Other collaborative hydropower projects with nearby nations are also under development. In the last 10 years, Rwanda's hydropower industry has advanced significantly. About 238.36 MW of the total installed capacity (Rwanda Energy Group, 2022) or 50.5%, is made up of hydropower. There are 11 remote grid-connected micro-hydropower stations and 37 grid-connected hydropower plants having a combined installed capacity of 119.44 MW.

Publicly owned and operated hydroelectric facilities are leased to private businesses or private ownership (IPP). The public power plants are managed by the country's energy provider, REG/EUCL. Hydropower is energy that is obtained from the force or energy of moving water and applied to productive uses. The amount of water flowing through the turbine at once, the water column, and the turbine's efficiency primarily affect the power output of a hydroelectric power plant. Hydroelectric power generation is

Figure 4
The block diagram of the hydropower plant



greatly impacted by variations in river flow and timing, even though many factors in the power equation are typically constant for a specific hydroelectric plant.

Hydroelectric facilities can be built on rivers, streams, and canals, but dams are required to provide a constant flow of water (Acakpovi et al., 2014; Bongio et al., 2016). Dams store water for later release for agriculture, power generation, and other domestic and commercial applications. The reservoir, which serves as a battery, releases water when it is required to generate energy. Another result of dams is the head or the height at which water flows. Figure 4 shows a typical structure of a hydroelectric power plant and its basic components and damaged runner is shown in figure 8 The principle of hydropower lies in converting the gross head to mechanical and electrical energy, so the available power is directly proportional to the flow rate of water and net hydraulic head (Okot, 2013; Paish, 2002).

$$P_O = \rho g H Q \tag{1}$$

where P_O is the hydraulic power measured in kW, ρ is the water density (kg/m^3), g is the gravitational acceleration (m/s^2), Q is the discharge rate (m^3/s), and H is the head (m). The main components in small hydropower plants are intake, penstock, turbine, and tailrace (see Figure 4). The turbine efficiency η, also called power coefficient, is the ratio of the turbine power output (Pe) to the power of either the water head for traditional design or unconstrained water current (Pi) (see Figure 12).

$$P_O = P_i \tag{2}$$

$$P_e = EI \tag{3}$$

The values from each equation above were processed to verify the correlated system efficiency by the equation as follows:

$$\eta = \frac{P_e}{P_i} = \frac{\rho g H Q}{EI} \tag{4}$$

where E is the voltage (volt, V), I is the current (Ampere, A), and P_e is the electrical power (Watts, W) (Sritram and Suntivarakorn, 2021). Hydropower is one of the oldest and largest renewable energy sources and uses the natural flow of tap water to generate electricity, and its location on the map of Rwanda is shown in Figure 5.

4. Data analysis

In order to produce electricity, water is either trapped in a dam (after being released from a potential head, it runs on a turbine) or flows via the Archimedes spiral. Hydropower plants strongly depend on the availability of water (rainfall) (Figure 6). Climate change's consequences have the potential to alter weather patterns, resulting in both floods and droughts. Water shortages in dams or rivers during a drought will lower the power generation capacity of power plants, making it impossible for utilities to meet demand for electricity (power shortage). Utility companies rely on diesel power stations in these situations, particularly during the summer, but these facilities have very high variable costs because diesel fuel is expensive.

Figure 5
Location of hydropower plants in Rwanda

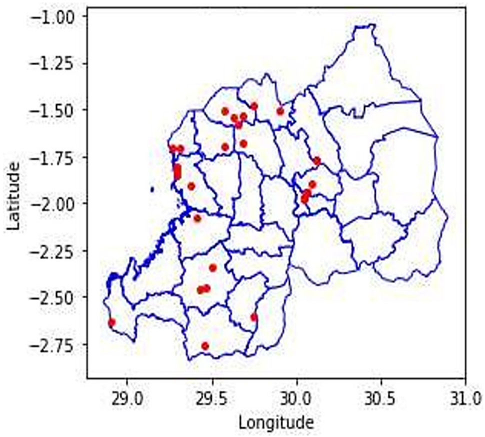


Figure 6
Impact of heavy rain on hydropower plant

Figure 7
Impact of long dry season on hydropower plant

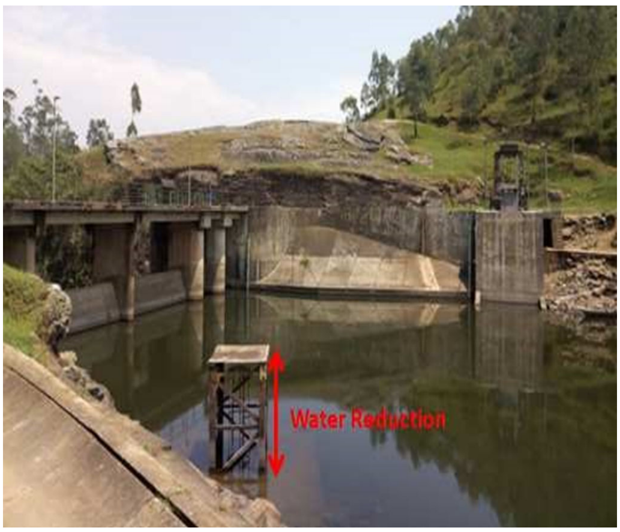


Figure 8
Runner

As a result, even though consumer purchasing power has not changed, the price of electricity will increase as a result. Flooding of dams and rivers during severe weather events, such as torrential rain, may devastate the environment, perhaps inflict extensive damage on infrastructure, worsen agricultural production, and generate food shortages. In addition, heavy rains have also reduced the capacity of the dam and the power output of the power station because of the significant amount of debris and sludge that has accumulated in the dam over time from erosion and industrial processes, water treatment, wastewater treatment, or on-site sanitation systems. The accuracy of utility power generation estimates can also be impacted by unexpected and unanticipated weather changes, which could lead to the need for greater spinning reserves to keep the balance between power generation and demand stable. A hydropower plant's capacity to generate energy is influenced by two things: the length of the water's fall. The waterfall comes next; the stronger it is. The size of the dam affects how far the water falls. Turbines are propelled by the kinetic energy of the water as it travels through the dam. The turbine's mechanical energy is transformed into electrical energy via the generator (Conner et al., 1998; Gulliver and Arndt 1991; Hall et al., 2002). After that, several transmission procedures are used to get the electrical energy to the customer or consumer.

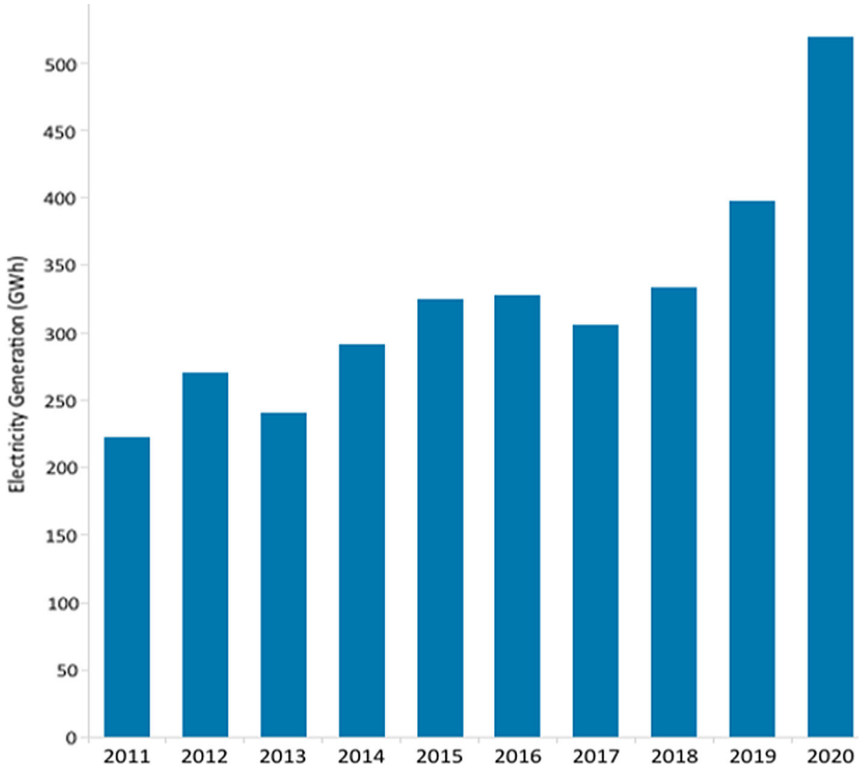
In Rwanda, most hydroelectric plants generate electricity by building dams on high-flowing rivers. The dam reduces the normal flow rate of the river, and sediment (refer to Figure 6) normally carried downstream by the water is instead deposited in the reservoir. Eventually, the sediment would lengthen the penstock, rendering the dam unusable for generating electricity. When rivers were originally dammed, farmland was sometimes flooded, and entire populations and wildlife were displaced by the rising water behind the dam. Reduced flow downstream from dams can also negatively impact human and wildlife populations living downstream. Hydropower is also a clean energy source, and even the initial construction and maintenance costs are relatively cheap in the long run.

Hydropower generation has also been significantly impacted by an increase in extreme weather occurrences and increased erosion CITE (International Renewable Energy Agency (IRENA, 2020)). Global water cycles become more intense as a result of increasing

Table 1
Main operational of hydropower plant generations in Rwanda

Power plant	Installed capacity (MW)	Available capacity (MW)	Year of completed	Types	River
Ntaruka	11.25	9	1959	Runoff	Mukungwa River
Mukungwa I	12	12	1982	Runoff	Mukungwa River
Mukungwa II	3.6	1.8	2013	Runoff	Mukungwa River
Nyabarongo I	28	28	2014	Runoff	Nyabarongo River
Rukarara	9.5	8	2010	Runoff	Rukarara River
Rusizi I	30	21	1958	Runoff	Rusizi River
Rusizi II	44	23	1989	Runoff	Rusizi River

Figure 9
Evolution of electricity generation from hydropower plant in Rwanda



temperatures; typically, dry areas become drier and wet areas become wetter. Economic growth and improved flood protection are the key social benefits, while relocation, detrimental effects on human health, and changes in means of subsistence are the main social drawbacks. Power generation and demand are predicted to be significantly impacted by climate change, with hydroelectric plants projected to be the hardest effected. Researchers in this area create projections for changes in precipitation, water availability, and hydroelectric power production on a national scale per Table 1 (Da Rosa 2005; Gaudard et al., 2013).

5. Research findings

According to Figure 5, the northern, southern, and western provinces of the nation have good hydropower potential. Another method of producing electricity without producing greenhouse gases is hydroelectric power and evolution of electricity generation is show in figure 9 (Levy et al., 1999). It may also result in hazards to the environment and to society, including habitat loss, restrictions on leakage, restrictions on reservoir levels, seasonal water flows, issues with water quality, and river consequences. Hydropower declines by 30% during the dry season and is replaced with diesel power at a greater price (Figure 11). Rainfall is necessary for hydropower to provide a steady stream of electricity. Water levels in dams and reservoirs must be sufficient to run the electricity-generating turbines (Figure 10). Tap water is being impacted by climate change in a number of ways, including temperature, sediment load, volume and timing, and ecosystem changes.

Changes in temperature, precipitation patterns, floods, and droughts are among the early warning signs of climate change. These events have a considerable impact on river systems and, in turn, hydroelectric power generation. The findings demonstrate that weather variations can considerably change the runoff flow regime, which may have long-term consequences for hydropower potential. Planning local water resource management in many

Figure 10
Load balance during the rainy season

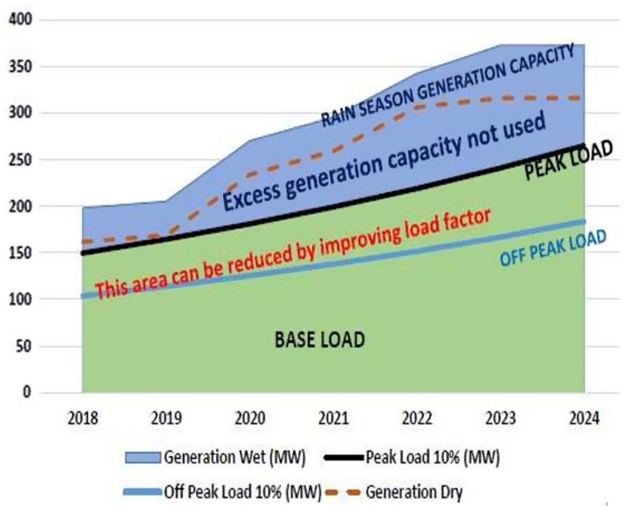


Figure 11
Load balance during the dry season

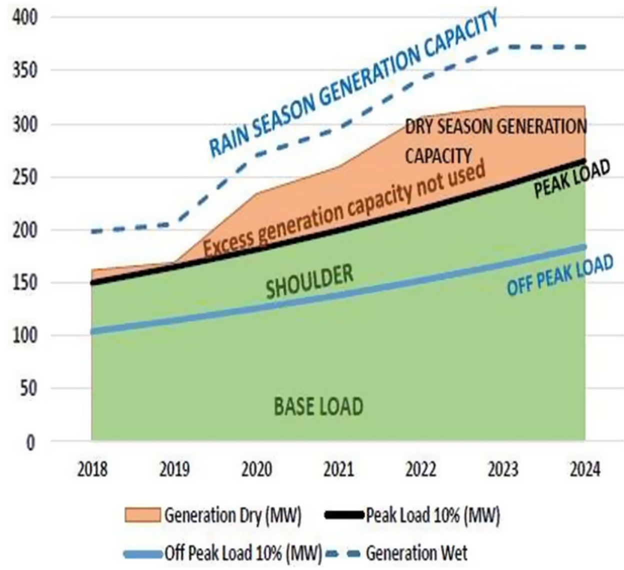
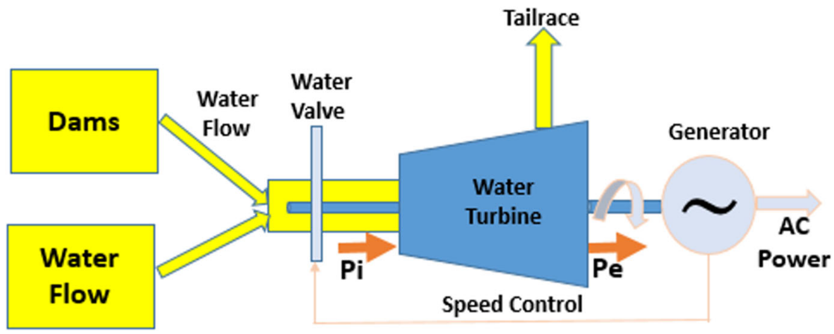


Figure 12
Hydropower generation and sources



sectors of the study region can take into account water resources, especially irrigation, agriculture, and hydropower.

Precipitation and hydropower generally go hand in hand. Power generation rises when precipitation increases, and it declines when precipitation is infrequent or absent for an extended period of time. Less water enters the reservoir during dry periods when there is less rain and snowfall. The amount of hydropower generated is decreased since the reservoir is low and little water is released. Flooding, overflowing rivers, and standing water are all possible effects of heavy rain. Evacuations, power outages, supply shortages, traffic jams and road closures, infrastructure damage, and debris can all result from these catastrophes.

Due to existing (operating) and planned hydropower in Rwanda, dams and reservoirs will always be located in areas at high risk of flooding due to climate change. Therefore, regional variations in precipitation/rainfall, temperature fluctuations, water availability, and slope have a negative impact on hydropower generation. Government agents and private energy companies need to understand how climate change will continue to affect hydropower and how to adapt hydropower generation to extended drought conditions and they should adjust their priorities to find ways to develop energy while minimizing environmental impact with proper planning.

Characteristics of run-of-river hydropower plants in Rwanda: Run-of-river refers to assets that do not rely on submerging large areas of land to form dams. Instead, a constant source of water may come from upstream natural lakes and reservoirs. Water from a fast-flowing river or stream is diverted by a turbine that drives an electrical generator, usually a bucket wheel as we can see in Figure 12. Where the water column must not be higher than zero, the turbine converts the kinetic energy of the flowing water into rotational energy for the turbine and generator. Therefore, the energy depends on the amount of water flowing through the turbine and the square of its velocity.

Reduced water flow during dry seasons has a major impact on hydropower because of limited water availability and lack of storage to keep power plants running during dry seasons. Heavy rains cause landslides, floods, droughts, and diversion of water around turbines and dams, which can lose the potential power generation capacity of increased water flow. There were also some power outage issues during this time.

6. Conclusion

The only renewable energy source that makes a significant contribution to Rwanda's overall energy mix is hydropower.

It also produces the fewest greenhouse gases, making it the most reliable source of renewable energy. Efforts must be intensified to diversify the country's energy resources. Environmental and social impact studies should always be carried out before the construction of a hydropower projects in order to identify and reduce the negative impacts of the project. Finally, Rwanda has enormous potential for climate change mitigation through hydropower projects. Hydropower development should be considered sustainable, technically and commercially attractive and socially and environmentally friendly as it uses water resources and is a mature technology, as it uses water resources and is a well-established technology.

Overall, climate change is expected to have little impact on clean water storage and a slightly more negative impacts on run-of-river hydroelectric facilities. Hydropower generation will continue to be affected by the changes in river flows and flows due to climate change. As shown in Figure 7, the operating capacity of hydropower plants is limited by the upstream water level, and availability decreases significantly during the dry season. The current installed capacity of the power plant (238.36 MW) will not produce electricity continuously at its maximum power. Researchers should continue to study this topic and use optimization/simulation models of hydropower systems in their future work.

A well-established technology that contributes significantly to the country's electricity production is hydroelectricity. Weather variability can be critical when determining how to adapt to climate change related to water availability. However, the significant environmental, economic, and social impacts of hydroelectricity must be carefully considered. Rivers, lakes, and water availability are significantly affected during the dry season. Floods, droughts, soil, sand, and sediment loads are important indicators that hydropower is being negatively affected, as well as observation of dams/reservoirs showing signs of reduced water volume, which is also affected by hydropower, there will often be electricity due to lack of flow and hydroelectricity generation will increase significantly during the rainy season.

In Rwanda, some hydropower plants are located upstream of rivers and lakes, helping to regulate large fluctuations in water flow. By increasing water flow during the dry months, the power plant generates electricity that helps improve aquatic habitats. Instead, by reducing the flow during periods of high runoff, the plants prevent damage to vegetation and wildlife along the riverbanks. Hydropower also presents environmental and social challenges. Reservoirs significantly alter the terrain and waterways in which they are found. Dams and reservoirs can damage pleasant water sources, reduce river waves, hot water, and silt buildup. It has adverse effects on fish, birds, and other wildlife.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

References

Acakpovi, A., Hagan, E. B., & Fifatin, F. X. (2014). Review of hydropower plant models. *International Journal of Computers and Applications, 108*(18), 33–38. https: doi/org/ 10.5120/19014-0541

Bongio, M., Avanzi, F., & De Michele, C. (2016). Hydroelectric power generation in an Alpine basin: future water-energy scenarios in a run-of-the-river plant. *Advances in Water Resources*, *94*, 318–331. https://doi.org/10.1016/j.advwatres.2016.05.017

Conner, A. M., Francfort, J. E., & Rinehart, B. N. U.S. (1998) Hydropower resource assessment final report. https://doi.org/10.2172/771504

Da Rosa, Aldo Vieira, (2005). *Fundamentals of Renewable Energy Processes*. USA. Academic Press.

Gaudard, L., Gilli, M., & Romerio, F. (2013). Climate change impacts on hydropower management. *Water Resource and Management, 27*, 5143–5156. https://doi.org/10.1007/s11269-013-0458-1

Gaudard, L., Avanzi, F., & De Michele, C. (2018). Seasonal aspects of the energy-water nexus: The case of a run-of-the-river hydropower plant. *Applied Energy*, *210*, 604–612. https://doi.org/10.1016/j.apenergy.2017.02.003

Gaudard, L., Romerio, F., Dalla Valle, F., Gorret, R., Maran, S., Ravazzani, G., . . . , & Volonterio, M. (2014). Climate change impacts on hydropower in the Swiss and Italian Alps. *Science of the Total Environment, 493,* 1211–1221. https://doi.org/10.1016/j.scitotenv.2013.10.012

Gulliver, J. S., & Arndt, R. E. A. (eds.). (1991). *Hydropower Engineering Handbook.* USA. McGraw-Hill, Inc.

Hall, D. G., Carroll, G. R., Cherry, S. J., Lee, R. D., & Sommers, G. L. (2002). Low head/low power hydropower resources assessment of the arkansas white red hydrologic region. DOE/ID-11019.

Hamududu, B., & Killingtveit, A. (2012). Assessing climate change impacts on global hydropower. *Energies, 5*(2), 305–322. https://doi.org/10.3390/en5020305

International Energy Agency. (2012). Key world energy statistics 2017. https://doi.org/10.1787/key_energ_stat-2017-en

International Renewable Energy Agency. (2020). Hydropower data. Retrieved from: https://www.irena.org/Energy-Transition/Technology/Hydropower

Fan, J. L., Hu, J. W., Zhang, X., Kong, L. S., Li, F., & Mi, Z. (2020). Impacts of climate change on hydropower generation in China. *Mathematics and Computers in Simulation, 167*, 4–18. https://doi.org/10.1016/j.matcom.2018.01.002

Kseniia, M., Enock, M., & John, K. (2015). Effect of climate change on crop production in Rwanda. *Earth Sciences*, *4*(3), 120–128. https://doi.org/10.11648/j.earth.20150403.15

Levy, J.I., Hammitt, J.K., Yanagisawa, Y., & Spengler, J.D. (1999). Development of a new damage function model for power plants: Methodology and applications. *Environmental Science and Technology*, *33*(24), 4364–4372. https://doi.org/10.1021/es990634+

MININFRA. (2018). *Energy Sector Strategic Plan 2018/19–2023/24*. Ministry of Infrastructure. Retrieved from: http://www.reg.rw/fileadmin/user_upload/Final_ESSP.pdf

Ministry of Foreign Affairs. (2018). Climate change profile Rwanda. Government of the Netherlands. Retrieved from: https://reliefweb.int/report/rwanda/climate-change-profile-rwanda.

Okot, D. K. (2013). Review of small hydropower technology. *Renewable and Sustainable Energy Reviews*, *26*, 515–520. https://doi.org/10.1016/j.rser.2013.05.006

Paish, O. (2002). Small hydro power: technology and current status. *Renewable and Sustainable Energy Reviews, 6*3(6), 537–556. https://doi.org/10.1016/S1364-0321(02)00006-0

Rwanda Energy Group. (2021). *Facts & Figures details*. Retrieved from: https://www.reg.rw/facts-figures/facts-figures-details/facts/installed-generation-capacity-on-the-nationalgrid/

Rwanda Energy Group. (2022). *Facts & Figures details*. Retrieved from: https://www.reg.rw/facts-figures/facts-figures-details/facts/installed-generation-capacity-on-the-nationalgrid/

Rwanda Environment Management Authority. (2023). *Facts about climate change in Rwanda*. Retrieved from: https://climateportal.rema.gov.rw/index.php?id=2#:~:text=Rainfall%20Fluctuations,the%20northern%20and%20western%20provinces

Solaun, K., & Cerdá, E. (2017). The impact of climate change on the generation of hydroelectric power—a case study in Southern Spain. *Energies, 10*(9), 1343. https://doi.org/10.3390/en10091343

Sritram, P., & Suntivarakorn, R. (2021). The efficiency comparison of hydro turbines for micro power plant from free vortex. *Energies, 14*(23), 7961. https://doi.org/10.3390/en14237961

Wagner, T., Themeßl, M., Schüppel, A., Gobiet, A., Stigler, H., & Birk, S. (2017). Impacts of climate change on stream flow and hydro power generation in the Alpine region. *Environmental Earth Sciences, 76,* 1–22. https://doi.org/10.1007/s12665-016-6318-6

How to Cite: Eustache, H., Garba Wali, U., & Venant, K. (2023). Understanding the Potential Impact of Climate Change on Hydropower Generation in Rwanda. *Green and Low-Carbon Economy* 1(3), 138–146, https://doi.org/10.47852/bonviewGLCE3202762