UNIVERSITY of RWANDA COLLEGE OF SCIENCE AND TECHNOLOGY ACE-ESD AFRICAN CENTER OF EXCELLENCE IN ENERGY FOR SUSTAINABLE DEVELOPMENT

TECHNICAL FEASIBILITY STUDY OF A GRID CONNECTED PUMPED STORAGE HYDROPOWER PLANT ON LAKE LIVU

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By

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in

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KIGALI-RWANDA

DECLARATION

I, the undersigned declare that this dissertation work is my original work and has not been presented or submitted for a degree in University of Rwanda or any other universities. All sources of materials which have been used for the thesis work have been fully acknowledge.

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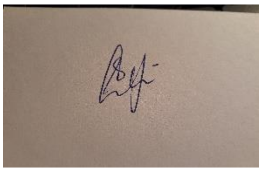
APPROVAL

Date of submission: 4th November 2021

This thesis work has been submitted for examination with my approval as a university advisor.



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ABSTRACT

Electrical energy and the other forms of energy in general play an important role in the global economy and the significant portion of global energy demand is met by burning fossil fuels which are non-renewable and with limited lifespan. To gradually decouple the economic development from non-renewable energy sources and to address climate change issues, exploring more renewable energy alternatives is widely encouraged. Rwanda has the plan of increasing the generation of electric power from renewable energy through solar power plants. One of the difficulties the electrical industry is facing currently is the production and efficiency utilization of energy. Energy management means production of energy and efficiency utilization of energy and finally storing the energy for future use. Due to environmental issues, the entire world is encouraged to develop different renewable energy technologies in electrical power generation to save the planet. On Rwanda national electric grid, different renewable energy generations are connected where solar energy generation (intermittent) is among them. The energy on Rwanda national electric grid can be managed well by bringing in an efficiency, reliable and environmentally friendly storage system. A very well-known worldwide energy storage technology is chemical battery. Chemical batteries are technically suited to be used with small scale distributed renewables and the main problem of that technology is the short life which is equivalent to 3 to 5 years when daily used. However, due to the intermittency of solar energy, short life span of chemical batteries and its environmental issues, pumped hydroelectric energy storage technology has been found advantageous to Rwandan electric network. During this thesis work, the study and analysis of power generation and load demand on the Rwandan network have been done to know the availability of renewable energy which needs to be stored during light loads and released during peak loads hours. As per the study, there are 204 MWh which can be stored on daily basis. After concluding that Rwandan electric network has renewable energies to be stored during light loads, the survey around Lake Kivu on Rwandan side to find out the candidate places suited for pumped hydroelectric energy storage have been carried out where one site among five candidate sites has been selected as the best-suited place. Then, 36 MW pumped hydropower plant has been designed and its operational economic feasibility study has been also done. Simulation with MATLAB/Simulink has been carried. The study results show that currently having the storage system will remove completely 27.6% of diesel power generation on Rwandan electric network. Moreover, the studies confirmed better operability of the system with a round trip efficiency of 81%.

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LIST OF ABREVIATIONS

PHES: Pumped hydroelectric Energy Storage

EPRI: Electric Power Research Institute

MW: Megawatt

GW: Gigawatt

IHA: International hydropower association

hp: Horse power

ONEE: National office of electricity and drinking water, Morocco

CAES: Compressed air energy storage

IZ: Intermediate resource zone

PRZ: Potential resource zone

URZ: Upper resource zone

LRZ: Lower resource zone

Pa: Pascal

S: Second

Q: Volumetric flow rate of water

KWh: Kilowatt hour

PV: Photo voltaic

RDC: Democratic Republic of Congo

Km: Kilo meter

REG: Rwanda Energy Group

MWh: Megawatt hour

P_P: Rated power of pump

Q_P: Rated flow rate

η_P: Pump efficiency

g: Gravitational acceleration

ρ: Water density

h: Head

V_R: Upper dam volume

T: Rated pumping time in seconds

η: Round trip efficiency of storage system

η_p: efficiency of the pump

η_g: Efficiency of the generator

A: penstock cross section area

v: Water velocity in the pipe

D: diameter of penstock

L: Pipe/Penstock length

e_m: Energy per unit mass

e_v: Energy per unit volume

E_t: Total energy

RURA: Rwanda utilities regulation authority

RWF: Rwandan franc

CHAPTER1. INTRODUCTION

1.1 General introduction

Renewable energy sources such as solar, biomass, geothermal, hydro, tidal, and wind generate electricity in the electrical power industry. Solar energy is the most well-known renewable energy source on the planet [1]. Energy management has been a problem for the electrical sector since humans began to use various types of energy for their comfort and necessities. Energy management refers to the process of producing energy, utilizing it efficiently, and then storing it for future use. By incorporating correct storage systems, the energy can be properly utilized. Because electrical energy is so crucial to the development of the economy, it must be properly stored and managed. This could be done to serve many grid needs to overcome the gap between available generation and load demand[2]. The chemical battery is the most well-known man-made energy storage technology in today's world, and it is used to store electricity from solar photovoltaic systems in locations where the grid is not available to back up solar output. Chemical batteries are electrochemical energy storage systems that, when charged and discharged at modest rates, can be relatively efficient (70-80%).

Batteries are more technically viable for use with small scale distributed renewables since they are modular. The main challenges with battery technology are their short life (1000s of cycles, or 3-5 years in everyday usage) and their high capital costs ($100-200/kWh of storage capacity. Furthermore, in the context of significant greenhouse gas reductions, the sheer volume of raw material required for batteries (billions of tonnes) would certainly exceed known reserves of common battery materials (lead, nickel, and cadmium), driving up battery costs even more. To reduce disposal concerns and environmental implications, such large volumes of battery materials may need to be recycled nearly indefinitely[3].

Pumped hydroelectric energy storage (PHES) has been in use for over 70 years all over the world and it is the most widely used energy storage technology nowadays in large-scale energy storage installations[4]. Pumped storage is the world's largest kind of grid energy storage, with the Electric Power Research Institute (EPRI) reporting that PHES accounts for more than 99 percent of global bulk storage capacity, or roughly 127,000 MW, as of March 2012. In actuality, the round-trip energy efficiency of PHES varies between 70% and 80%, with some claiming as high as 87 percent[5].

1.2 Background

Pumped hydro energy storage (PHES) has been utilized for utility-scale electricity storage since the 1890s and is a well-established and economically accepted technology. Hydropower is not only a renewable and sustainable energy source, but it also adds flexibility and storage capacity to the grid, allowing for the development of other intermittent renewable energy sources like wind and solar. The Rwandan electric system currently consists of 132.778 MW (55.703%) renewable energy and 103.590 MW (43.458%) non-renewable electricity. 12.230 MW of the 132.778 MW of renewable energy comes from five solar power facilities with no storage devices. The storage system is required to store electrical energy during light loads and release it during heavy loads, as the Rwandan government plans to increase the number of solar power plants to cut production costs and take advantage of Rwanda's existing renewable resources According to national daily load curves of Rwandan electric network, the connected load is less than the total installed renewable energy capacity during light loads, and during heavy loads, non-renewable energy power plants, such as diesel and heavy fuel power plants, are operating, emitting hazardous pollutants. Due to the aforementioned disadvantages, a pumped-storage hydroelectricity station is required to make Rwanda's electrical grid more stable and efficient, as well as to reduce greenhouse gas emissions.

1.3 Statement of the problem

Rwanda’s electricity generation connected to the grid is composed by 55.703% of renewable energy and 43.458% of non-renewable energy. Five solar power plants with no storage systems generate 12.230 MW, accounting for 55.703 percent of renewable energy. The storage system is required to store electrical energy during light loads and release it during heavy loads, as the Rwandan government plans to increase the number of solar power plants to cut production costs and take advantage of Rwanda's existing renewable resources. Pumped hydroelectricity energy storage power plants have proven to be the most cost-effective form of energy storage. They provide cutting-edge technology with low risks, low operating costs, and the ability to balance grid variations due to their great operational flexibility, enabling for the successful integration of intermittent renewable energy sources. As a result, they make a substantial contribution toward a sustainable energy future. A grid-connected pumped storage hydropower power facility on Lake Kivu will improve power availability at short notice when needed, minimizing power shortages and facilitating the successful integration of intermittent renewable energy into

Rwanda's electrical grid. Having such a storage system will also aid in the removal of diesel power plants from Rwanda's electric grid.

1.4 Objectives

1.4.1 Major objective

The feasibility of having pumped storage hydropower power plant on lake Kivu with possible integration of intermittent renewable power on Rwanda's electrical grid will be studied.

1.4.2 Specific objectives

a. Study and analysis of Rwanda electric network
b. Collect data related to lake Kivu and mountains around the lake on the side of Rwanda and then the data will be studied.
c. Choosing the ideal location for a pumped storage hydropower plant
d. Pumped storage hydropower plant design.
e. Model and simulate the system using MATLAB Simulink software to validate the improvement by integrating the identified technology.
f. Draw relevant conclusions and recommendations

1.5 Scope of the research

The research will be carried out on technical feasibility study of pumped storage Hydropower power plant on Lake Kivu. Internal structure of lake Kivu, the structure of electrical energy sources connected to Rwanda electrical grid and mountains around the lake on Rwanda side will be studied. Selection of different suitable sites on PHES and the design of PHES on the most suitable site will be done.

1.6 The study's expected outcome and significancy

1.6.1 The study's expected outcome

The outcome of this study is to obtain a research report that highlights the possibility of having a pumped storage hydropower plant on Lake Kivu.

1.6.2 Significant of the study

This study will contribute its part in making Rwandan electrical grid more stable, more efficient and environment friendly. In addition to the above, having a grid connected pumped storage hydropower power plant on lake Kivu will enhance the power availability at short notice when needed, avoiding power shortages and allowing the successful integration of intermittent renewable power on Rwanda's electrical grid.

CHAPTER2. LITERATURE REVIEW

2.1 Introduction to pumped hydroelectric energy storage system

Pumped hydroelectric energy storage is a proven technique with a long storage time and good efficiency. Pumped hydroelectric energy storage has been around for over 70 years and is a safe and efficient way to store energy. The pumped hydroelectricity energy storage technology operates on the same principles as hydroelectric power. A producing unit plus a storage unit make up a pumped hydroelectric energy storage system. The system comprises of two reservoirs that are connected by a conduit. The power and energy rating of the system is controlled by the height difference between the reservoirs[1]. Pumped hydropower storage systems have the ability to produce significant amounts of electricity over long periods of time. Furthermore, these plants have round trip efficiencies ranging from 70 to 80 percent. Their storage capacity is solely determined by the reservoir's size. As a result, instead of a few hours of energy storage, days may be required. Surplus power is utilized to pump and store water in the high reservoir during off-peak hours, while water is released from the high reservoir to the low reservoir during peak demand hours, turning the turbine to produce energy[2]. Currently, there is no related study “Pumped storage hydropower plant “carried out on the Rwandan electrical network.

2.2 World’s usage of pumped hydropower storage facilities

Hydropower is responsible for more than 95% of the world’s energy storage capacity. Pumped hydropower storage is viewed as a facilitator of variable renewable energy sources like wind and solar power since it absorbs excess electricity and supplies it when needed. The hydropower pumped storage tracking tool, which maps the locations and information for existing and future pumped storage projects, was launched in November 2017 by IHA (International Hydropower Association)[5]. 3.2 GW of hydroelectric pumped storage capacity was added globally in 2017, bringing the total pumped storage capacity to 153 GW. More than 100 pumped storage hydropower projects with a total capacity of 75 GW are in the works. By 20230, these projects will have increased world storage capacity by 50% reaching over 225 GW[3]. The global map in figure2.1 below depicts all operational, under construction, and proposed pumped hydro storages around the world.

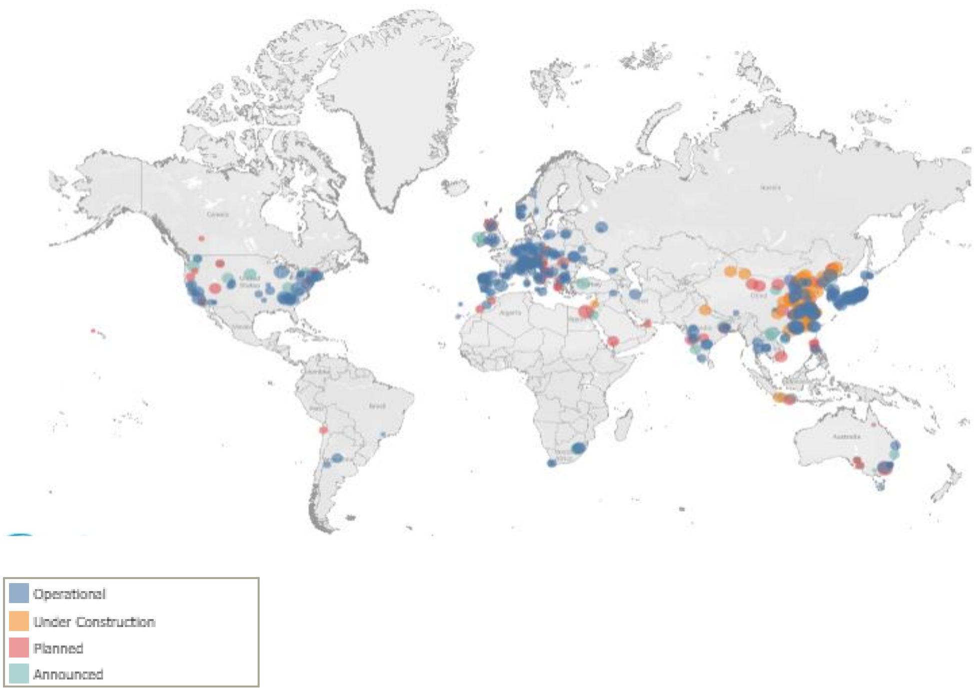


Figure2. 1: All worldwide operational, under construction and proposed PHES plants map [5]

2.3 Pumped hydropower storage plants in Africa and its development

Egypt, Morocco, and South Africa are the African countries having the most pumped hydropower storage plants. Attaqa Mountain pumped storage station in Suez, Egypt, is a 2.4 GW hydroelectric power project in the works. A $2,7 billion investment is expected to be made in the project. It will be Egypt's first power plant to generate energy utilizing water storage and pumping during peak hours, with a completion date of 2024[6].

Morocco has four pumped storage facilities, one of which is operational and the other three are in the planning stages. The Afouer pumped storage station is a pumped storage hydroelectric project in Marocco's Azzilal Province, located in the hills above Afouer. The project has two power plants with a total installed capacity of 465 MW. The project's construction began in 2001 and ended in 2004. It cost US$220 million and was supported by the Arab fund for economic and social development[7]. The second project is the Abdelmoumen pumped hydropower storage plant in Morocco, which is now under construction and will be connected to the national power grid to help handle demand spikes. With a capacity of 350 MW, it is expected to be finished in April 2022[8]. The project will strengthen the national electrical grid in the south and deliver with yearly efficiency of 76%. [9]. In 2017, ONEE (Morocco's National office of electricity and drinking water) announced the building of two more new pumped storage stations with a combined capacity of 600 MW. The first, EI Menzel II, will be erected in the upper Sebou, while the second, Ifasha, will be developed on the right bank of the Oued Laou. Each of these plants will have a 300 MW installed capacity. Ifasha is expected to be finished in 2025[5].

The total installed capacity of big pumped storage schemes in South Africa is currently around 2910 MW. There are now four big storages in operation across the country, with the Steenbras (180 MW) being a municipal asset of the city of Cape Town and three plants owned by Eskom, notably the Drakensberg (1000 MW), Palmeit (400 MW), and the new Ingula (1330 MW)[10].

2.4 Storing energy in potential energy form

Energy can be stored in the form of potential energy by raising a mass m to a height h and the stored energy can be calculated as per the equation (2.1)

$$E = mgh \tag{2.1}$$

Where g=9.81m/s^2 is gravitational acceleration

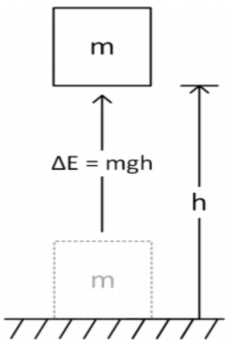


Figure2. 2: Potential energy explanation diagram **[10]**

If we allow the mass to fall back to its original height, we can capture the stored potential energy as follows: Potential energy is converted to kinetic energy as the mass falls, then kinetic energy can be captured to perform work. The same energy will be transformed to rotational energy and then to electrical energy.

2.5 Fundamentals working principles pumped hydropower storage energy system

The system has two reservoirs which are upper and lower reservoirs. A river or even the sea or lake can serve as lower reservoir. The two reservoirs are separated by h height where it is assumes h>>depth of upper reservoir and remains constant throughout charge/discharge cycles. The upper reservoir can store a volume of water (Vu).

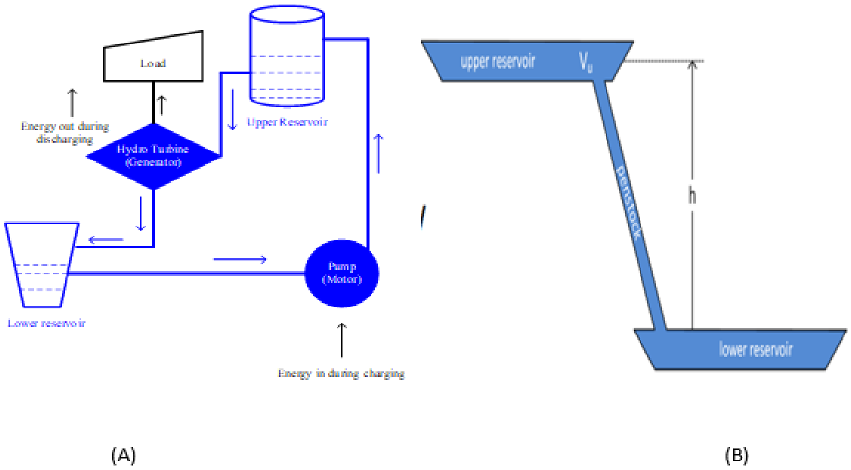


Figure2. 3: Fundamental working principal diagram

2.6 Components of a pumped hydropower storage plant

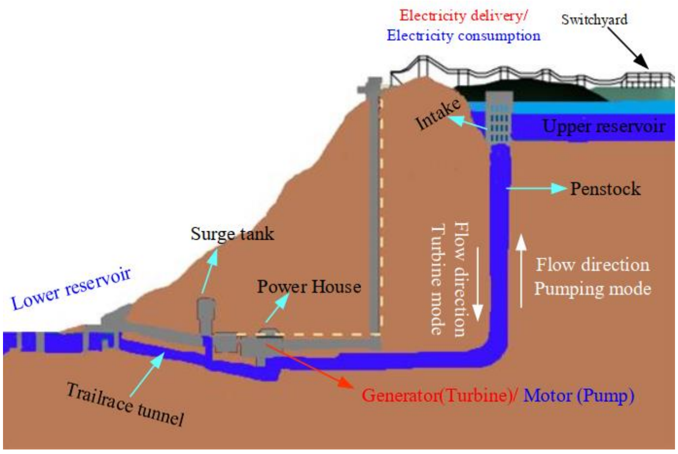


Figure2. 4: Parts of pumped hydropower storage plant

♦**Penstock:** It is a conduit connecting upper and lower dams**.**

♦**Turbine/pump:** During the generation phase, turbines are utilized to convert hydraulic energy into mechanical energy. The unit functions as a pump in pumping mode. This is done through a reversible turbine or by different turbine and pump according to the adopted configuration.

♦**Generator/Motor:** During generation mode, generator converts mechanical energy into electrical energy. Motor converts electrical energy into mechanical energy during pumping mode.

♦**Tailrace tunnel:** It is a conduit that conveys water away from the turbine after high pressure water has worked on the turbine, and the water re-enters the lower dam.

♦**Surge tank:** It is an accumulator tank that absorbs high pressure transients during start up and mode switching. It is especially significant for longer tunnels and can be found on the penstock or tailrace.

♦**Powerhouse:** The building that holds the turbines and generators and into which penstocks feed them.

Configurations of PHES system

Four units (quaternary set): Pump, turbine, motor and generator are all distinct components. A turbine connected to a generator and a separate pump connected to a motor.

Three units (ternary set): This is a configuration with a single pump, a single turbine and a single motor/generator. A single reversible motor/generator drives both a pump and a turbine.

Two units (binary set): This is a configuration with one motor/generator and one pump/turbine units. A reversible motor/generator is connected to a reversible pump/turbine. In comparison to the other two, this layout takes up less room and costs less to install[11].

2.6.1 Classification of turbines

Turbines are used to transform hydraulic energy into mechanical energy, and as they are needed to produce electricity, they are one the key components to be employed to contribute to creation of power. They are divided into the following categories:

- ✓ Francis turbine
- ✓ Kaplan turbine
- ✓ Pelton turbine

Francis turbine is well-suited to medium-head and medium-discharge applications. It can be found in large quantities all around the globe. It is usually used at head ranges of 20 to 750 meters, with power levels ranging from 0.25 to 800 MW per unit.

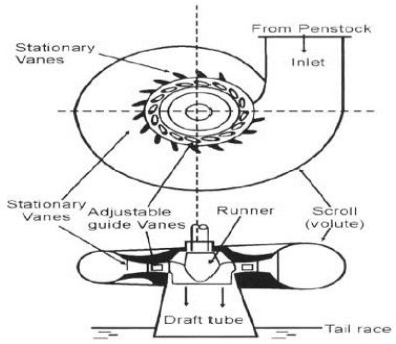


Figure2. 5: Francis turbine [7]

The Kaplan turbine is essentially an adjustable blade turbine within the tube. It is an axial-flow turbine, which ensures that the direction of the flow does not change as it passes the rotor.

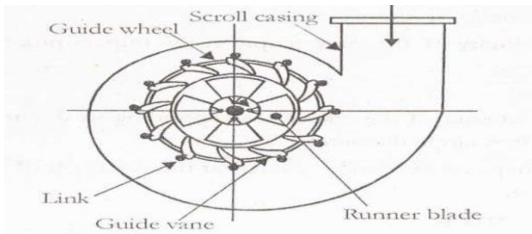


Figure2. 6: Kaplan turbine [7]

Pelton is a high head turbine, which gets its water from a high head via a long pipe known as a penstock. The water is accelerated in the pipe, and the head is converted to velocity, resulting in high-speed discharge. Its head can range up to 1000 meters as it can be found in figure2.8.

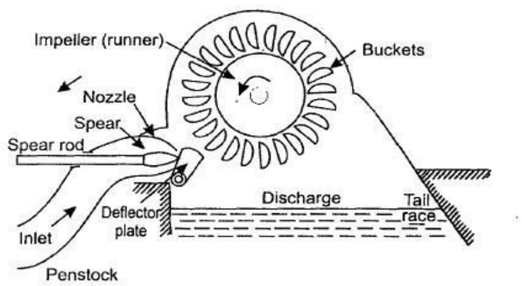


Figure2. 7: Pelton turbine [7]

Table2. 1: Types of turbines and related head [11].

Head	Head range in meters	Suitable turbine	Notes
Very low	3-10	Bulb	Kaplan turbines are also suitable but uneconomical for very low head
Low	10-60	Kaplan	Propeller turbines are also suitable up to 15 meters but there should not be load variations
Medium	60-150	Francis	_
High	150-350	Pelton or Francis	One of them is selected based on the speed
Ver high	>>350	Pelton	_

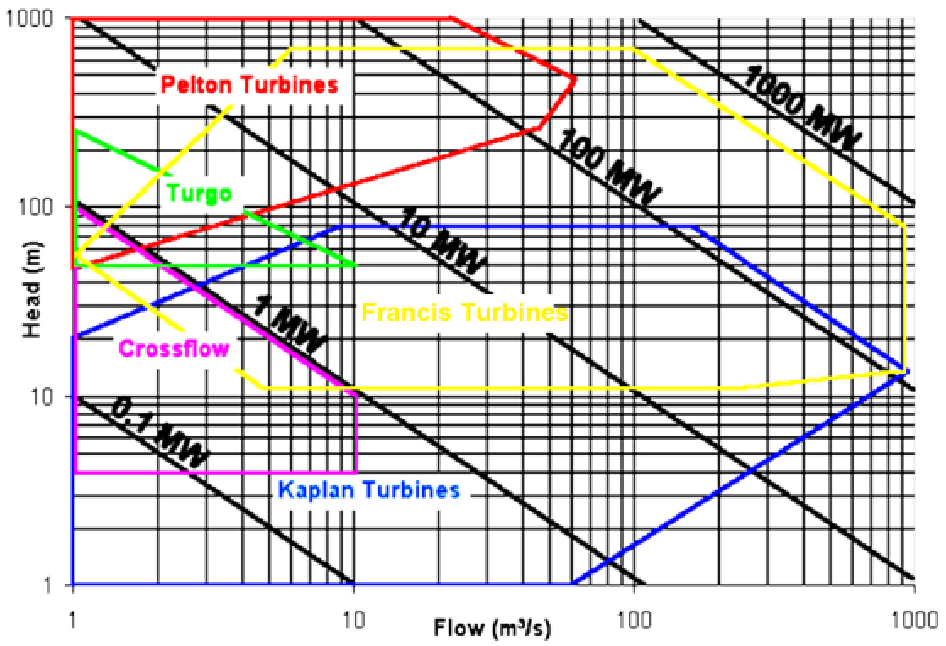


Figure2. 8: Power capacity P (MW) of the main hydraulic turbines with head (m) [11].

2.7 The advantages of pumped hydropower energy storage systems

Some of advantages of pumped hydropower energy storage are: more than a century of experience into operation, high efficiency (70 to 85 percent), multipurpose facilities, quick response to load variation, reserve capacity, highest availability compared to other technologies, and environmental friendliness[11].

2.8 Application of PHES with renewable energy system

Using hydro-pumped storage system improves the quality of electricity delivered while lowering the peak power of other energy-generating systems. This system smooths out demand variations on the power grid, allowing thermal power plants that generate base load electricity to operate at peak efficiency while minimizing the need for expensive and polluting peaking power plants. A pumped storage system also aids in the regulation of electrical network frequency and provides reserve generation. thermal plants have a substantially lower ability to respond to abrupt fluctuations in electrical demand, which can lead to frequency and voltage instability. within seconds, the hydro-pumped system can adjust to load variations. these machines create in synchrony with the network frequency but as motor pumps can operate asynchronously (independent of the network frequency). Pumped storage is being used for the first time to level the variable output of intermittent power sources. Pumped storage absorbs load during periods of strong output and low demand while also adding peak capacity. I tis projected to become increasingly significant as a balancing for very large-scale photovoltaic power.[11]. Its working principle is illustrated in figure2.9 below.

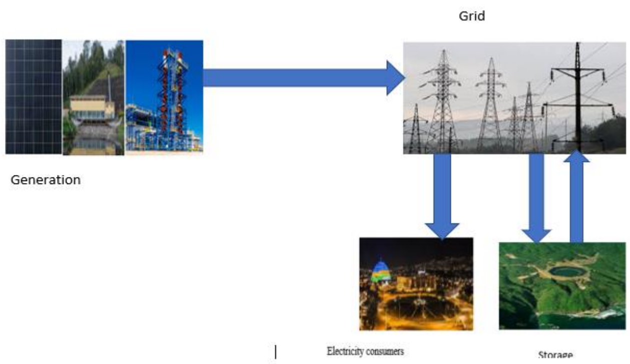


Figure2. 9: Principle of coupling between renewable energy sources and hydro-pumped system

2.9 Rwanda energy mix with intermittent renewable energy

Rwanda's total installed power capacity is around 238.368 MW, with hydropower accounting for 50.6 percent and solar power plants accounting for 12.25 MW[12]. Furthermore, the current average solar radiation for most of the country is around 4.5KWh/m^2 per day, with an average of 8 hours of sunshine per day, making solar energy in Rwanda economically viable. Feasibility studies are currently being conducted with various partners on the development of a 30 MW solar power plant in the Eastern province of Rwanda[12]. Rwanda's government is aiming for universal access to electricity by 2024, supporting the use of renewable energy, namely on-grid and off-grid solar PV systems[12]. With all above, the Rwanda's electrical grid does not have any electrical storage system which is the challenging issue on the grid stability. The following chat shows the Rwanda 's energy mix.

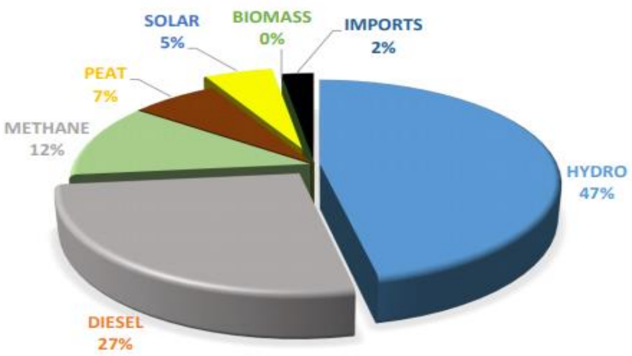


Figure2. 10: Rwanda's Energy Mix [13]

2.10 Introduction to lake kivu

Lake Kivu is a tectonic rift lake in East Africa, located between Rwanda and the Democratic Republic of Congo. It was produced about 1-5 million years ago by volcanic activity. There are around 28 fish species in lake Kivu, half of which are cichlids that are uniquely found in lake Kivu. It is Rwanda's main local fish source, supplying more than 20 000 tons of fish per year. There are around 500 000 people in fishery industry in both Rwanda and the DRC. Also, extraction of methane gas in Lake Kivu is the main activity; the methane as is used to generate electric power and 25MW power plant (Kivuwatt project) is running and 56MW plant (Shema power lake Kivu project) is under construction. Rainfall, numerous minor rivers, and ground water provide the majority of the water input. Evaporation and Rusizi river into Lake Tanganyika are main sources of water losses. Long rainy periods occur from February to May, and short rains occur from October to December. The air temperature near the lake varies between 22 and 24 degrees Celsius. / https://africangreatlakesinform.org/page/lake-kivu

The following are characteristics of the lake:

- Age: ~1 to 5 million years old
- Maximum depth: 485 m
- Surface: 2370 km^2
- Volume: 560km^3

It is located between 1º 30' and 2º 30' S of latitude and 28º 50' and 29º 23' E of longitude with altitude of 1463 m above sea level.

Figure2. 11: Fishing activity in lake Kivu

2.10.1 Structure of lake kivu

Biozone, intermediate zone, potential resource zone, upper resource zone, and lower resource zone are the five principal zones of lake Kivu.

Biozone

This is the oxygen-rich upper section of the lake's water body. It's roughly 60 meters deep, and it is where zooplankton and fish feed. During the dry season, this zone becomes nearly homogeneous, but during the rainy season, it becomes highly stratified, with just the top 40 meters containing oxygen. The biozone's bottom limit is the top of density gradient that runs from 60 to 120 meters deep, with its centre at about 85 meters. The concentration of hydrogen sulphide is zero at the top of the gradient below, whereas methane and carbo dioxide concentration are relatively low, as in the zone. These gases ‘concentrations rise as you go deeper into the resource zone.[15].

Intermediate zone

The intermediate zone extends from around 120 to 180 meters below the surface. A density gradient runs from 180 to 200 meters below it, with the centre at 190 meters. This zone’s methane resources are unlikely to be utilized for decades, if not ever.

Potential resource zone

This zone extends from around 200 meters to roughly 250 meters below the surface. Below it, the lake’s primary density gradient stretches from 250 to 270 meters, with its centre at 260 meters. If methane build-up continues at its current rate or increases more, some of the methane in this zone may become exploitable within the next several decades.

Resource zone

The resource zone, which extends from 270 meters to the lake’s bottom and includes the majority of the commercially usable methane, is located beneath the main density gradient. It also has significant levels of Carbone dioxide, fertilizers, and salts. As a result, the water in the resource zone is substantially denser than the water in the remainder of the lake. A secondary gradient between 300 and 3200 meters depth, with its centre at 310 meters depth, divides the zone into higher and lower resource zones[15]

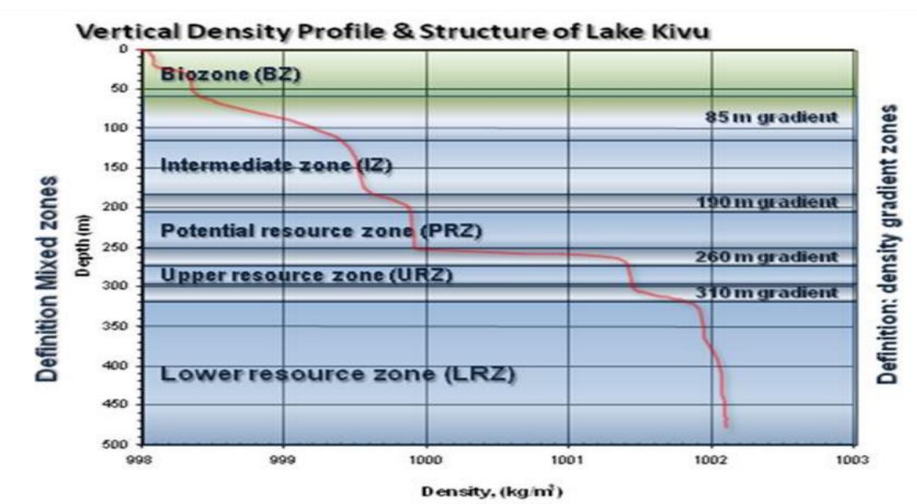


Figure2. 12: Vertical density profile in Lake Kivu (excluding pressure effect) and the associated definition of zones and of density gradients [15]

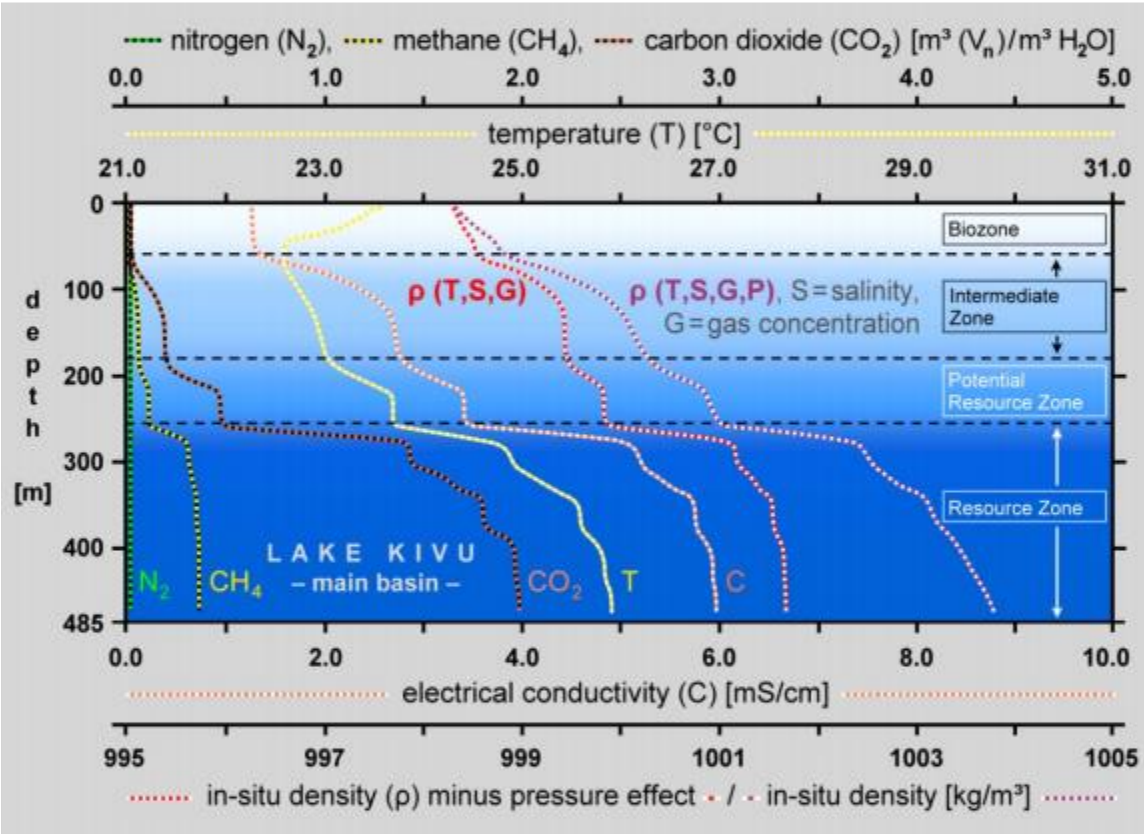


Figure2. 13: Vertical profiles in Lake Kivu of temperature (T); electrical conductivity (C); methane (CH4), carbon dioxide (CO2) and nitrogen (N2) concentrations; and in-situ densities (ρ) (EWG 2008) [15].

2.11 Economic analyisis and comparison of different energy storage technologies

2.11.1 Other types of energy storage technology

Engineers and policymakers are increasingly turning their attention to energy storage options as concerns about the environmental implications of fossil fuels and the capacity and resilience of energy systems around the world rise. Indeed, energy storage can assist alleviate renewable energy's intermittency; it can also, in many situations, respond quickly to major demand swings, making the grid more responsive and decreasing the need for backup power plants. The success of an energy storage facility is defined by its ability to respond fast to changes in demand, the rate of energy loss throughout the storage process, its overall energy storage capacity, and its ability to be recharged quickly[18].

2.11.1.1 Compressed air energy storage

This energy storage technology works by compressing air and storing it in underground caverns using electricity. When needed, the air is released and passed through a turbine, which generates power. Its average power ranges from several kilowatts to a few megawatts [17].

2.11.1.2 Flywheels

A kinetic energy storage system that uses rotor rotating through a virtually frictionless cage to supply short term power through inertia. Its typical output power is in the range of 20 MW.

2.11.1.3 Ultracapacitor

Ultracapacitors store energy in a double layer separated by a dielectric between each electrode and can discharge it instantly. The cycle life is orders of magnitude longer than battery cycle life due to the lack of chemical interaction. Its normal output power ranges between 250 KW and 2 MW.

2.11.1.4 Electrochemical Energy Storage

This technology includes also different sub technologies and their technology description, typical power and energy ranges are described in table 2.2.

Table 2. 2: Electrochemical technology definitions and descriptive characteristics [17]

Technology	**Description**	**Power range**	**Energy range**
Sodium-sulfur battery	A molten-salt battery made up of sodium (Na) and sulfur (S) that operates at high temperature ranges and primarily suitable for> 4 hours duration applications	Several KW to MW	100KWh or higher
Li-ion battery	A battery based on charge and discharge reactions from a lithiated metal oxide cathode and graphite anode. This battery technology is used in a wide variety of applications.	1 KW to 100 MW	<200 MWh
Lead-acid battery	A battery made up of lead dioxide (PbO_2) for the positive electrode and a strong lead (Pb) negative electrode. Vented and valve regulated batteries make up two subtypes of this technology.	Up to few KW	<10 MWh
Sodium metal halide battery	A molten battery made up of nickel (Ni), sodium, chloride (Nacl) and sodium which is kept at a temperature between 270^{0}c and 350^{0}c. Batteries using other materials are being developed to decrease cost and operation temperature.	Several MW	4KWh to several MWh
Zinc-hybrid cathode battery	A high energy density battery storage technology that uses unexpensive and widely available materials. Zinc-hybrid cathode batteries use non-flammable, near neutral pH aqueous electrolytes that are non-dendritic and do not absorb CO_2	250 KW subsystem repeat unit up to 2 MW	1 MWh subsystem repeat unit up to 8 MWh
Redox flow battery	A battery in which energy storage in the electrolyte tanks is separated from power generation in stacks. The stacks consist of positive and negative electrode compartments divided by separator or an ion exchange membrane through which ions pass to complete the electrochemical reactions. Scalability due to modularity, ability to change energy and power independently, and long cycle and calendar life are attractive features of this technology.	Several KW to 30 MW	100 KWh to 120 MWh

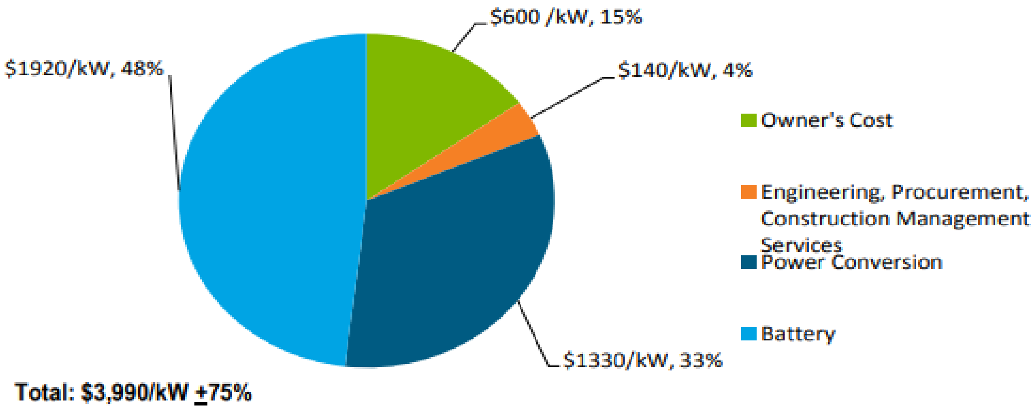


Figure2. 14: Capital cost breakdown for a battery (electrochemical) energy storage plant

2.11.2 Cost analyisis and comparison

2.11.2.1 Pumped storage hydropower technology

The point estimate was based on historical data and was based on secret in house reference study for an independent power company. The PHSE cost estimate was based on anet capacity of 500 MW and storagr capacity of 10 hours. A 2010 capital cost of 2004$/KW was anticipated to be +50 percent[17]. Table 2.3 shows the cost and performance data for PHSE.

Table2. 3: Breakdown of PHES capital cost of components of 500 MW,10 hours duration projects [17]

Cost component	**$/KW (2010 USD)**	**$/KW (2020 USD)**	**Percent of total direct costs**	**Percent of total installed costs**
Upper and lower reservoir	840	1016	-	32.2%
Tunnels	135	163	-	5.1%
Powerhouse excavation	80	97	-	3.0%
Powerhouse structure, equipment, BOP	835	1010	-	31.3%
Total direct costs	**1910**	**2311.12**	**-**	**71.5%**
EPC management services (project management, construction management, and contingency fees	390	472	20.4%	14.6%
Owners 'cost	370	448	34.4%	13.9%
Total indirect costs	750	915	54.8%	28.5%
Total installed cost	**2650**	**3206**	**-**	**-**

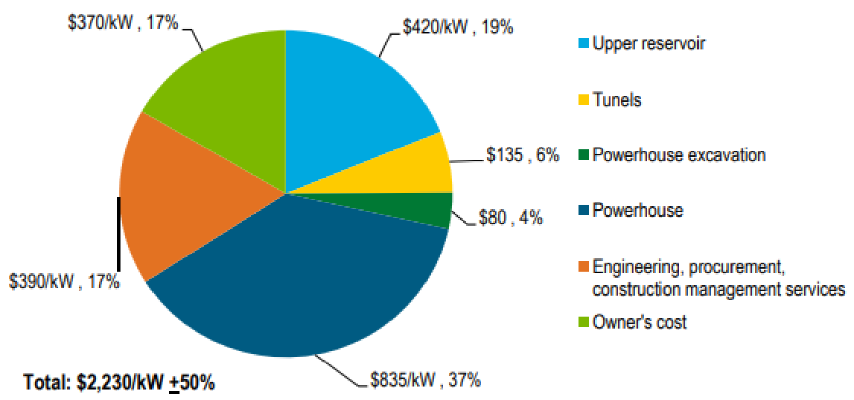


Figure2. 15: Capital cost breakdown for a battery PHS energy storage plant [17]

2.12 Related work research in Rwanda

MUVUNYI Richard[19] was interested in studying the feasibility of hydro/PV system and its energy storage system for rural areas in Rwanda to sustainably and efficiently satisfy the energy demand of the population, where central grid electricity has not yet reached due to many geographical and economic constraints. The study was done on Mwogo Sector / Bugesera District which is composed by more than 250 households without electricity for lighting and entertainment (TV and Radio). In his work, he came out with design of a 25 KW stand-alone off grid solar-micro hydropower Hybrid system consisting of photovoltaic system running water pump supplying hydro power plant storage which is viable solution compared to batteries system normally used to keep the supply working in the nights or absence of sun that are expensive.

On their paper" key technological development needs and application analysis of renewable energy hybrid technologies in off grid locations from the Rwanda power industry," Jean De Dieu Niyonteze, Fumin Zou, Godwin Norense Osarumwense Asemota, Samuel Bimenyimana, and Gilbert Shyirambere [20]. The goal of their research was to determine the best hybrid combinations for lowering energy costs and increasing access to electricity generation that maximized available renewable energy resources, as well as to look into certain new technological development needs in Rwanda's power industry. Four distinct 100 percent renewable energy hybrid systems were created and simulated in their study to deliver power to rural areas in Rwanda, and the simulation findings showed that the combination of hydro/solar/battery is the ideal off-grid system for use in remote areas.

Marvin Karugarama[21] in his research work "Mitigation of Blackout in Kigali Using a microgrid with advanced energy storage and solar photovoltaics", he proposed a solution that uses a microgrid with advanced energy storage and solar PV to mitigate blackouts in Kigali, the capital of Rwanda and a description and steady state analysis of major weaknesses in the Rwandan electric grid is presented in his work. The work came out with a PV-diesel microgrid in the area surrounding the Kigali International Airport with a peak load of 12.5 MW with a battery storage system and it was shown to alleviate the main causes of blackouts. In this study, a chemical storage battery storage is chosen. Marvin states that battery storage has been chosen for its relevance to the application in cost, size, and physical considerations and also other mature technologies such as CAS or PHS are too big for the application, and physical and geological constraints render them unlikely near the city.

Mugisha Jean Claude[22] in his research "A study on Auxiliary Battery Energy Storage to Mitigate PV Output Power Fluctuations: Case Study: 8.5 MW Agahozo Shalom Youth Village (ASYV) PV Power Plant in Rwanda**"** (This solar power plant is connected to national electric grid), he analysed the annual data for year 2017 to find the worst-case scenario which is the day with highest irradiance variation. Both PV power and ambient temperature data for this day were used as input to the model and four smoothing approaches namely Low Pass Filter (LPF), Simple moving average (SMA), Exponential moving average (EMA)) and Ramp Rate Control (RRC) were investigated in detail, applied to the model. The aim was to compare in terms of performance and battery size that each approach would require. In his results, at ±20 % and ±30 % RRL, the RRC method was found to be the best option since it needs less capital cost than EMA smoothing approach.

2.13 Literature gaps

Electricity is a force to be reckoned with. To take use of its benefits, the amount of electricity in the system must correspond to actual consumption needs. One of the key challenges facing the electrical industry is energy production and efficient consumption. Energy management entails the generation of energy, its efficient use, and finally the storage of energy for future use. In order to rescue the planet, the entire world is encouraged to develop various renewable energy technologies in electrical power generation. On Rwanda national grid, different renewable energy generations are connected where solar energy generation (intermittent) is among them. The energy on Rwanda's national electric grid can be effectively managed by implementing an efficient, dependable, and environmentally friendly energy storage system. Chemical batteries are a well-known energy storage technology around the world. Chemical batteries are theoretically ideal foe usage with small scale distributed renewables, but their main drawback is their short life, which is comparable to 3 to 5 years when utilized on daily basis.

Regarding to related literatures to Rwanda, pumped hydro energy storage system has been discussed by different researchers. Such studies were done on off grid hybrid systems. Marvin Karugarama[22], discussed on a grid connected storage system. In his work came out with a PV-diesel microgrid in the area surrounding the Kigali International Airport with a battery storage system.

This research work will contribute in terms of helping Rwandan electric grid in finding an environmentally friendly storage with large storage capacity. Pumped storage is important as a balance for very large-scale renewable generation integration.

CHAPTER 3. RESEARCH METHODOLOGY

3.1 Introduction

This part of thesis work presents the way followed during the implementation of our research. After understanding the task to do, we had to find data concerning the project. This chapter explains in details various methods, techniques and procedures used. The methodology of the research includes: literature review through internet search, data collection from national control centre, data analysis, sites survey and data collection from the field, design and relevant conclusions and recommendations.

3.2. Questionnaire

The research started with the arranging the questions related to Rwandan load curve from national control centre. Due to risks of the spread of COVID 19 pandemic and other restriction, it was not allowed to reach to the field physically. From this questionnaire we got reply email from national control centre engineer. Information from the manager were the hourly load demand from the national electric network with all electrical generation plants connected to the network.

3.3. Phone calling

After receiving the email from the site manager, we have been in touch with him through mobile telephone. This helped us to get more understanding about the data given. This method helped us also during sites survey in different districts of western province.

3.4. Data analysis, site survey, design and simulation

From received data from national control centre, daily load curves containing daily generation curves of total renewable energies connected to the grid have been have formulated. This analysis has been conducted to better know and understand if on the national electric grid there is enough renewable energy to be stored. After the analysis of the data, the results have shown that the national electric grid needs energy storage system. Sites visits have been conducted in the district around the Lake Kivu: Rubavu, Rutsiro, Karongi, Nyamasheke and Rusizi for sites selection. Different sites have been selected and different measurement have been collected and one best suited site has been selected for the design. In this part, different parts of the storage system have been designed. Also, MATLAB Simulink Simulation of the designed systems to verify the potential solution will be carried out.

CHAPTER 4. DATA COLLECTION AND ANALYSIS

4.1 Introduction

Knowing that there are electrical renewable energies that can be stored and released when needed on national electric grid is essential. The analysis of daily load curves of different days and comparing them with the total renewable energies connected to the national electric grid is the tool to be used. Data related to all power plants connected to Rwanda electric grid with their hourly generation of different days have been collected from Rwanda energy group (REG). Also, sites survey and different analysis to select to pumped storage system have been carried out in this section.

4.2 Daily load demand and total on grid renewable energies analysis

Figure 4.1 represents the total load demand and total renewable energies connected to the grid in 24 hours. It represents the daily load curves of 15 and 16 August 2021 based on the data collected from Rwanda energy group (REG). These daily load curves are plotted of the load demand in MW (on the y-axis) versus the time in hours (on the x-axis) in the chronological order. The following are information that can be captured from figure 4.1:

1. Variation of load on the power system during different hours of the day,
2. MWh generated in a day
3. The maximum power demanded on the electric power grid
4. Off peak and peak demand hours.
5. The time when the total renewable energies connected to the grid is higher than total load demand from the system.
6. The amount of renewable energy available on the grid to be stored during light loads.

Knowing the maximum power demand on the grid system helps in the selection of the rating of PHES and number of generating units to be designed.

The total renewable energies connected to the grid curves are plotted based on the following:

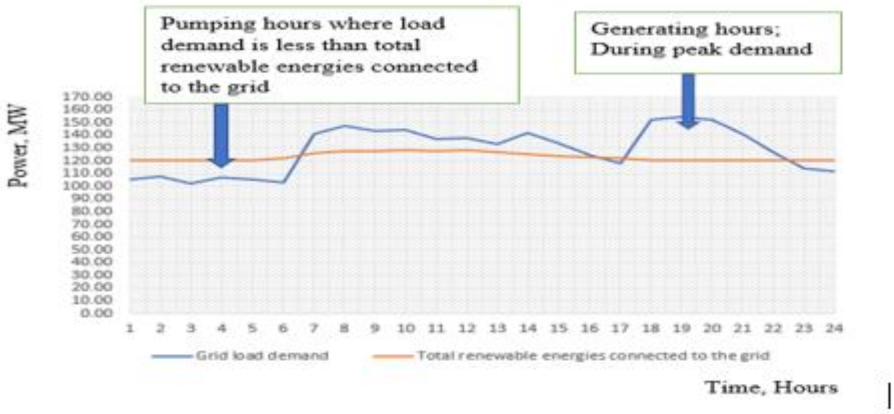
1. The total renewable energies connected to the grid is equivalent to 132.778 MW and 12.230 MW of them are from solar power plants (as stated on page 9).
2. The solar power plants generate power from 7:00 am to 5:00 pm hours.

3. And the hourly MW generation from grid connected solar power plants of 15 and 16 August 2021 are presented in table 4.1.

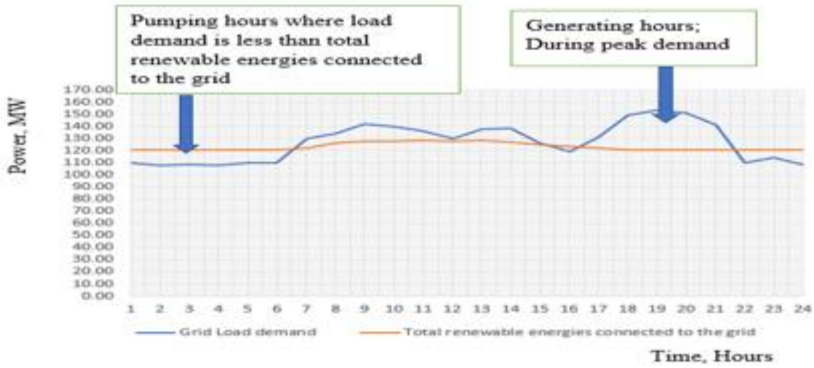
Table4. 1: Hourly generation of grid connected solar energies of 15 and 16 Aug 2021

Time	Hourly MW generation from grid connected solar power plants	
	15 August 2021	16 August 2021
7	2.05	0.9
8	6.12	3.76
9	7.38	5.19
10	6.98	3.36
11	7.29	5.44
12	5.89	6.11
13	6.78	6.96
14	6.09	4.79
15	6.21	3.76
16	5.63	1.33
17	07	2.35

The total renewable energies generation when solar power plants are off is the difference of total renewable hourly power generation and total solar power generation (132.778 MW-12.230 MW). The time solar power plants are generating (from 7 AM to 5PM), the total hourly renewable power generation is the sum of 120.54 MW and hourly generation of grid connected solar power plants.



(A) 15 Aug 2021



(B) 16 Aug 2021

Figure4. 1: Grid load demand and total renewable energies connected to Rwanda electric

As per the Figure 4.1, during light loads on the grid, the total renewable energies connected to Rwandan electric network is greater than the total load demanded from the grid and this is from 10 PM hours of the previuos day to 6:30 AM in the morning. This makes energy storing time to 8.5 hours. During this period, the renewable energy from the grid is supposed to be stored for future use during peak load. From 06:30 AM in the morning to around 10 PM , the load demanded from the grid is higher than the total renewable energies connected to the grid. The critical period is from 5 PM to 10 PM. During this period of time, the stored energy is supposed to support the grid. According to Figure 4.1, the power gapes between peak load demand and total renewable energies connected to the grid are 33.96 MW and 32.93 MW in both (A) and (B) of Figure 4.1. respectivelly and this happens at 7 PM. Knowing this difference is of more importance because it is the one which helps in deciding the power rating of energy storage system to support the grid. On the graph of 15 August 2021, total energy required from energy storage to support the grid is the area between the two curves and it is 115 MWh and 110 MWh for 16 August 2021 day. The duration of peak load demand in both situations is 5 hours.

4.3 Overview of grid connected diesel power plants in Rwanda

As per the data from Rwanda Energy Group (REG), 5 diesel power plants are connected on Rwanda national electric grid with 57.8 MW as installed capacity in total and those power plants are found in table 4.2. Also, table 4.2 summarises the operational details of these 5 power plants on 15th,16th, 17th, 18th, 19th, 20th and 21st August 2021 days.

Table4. 2: Diesel power plants connected to Rwanda national grid

No	Power plant	Capacity (MW)	Average daily run hours (Hours)	Reason of stoppage	Daily average generation (MWh)
1	SO Energy Mukungwa	10	15.2	Normal stoppage	148.6
2	SO Energy Birembo	10	8.2	Normal stoppage	50.4
3	SO Energy Masoro	10	13.9	Normal stoppage	126.6
4	Jabana I	7.8	12.71	Normal stoppage	26.5
5	Jabana II	20	21.71	Normal stoppage	245.6

4.4 Reduction of grid connected diesel power enhanced by new storage system

According to figures 4.2 and 4.3 there are 204 MWh of electrical energy on Rwandan national electric grid which can be stored during off peak hours and released when needed. Having a storage system with round trip efficiency of 0.81, the stored energy will become 165.24 MWh after converting it back to electrical energy. On the other hand, the total daily average energy generation of SO Energy Mukungwa diesel power plant is 148.6 MWh and 153.1 MWh for both SO Energy Masoro and Jabana 1 diesel power plants combined produce 153.1 MWh as average daily generation. This analysis shows that currently having the pumped hydroelectricity energy on Rwandan national electric grid will eliminate either Mukungwa SO Energy diesel power plant or SO Energy Masoro and Jabana 1 diesel power plants.The pumped storage system is pure with no harmful gas emission and it will remove some percentage of diesel power plants on Rwandan electric network. It will also contribute on maximizing the power distribution for peak hour demand and improve the quality of generated power.

4.5 PHES plant's location survey around lake kivu

4.5.1 Introduction

Rwanda intends to enhance renewable energy generation, and an energy storage system will play a key role in integrating intermittent renewables into the existing system. The increased use of renewable energy in Rwanda's electric grid would necessitate better grid management of power supply and load demand. The survey's goal is to find the optimal sites for pumped hydroelectricity energy storage plants to store energy generated by renewable plants during light loads hours and reuse it during heavy load loads hours.

4.5.2 Identification of best sites location for PHES

The survey has been conducted in 5 districts (Rubavu, Rutsiro, Karongi, Nyamasheke, Rusizi) of western province of Rwanda around lake Kivu. The aim of the survey was to select the best suitable locations for PHES.

The conditions were to find mountains with valley on the top, located near the Lake Kivu and with enough head. The following table shows the selected sites with their characteristics.

Table4. 3: Selected sites for PHES with their characteristics

Name	Coordinate	Head (m)	District	Use of the land
Burunga	E00430364 N04771283	110	Karongi	Agriculture and residence
Sure	E00429822 N04776988	100	Rutsiro	Agriculture and residence
Rukaragata	E00426595 N04781871	162	Rutsiro	Agriculture and residence
Ngoma	E00420781 N04759242	259	Karongi	Agriculture and residence
Nyabitekeri	E00393125 N04741192	196	Nyamasheke	Agriculture and residence
Nyamyumba	E00420578 N04807132	182	Rubavu	Agriculture and residence

4.5.3 Identification and selection of best suitable site for PHES plant

Mountain with wide valley on the top has been selected for storage system. Having wide valley facilitates the construction of the dam, increases the possibility of extension when needed and reduces the entire cost. L/H ratio (length in to height ratio between two reservoirs) should be kept at minimum value for the cost optimization and reduced head loss. Areas with public infrastructures like schools, hospitals and churches were avoided during the selection. The selection of densely populated areas has been also minimized. The selected site is feasible to access the construction areas easily and deliver material equipment quickly.

The characteristics of selected site are as follows:

Name: Rukaragata

District: Rutsiro District

Coordinates: E00426595 N04781871

Maximum head: 162 m

Length from Lake to top reservoir: 521 m

Ratio L/H: 3.3

Use of the land: Agriculture, residence and road as a public infrastructure.

Figure4. 2: Image of selected site for PHES plant at Rukaragata mountain

The site has been selected due to availability of valley on the top mountain with enough space for top reservoir which will facilitate the construction, availability of roads, enough head and minimum value of L/H ratio (length in to height ratio between two reservoirs) for the cost optimization and reduction in head loss.

CHAPTER5. DESIGN AND SIMULATION OF PHES PLANT

5.1 Design of Upper dam

The upper dam of pumped hydroelectricity energy storage system is proposed at the top of Rukaragata mountain in Rutsiro District. This suitable site of the upper dam is located at 1622 meters above sea level whereas the lower reservoir (lake Kivu) is located at 1640 meters above sea level. This makes the maximum head to be 162 meters. reservoir of PHES is proposed at the top of Rukaragata Mountain in Rutsiro District. This suitable site of the upper storage has a contour at 1622 m above sea level whereas the lower reservoir (Lake Kivu) is at 1460 m above sea level. This makes the maximum head equal to 162m. The rated head is considered to be 158m by considering waves which might be produced by seismic and wind activities and other facts. The design of upper reservoir is necessary in calculating how much energy the system can store in the form of potential energy.

The following steps help in calculating the capacity of upper reservoir of pumped hydroelectricity energy storage system:

1- Identification of the system rated head. The identified maximum head is 162m and the head to be considered in our calculation in 158m.
2- Calculation of Q_p (water volume flow rate), reversible pump running at 1 MW rated power to take water from lower reservoir to the upper reservoir by using equation 5.1.

$$Q_P = \frac{P_p \times \eta_P}{g \times \rho \times h} = \frac{1 \times 0.9 \times 1000000}{9.81 \times 1000 \times 158} = 0.58\, {m^3}/{S} \text{ (pumping flow rate per 1 MW)} \quad (5.1)$$

Where: Q_P: Rated volume flow rate (m^3/s).

P_P: Rated Pump Power (W); assumed to be 1MW

η_P: Pump efficiency; assumed to be 0.9

g: Acceleration of gravity (9.81 m/s^2).

ρ: Density of water (1000Kg/m^3).

h: Head (m); Its value is taken as 158m

Pumping flow rate per one unit is $0.58 \times 18 = 10.44 m^3/s$

3- Identification of continuous pumping hours of the pump at rated power. According Figure 4.1, the pumping operation is supposed to start at 10:00 pm of the previous day to 06:30 am which makes 8.5 hours of operating the station running at 24 MW as maximum power approximatelly.

4- After getting Q_p (water flow rate) in step 2 and having the time of continuous pumping in step 3, the volume of upper dam can be calculated as follows by using equation (5.2).

$$V_{R\ at\ 1MW} = Q_P \times T = 0.58 \times 8.5 \times 3600 = 17748m^3 \quad (5.2)$$

$$V_{R\ at\ 24MW} = 17748 \times 24 = 425952m^3$$

The upper reservoir is approximated to 800000 m^3 for future integration of renewable energies in the Rwandan electric grid and other losses consideration.

Where: VR: Volume of the upper reservoir.

T: Rated pumping time in second.

An upper dam with the following dimensions (length 250 meters, width 200 meters and 16.5 meters of depth) will be constructed. The capacity of upper dam is proposed to be 800 000 m^3 of water. Lining activity during construction will be done to prevent infiltration of water into the soil as water losses.

5.2 Penstock sizing

The total length from upper reservoir to lower reservoir is 526 m. The water velocity (V) in pumping mode is selected to be 4m/s through all the conduit. Having low water velocity helps in minimising the friction loss, hydraulic chock, the damage to the inner wall of the pipe, noise and vibration.

$$A = \frac{Q}{V} \quad (5.3)$$

Where A: is cross section area of penstock in m^2,

Q: is water volumetric flow rate in m^3/s

V: velocity of water in m/s

The diameter (d) of penstock can be calculated by using the following formula as it has a circular shape.

$$A = \pi \times \frac{d^2}{4} \tag{5.4}$$

With volume flow rate Q= 10.44m^3/s and water velocity (V) set to 4m/s in pumping mode, the inner diameter (d) of penstock is calculated to be 1.823m.

Once the calculated diameter is brought in generation mode where volume flow rate Q=12.9 m^3/s and the diameters remain the same in both modes, the water velocity is found to be 4.94m/s by using formular (5.3)

5.3 Lower dam (lake Kivu)

The lower dam of pumped hydroelectricity energy storage system will be located at the bottom of Rukaragata mountain on the lake kivu. No construction work will be required and this is an economical benefit as the lower dam is a natural reservoir. The lower dam is at 1460 meters above sea level. The environmental issues caused by the variation of water level in the lake during operation will be negligeable as the maximum level reduction will around
0.3 mm at the initial filling of the upper reservoir by considering 800000m^3 of upper storage capacity and Surface 2370 km^2 of the entire lake.

5.3 Power House

Referring to Figure 4.1 and analysis from section 4.2, the peak load demand start at around 05:00 pm to around 10:00 pm which makes 5 hours of operating station in generating mode and the maximum power difference between the total load demanded from grid and total renewable energies connected to the grid is 36 MW. This makes our system to be designed at rated power output of 36 MW with 2 generating sets for flexible operation. A reversible motor/generator configuration is selected. The powerhouse will be constructed at the end of penstock near to lake kivu (lower dam). The output power from the generator is calculated by using equation (5.3)

$$P_g = \mathrm{Q_g} \times \mathrm{g} \times \rho \times \eta_g \times \mathrm{H_g} \tag{5.3}$$

$$Q_g = \frac{P_g}{g \times \rho \times \eta_g \times H_g} = \frac{18 \times 1000000}{9.81 \times 1000 \times 0.9 \times 158} = 12.9\mathrm{m}^3 \text{ (Discharge per one generating set)} \tag{5.4}$$

P_g= System rated power in Watt

η_g = efficiency in generating mode (0.9)

ρ = water density (1000kg/m^3)

g = gravitational acceleration (9.81 m/s^2)

H_g = rated generating head in m (estimated to 158m)

5.4 Turbine Selection

In designing process, there are some requirements of the machine which should be known in deciding which type of machine to be selected. In selecting a turbine to be installed, rotational speed, volumetric flow rate of water and the head are more important. Figure 2.8 presents the relationship those parameters and the power capacity in the selection. For our case we have 18 MW, 158 m as total head and 12.9m^3/s as volumetric flow rate. This makes Francis turbine is suitable for our study. A reversible pump/turbine configuration is selected.

Table5. 1: Station characteristics of designed storage system

Overall Capacity	36 MW
Capacity of each unit	18 MW
Number units	2
Machine Type (prime mover)	Reversible pump-turbine (Francis)
Machine Type (generator)	Reversible motor-generator (Synchronous)
Rated head	158 m
Capacity of upper reservoir	800 000 m^3
Efficiency of generation mode	0.9
Efficiency of pumping mode	0.9
Round trip efficiency	0.81
Rated generating mode discharge	12.9 (m^3/s) for each unit
Penstock length (L)	526m
Penstock diameter (D)	1.493m
Rated water velocity	4.94m/s
Generator efficiency	0.96
Turbine efficiency	0.96

5.5 Modelling and simulation

5.5.1 Parameters determination

This section describes and provides the required equations for estimating parameters of the of different system parts models. This is done to get transfer functions of different parts of the system.

Table5. 2: Storage System data

	Parameters	Symbols	Values
Penstock	Diameter	D	1.493m
	Length	L	526m
	Pressure wave velocity	a	1420
Turbine	Rated discharge	Q	12.9m^3/s
	Rated head	H_r	158m
	Position of gate at NL	g_{nl}	0.06
	Position of gate at FL	g_{fl}	0.96
	Turbine damping	D_a	0.46
	Rated water velocity	U_0	4.94
Generator	Rated power	P	36MW
	Initial time constant	H_g	5s
	Speed regulation parameter	Ri	1.2
	Rated voltage	V	11KV

1. **Water Starting Time (T_w)**

It is defined as the time it takes for water to accelerate from zero to rated velocity and it is calculated as per the following equation.

$$T_W = \frac{LU_0}{a_g H_r} \tag{5.4}$$

Where L: Penstock length, U_0: rated water velocity, H_r is rated head and a_g is acceleration due to gravity.

1. **Electrohydraulic (PID) Governors**

The name PID comes from the fact that it operates by utilizing the integral (the past control error), proportional (the present control error) and the derivative (the predicted control error).

PID controller gains estimation:

K_p: Proportional gain

K_i: Integral gain

K_d: Derivative gain

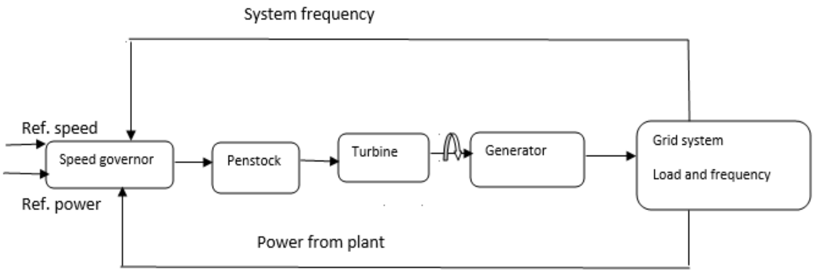


Figure5. 1: Controlling principle of hydropower plant interconnected to grid system

Table 5.3 Formulars for PID parameters calculations [22]

Gains	Kp	Ki	Kd
PI Controller	$\frac{T_M}{2T_W}$	$\frac{T_M}{8T_W^2}$	0
PID Controller	$\frac{0.8T_M}{T_W}$	$\frac{0.24T_M}{T_W^2}$	$0.27T_M$

Where T_M=2Hg (Hg is inertia constant of generator)

$$H_g = \frac{\frac{1}{2}JW^2}{MVA} \left(in \frac{MWs}{MVA} \right) \quad (5.5)$$

Where: J is moment of inertia of the mass in rotation

ω = rotational (rad/s)

MVA = MVA rating of the machine

Typical H_g for a synchronous generator can range from 2 to 9 seconds (MWs/MVA) and it is described by Manufacturer.[22]

Elastic time of penstock pipe T_{ep}:

$$T_{ep} = \frac{\text{Penstock lenght}}{\text{Pressure wave velocity}} = \frac{L}{a} \quad (5.6)$$

Pressure wave values are typically 1220 m/s and 1420m/s for steel and cement pipes respectively [22]

Hydraulic surge impedance of the conduit (Z_p) is expressed by:

$$Z_p = \frac{T_W}{T_{ep}} \tag{5.7}$$

Where Tep is Elastic time of penstock pipe

Turbine gain A_t

$$A_t = \frac{1}{g_{fl} - g_{nl}} \tag{5.8}$$

Where: g_{fl} is the gate position at full load which is equal to 0.96 and g_{nl} is the gate position at no load equivalent to 0.06

Speed regulation (Rp) lies in the range of 0.03 to 0.06 [22]

Calculated and typical parameters

Table5. 3: Control system calculated parameters

Parameter	Symbol	Value
Water starting time (s)	T_W	1.676
Mechanical starting time (s)	T_M	10
Integral gain	Ki	0.85
Derivative gain	Kd	2.7
Proportional gain	Kp	4.77
Elastic time of penstock pipe (s)	T_{ep}	0.37
Normalized hydraulic surge impedance of the penstock	Z_p	4.529
Turbine gain	A_t	1.11
Permanent droop	R_p	Set to 0.04
Resetting time (s)	T_R	Set to 0.5
Pilot valve and servo time constant (s)	T_p	Set to 0.1
Main servo time constant (s)	T_G	Set to 0.15
Inertia time constant of generator (s)	H_g	Set to 5
Position of the gate at full load	g_{fl}	Set to 0.96
Position of the gate at no load	g_{nl}	Set to 0.06
Damping of the turbine	D_a	Set to 0.46

Turbine model

$$Turbine(s)=\frac{1-ST_W}{1+ST_W} \quad (5.9)$$

Generator model

The generator is modelled by a gain K_G and a time constant T_G, as presented in equation below

$$G_{Generator}(s) = \frac{K_G}{1+T_{G}s} \quad \text{or Generator}= \frac{\frac{1}{R_i}}{S2H_g+D} \quad (5.10)$$

Here in, K_G and T_G are the constants dependent on generator loading conditions. K_G ranges from 0.7 to 1.0 and T_G is between 1.0 s and 2.0 s.

5.5.2 Simulation

Simulation tools

MATLAB/Simulink which is software developed by math works Inc, It is the software to be used in this study to simulate and analyse the results

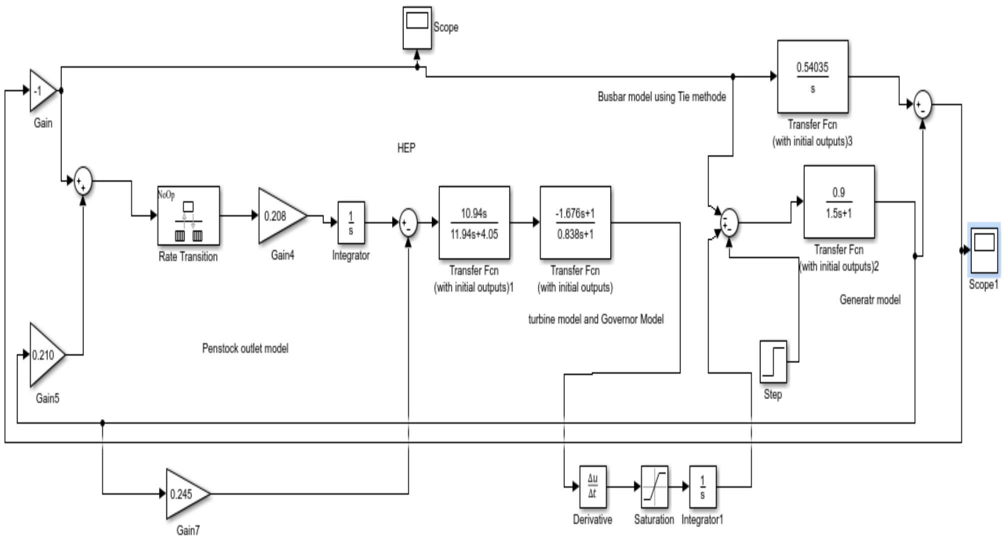


Figure5. 2: Plant load stability model Simulated in MATLAB/Simulink

Figure presents the plant load stability model formulated by using the system calculated parameters.

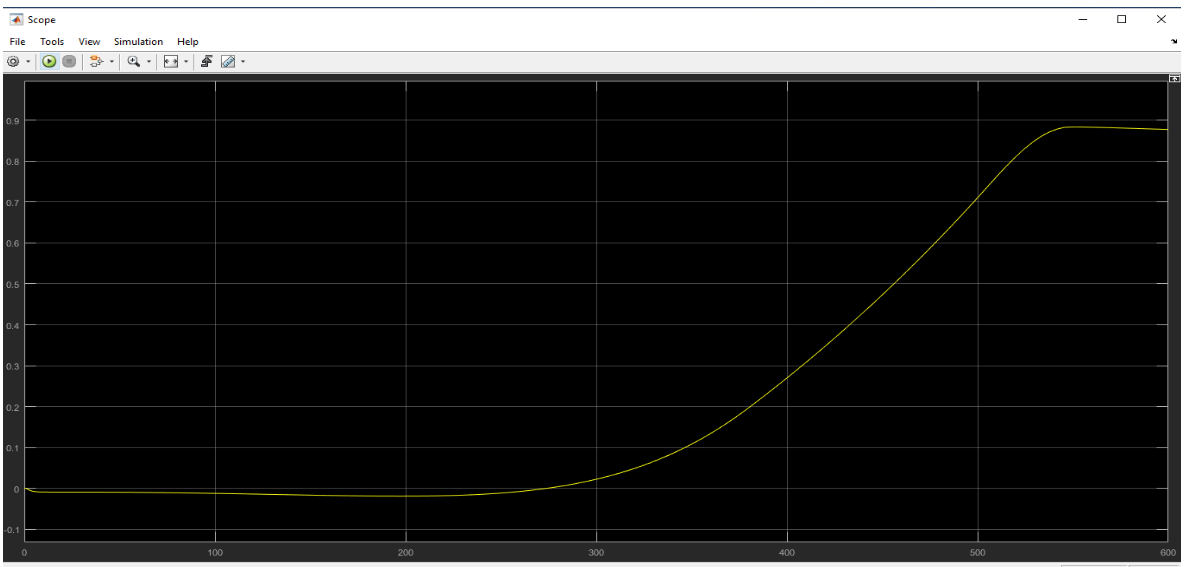


Figure5. 3: Plant generation response to 33% load increase

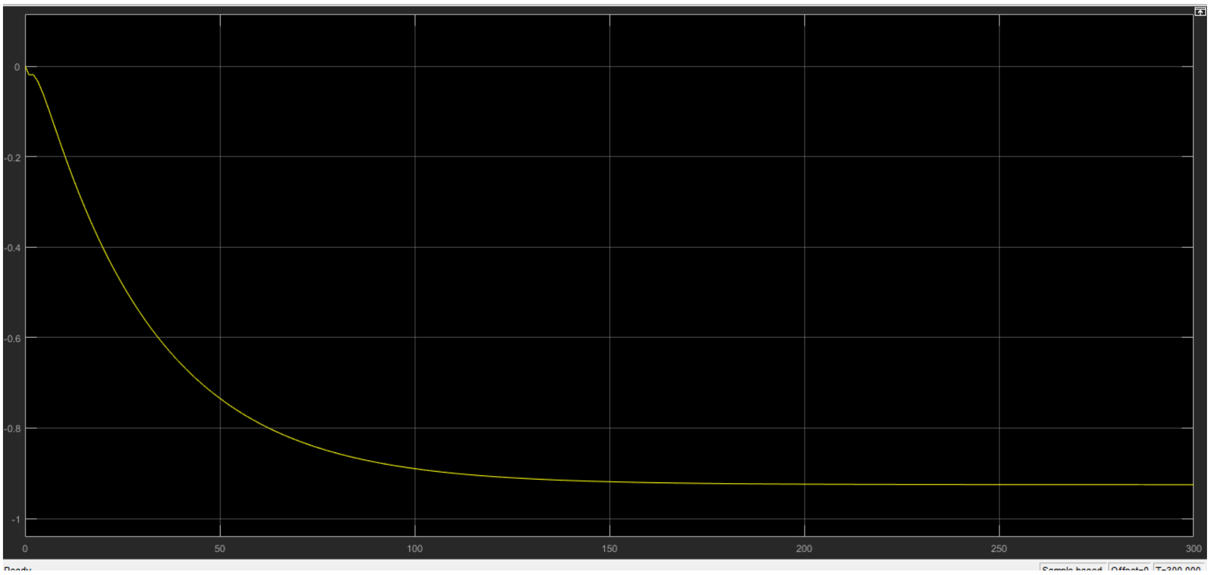


Figure5. 4: Plant generation response to 25% load rejection

5.6 Operational economic feasibility study of designed PHES

5.6.1 Introduction

Rwanda Utilities Regulatory Authority (RURA) is the only utility in Rwanda in charge of setting new electricity tariffs and it has been reviewed in January, 2020. According to current pricing gathered from www.reg.rw, houses that utilize between 0 and 15 KWh per month pay 89 Rwf ($0.09) per KWh, while those who consume between 15 and 50 KWh per month pay 212 Rwf per KWh. Customers who use more than 50 KWh per month pay 249 Rwf, whereas non-residential customers who use 0-100 KWh per month pay 227 Rwf per KWh, and those who use more than 100 KWh per month pay 255 Rwf.

As per RURA, industrial consumers are categorized as large, medium and small before placing prices per consumption rates. Industrial consumers pay as follows during off peak hours:

-Small industries pay 134 Rwf per KWh

-Medium industries pay 103 Rwf per KWh

-Large industries pay 94 Rwf per KWh

From there, cost tariff for electricity in Rwanda is not timely varied except for industry purposes where there is peak load and off-peak load tariff. For domestic purposes the tariff is uniform.

The cost variation between peak hour and off-peak hour in small industry is very large. Since the cost of power needed to charge this system will not vary with peak or off hours, as the purpose is that charging time should be in off-peak hours and its tariff is 94 Rwf /kWh.

And then, this designed system is said to be feasible when benefits with demand charge reduction and energy cost reduction must exceed the cost of storage otherwise using a storage system will not be feasible.

Two scenarios can be considered here; where the first one will be to consider the plant as large industry consuming electric energy during charging period in off peak load hours at off peak load hours tariff and as hydropower plant to generate electricity to be sold at peak load hours tariff. The second one is where the plant has to be considered as large industry consuming electric energy during charging period in off peak hours and as hydropower plant during peak load hours at a cost to be determined by power purchasing agreement between the storage system owner and REG. The first scenario is the one to be considered in our analysis.

5.6.2 Efficiency of the storage system

Technical study of this PHES has been studied and obtained results show that the system is planned to generate 36MW with round trip efficient of 0.81 which is from 0.9 efficiency for both charging and discharging efficiencies.

And then the system is planned to charge for 8.5 hours; with 81% round trip efficiency. Then the discharge time for 8.5 hours is calculated as 8.5×0.81 and is equal to 6.885 hours which is discharging time of the system.

5.6.3 The upper dam charging cost and income from power generated during generation mode

In light load hours on the electric network, there is excess electricity and the cost of electricity is low. During this period, the plant pumps water into the upper dam. The stored energy is released to generate electricity during heavy load hours at a high economic cost.

The cost of storage unit is directly dependent on the energy stored in the upper dam and inversely proportional to the system efficiency and as the power needed to charge the system is very large, we will consider the tariff setup for large industry tariff; which is 0.212$/kWh for peak hour and 0.094$/kWh for off-peak hour. The Power for the pump will be used from off-peak hours starting from midnight. Therefore; data used are as follow:

Peak hour tariff 0.212$/kWh

Off-peak hour tariff 0.094$/kWh (Our system is placed as large industry)

Data used in this analysis found at www.rura.rw

Designed capacity is 36 MW.

Energy discharge cost= Discharging hours * working hour cost, so there are 5.67 hours of discharge and it is considered to work for the whole year.

= 6.885 hours/day * 365day/year * 0.212$/kWh

= 532.76$/kW-year

For 36 MW, generated cash in a year is: $\frac{532.76\$}{\text{kW}} \times 36000\text{kw} = 19179406.8\$$

Charging cost (off-peak hour energy) = Charging hours * off- peak hour cost and there are seven hours of charging. =8.5 h/day * 365 day/ year * 0.094 $/kW = 291.635$/kW-year

For 36 MW, the cash to be paid is: $\frac{291.635\$}{\text{kW}} \times 36000\text{kW} = 10498860\$$

The cost reduction available is 241.125 $/kW-year

Cost reduction for 36 MW is: $\frac{241.125\$}{\text{kW}} \times 36000 = 8680500\$$

The cash generated from generation mode is much greater than the cost of storing the energy during charging mode, so this storage system is economically feasible.

5.7 Impacts to the society around the selected site

5.7.1 Social positive impacts

This project will provide number of local employments during the construction and operations phases. The project will also impact business growth with opportunities created by the presence of construction engineers, technicians and casual employees and then increase income of the society around the project. The project will enhance the improvement in infrastructure construction including roads, electricity, communications, water supply, hospitals etc.

These improvements will certainly enhance continuing development area. Also, the social responsibility activities from the project during the operation period will contribute in the development and wellbeing of the society if the operation is run by private company.

5.7.2 Technical negative impacts on existing projects or infrastructures

Proposed lower reservoir is the lake Kivu and there are hydropower plants located on rivers from lake kivu. Due to the capacity (MW generation) of the project, the hydropower plant taking water from the lake might be affected. The other thing is that the plant will be connected to the national grid through the existing transmission line which is near to the projects. This might cause the changes in the protection system on the nearest substation and the transmission system infrastructures.

5.7.3 Social negative impacts on the people in the vicinity of the project

The implementation of the proposed project will affect a number of residential houses, agriculture of bananas and other crops found in selected areas. Many residential houses and banana plantation areas are covered by upper reservoir. On the lower reservoir area where powerhouse will be constructed includes less amount of agriculture of bananas and the land which belongs to Rwandan government for lake protection. None of the schools, hospitals, churches, commercial buildings or factories are affected by the proposed plant. During the construction period considerable amount of waste would be accumulated. The debris collected during excavating and blasting can be used for land filling or solid can be used for civil construction industry. The dust during the blasting will cause respiratory diseases to the people nearby and contamination of rain water from the building roofs. Preventive methods should be used to avoid spreading dust. Heavy vehicles with huge load will be travelling in the access roads frequently to clear the debris during construction and hence the access roads will be damaged and the traffics will be formed. Also, the project area will be receiving people with different characters form worldwide. This will influence the regular habitual life of the public in the project area. Also, the negative implications include the introduction of new diseases into the community and population relocation owing to project's construction.

5.7.4 Environmental impacts

This study results show that currently having the storage system will remove completely 27.6% of diesel power generation on Rwandan electric network. The reduction of diesel power plants on Rwandan network will result in gas emission reduction. In addition, the effects of hydropower plants are linked to land floods. Here due to the capacity of plant and the volume of lake Kivu, the variation of the level of down reservoir is not significant. Those related effects depend on the size and location of the power plant. During the construction period, due to breaking up of soil and operating heavy vehicles will discharge certain amount of CO_2, toxic gases and dust to the atmosphere. But the CO_2 emission of this project is less than a thermal power plant with same generation capacity. When compared the lifetime this CO_2 emission is negligible. Another thing is that in deep of lake Kivu there is a mixture of methane, H_2S and CO_2 gases dissolved in water. Due the suction point of the pump during pumping mode, water with those gases might be pumped and upper reservoir serves as water gas separator. Those gases which are harmful to the environment might be released in the atmosphere. The environmental issues caused by the variation of the lake level during operation will be negligeable as the maximum level reduction will around 0.3 mm at the initial filling of the upper reservoir.

CHAPTER 6. RECOMMENDATIONS AND CONLUSIONS

6.1 Conclusions

A bulk energy storage system was required to make the Rwandan electric network more stable and allow the adoption of intermittent renewable energies. The analysis of daily load curves and connected renewable energies power plants revealed that an energy storage system is required to store energy during light loads hours and discharge it during heavy loads hours in this study. Different sites around Lake Kivu have been selected during the survey and the best-suited location has been selected. A storage system with a capacity of 36 MW has been designed. High efficiency ranging from 70 to 85 percent, CO_2 avoidance, multipurpose facilities; environmentally friendly, high availability compared to other technologies, and quick reaction to load variation are all benefits of the suggested technique. The study results also showed that currently having the storage system will remove completely 27.6% of diesel power generation on Rwandan electric network

6.2 Recommendations

On Rwanda’s electric network, 37.2 MW of diesel and 20.5 MW of heavy fuel power plants are currently operational. These electrical energy sources are both expensive and detrimental to environment. As a result, various clean alternative energy sources, such as solar energy, must be widely integrated into Rwanda’s electric grid. When renewable energies such as solar and wind are integrated at high level in an electric network, becomes unstable. To deal with network instabilities, an energy storage system is required, and the pumped hydroelectric energy storage system, once installed, can improve the energy sector by matching the power generated with the load expected from the grid. This will allow for the incorporation of renewable energy sources while also lowering the cost of diesel power plants. This study found that PHES technology can be used on Rukaragata and other mountains in Rwanda's Lake Kivu region. As a result, the Rwandan government is advised to consider the creation of a pumped hydroelectricity energy storage system as a viable solution.

6.3 Recommendation for future work

Lake Kivu contains a mixture of methane, H_2S, and CO_2 gases dissolved in water in tens of meters of depth. Due to the suction point of the pump during pumping mode, water with those gases might be pumped and the upper reservoir serves as a water gas separator. Those gases are harmful to the environment and they might be released into the atmosphere. Based on the foregoing considerations, we urge further research into the safest depth for the suction pipes of pumps to be situated in order to prevent the extraction of these gases into the upper dam.

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