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STUDY OF HYBRID POWER SYSTEM DEVELOPMENT AND OPTIMIZATION OF A MICRO -HYDROPOWER PLANT: CASE OF KIGWENA IN BURUNDI

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DECLARATION

I, **Egide MANIRAMBONA**, hereby declare that this thesis represents my personal work, realized to the best of my knowledge. I also declare that all information, material and results from other works presented here, have been fully cited and referenced in accordance with the academic rules and ethics.

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CERTIFICATION

I hereby certify that this master thesis by Egide MANIRAMBONA, an Energy Engineering master student of Pan African University Institute of Water and Energy Sciences (including climate change) (PAUWES), Tlemcen, Algeria was carried out under my supervision.

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ABSTRACT

A significant characteristic of the power sector in Burundi is the very low level of electrification, mostly supplied to urban areas. However, Burundi has considerable potential for developing renewable energy technologies such as hydropower and solar PV. Despite this potential, a number of micro-hydropower plants have been constructed especially for rural electrification and are managed by Burundian Agency for Rural Electrification (ABER). Many of them have failed to provide reliable electricity in most of the remote areas due to the general reduction in the level of water and due to energy demand growth for the communities. This study aimed to identify a simple, reliable, viable and cost-effective hybrid power system to overcome the power supply intermittency from small scale hydropower system. Sizing, operation and control of the renewable sources in a hybrid power system are very essential for its techno-economic feasibility and stability. HOMER (Hybrid Optimization model for Multiple Energy Resources) software was used to develop an optimal hybrid power system design. From this study, it has been found that the most suitable complementary renewable energy source to the existing micro-hydropower to overcome energy generation fluctuations is a combination of the Kigwena micro-hydropower plant, solar PV technology and utility grid for smoothing unexpected intermittencies. From the analysis, these renewable energies were found to be the most techno-economical viable option to upgrade the capacity of the hydropower with the lowest LCOE of $US\$\ 0.0334\ /kWh$. This cost is within the range in comparison to the current electricity tariff in Burundi ranging from $US\$\ 0.023/\ kWh$ to $US\$\ 0.072/kWh$. The study would be a replicable model for other areas facing similar challenges.

Key words: Micro hydropower, Hybrid power system, Optimization, Renewable Energy, Off/On grid system.

RESUME

Une caractéristique importante du secteur de l'électricité au Burundi est le très faible taux d'électrification. Néanmoins, le Burundi a un potentiel considérable pour le développement des énergies renouvelables telles que l'hydroélectricité et le solaire photovoltaïque. Malgré ce potentiel, un certain nombre de micro centrales hydroélectriques ont été construites spécialement pour l'électrification rurale et sont gérées par l'Agence Burundaise pour l'Electrification Rurale (ABER). Nombre d'entre eux n'ont pas réussi à fournir de l'électricité fiable dans la plupart des régions isolées en raison de la réduction générale du niveau d'eau et de la croissance de la demande énergétique des communautés. Cette étude visait à identifier un système d'alimentation hybride simple, fiable, viable et rentable pour surmonter l'intermittence de l'alimentation en énergie à partir d'énergies renouvelables. Le dimensionnement, l'exploitation et le contrôle des sources renouvelables dans un système d'alimentation hybride sont essentiels pour sa faisabilité et sa stabilité techno-économiques. Le logiciel HOMER (modèle d'optimisation hybride pour plusieurs ressources énergétiques) a été utilisé pour développer une conception hybride optimale. À partir de cette étude, une source d'énergie renouvelable complémentaire parfaitement adaptée à la microcentrale hydroélectrique existante a été définie comme une solution aux fluctuations de la production d'énergie dans la zone d'étude. Une combinaison de la microcentrale hydroélectrique de Kigwena, de la technologie solaire photovoltaïque et du réseau électrique de services publics pour lisser les intermittences inattendues de ces énergies renouvelables s'est révélée être une option viable sur le plan techno-économique pour améliorer la capacité de l'hydroélectricité avec le plus bas Coût d'électricité de $0{,}0334\ USD/kWh$. Ce coût se situe dans la marge par rapport au tarif actuel de l'électricité au Burundi, allant de $0{,}023\ USD\ /\ kWh$ à $0{,}072\ USD\ /\ kWh$. L'étude servirait de modèle à d'autres régions confrontées aux mêmes problèmes.

Mots clés : Micro-hydroélectricité, Système d'alimentation hybride, Optimisation, Énergie renouvelable, Système Non /Ou connecté au réseau.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND ACRONYMS

ABER	Burundian Agency for Rural Electrification
AC	Alternating Current
BuF	Burundian Franc
COE	Cost of Electricity
CRF	Capital Recovery Factor
CV	Cheval Vapeur Unit
DC	Direct Current
DGHER	Directorate General of Hydraulics and Rural Electrification
GHI	Global Horizontal Irradiation
GIS	Geographic Information System
GTI	Global Tilted Irradiation
HOMER	Hybrid Optimization model for Multiple Energy Resources
HPS	Hybrid Power System
IGEBU	Burundi Geographical Institute
LCOE	Levelized Cost of Energy
MEM	Ministry of Energy and Mining
MPPT	Maximum Power Point Tracking
NASA	National Aeronautics and Space Administration
NPV	Net Present Cost
PLL	Phase-locked Loop
PV	Photovoltaic
REEEP	Renewable Energy & Energy Efficiency Partnership
REGIDESO	Utility of Water and Electricity Distribution in Burundi
STC	Standard Test Conditions
TV	Television
U.S.A	United States of America
USD	United States Dollar

CHAPTER ONE: INTRODUCTION

1.1. Background information

The exhausting fossil fuel energy and climate change issues have made a dual pressure to the world, and consequently is leading to an urgent development of renewable energy technologies. Hence, a complete transition from fuel-based generation to renewable energy generation will need a non-single combination of these alternating energies. The sources like hydro, geothermal, bio-mass, wind, solar, hydrogen, nuclear need to be made to work together in different combinations as a single unit to meet a common energy demand in a specific area. As these sources are intermittent, integrating two or more resources that can compensate the drawbacks of one another was found to be a solution to overcome this problem (Fathima & Palanisamy, 2015). The idea is to use the strengths and disadvantages of one source to counterbalance those of the other.

For the case of Burundi, only about 10 % of its population has access to electricity (Ministry of Energy and Mining, 2013). Furthermore, rural areas are characterized by dispersed population and are more often not close the grid infrastructure, the accessibility to the grid prove to be exorbitantly expensive, hence more possibly unfordable. The over-dependence on hydropower as the one main renewable energy source for its electricity generation has been hampering the economy of the country. According to Renewable Energy & Energy Efficiency Partnership (REEEP), the total electricity production in Burundi had registered a reduction of 40% due to a reduced volume of water in 2009 (REEEP, 2012).

However, this country has many options for renewable energy development such as a major hydropower potential and extended periods of sunshine. The theoretical hydropower capacity of the country is estimated at 1,700 MW, with about 20 percent commercially viable (REEEP, 2012) while the average solar insolation of the country is estimated at 2000 kWh/m^2.year (Ministry of Energy and Mining, 2012). The decentralized energy systems have been recognized as the investments that should be taken to have the fastest and the most economical results. As even more there are no fossil fuels resources yet discovered in this country, renewable energies are becoming more and more important strategic component for diversification of its national energy supply (Poor People’s energy outlook, 2017).

Efforts to facilitate a distributed generation system have been facilitated by Burundian Agency for Rural Electrification (ABER), formerly called DGHER "Directorate General of Hydraulics and Rural Electrification". A number of micro-power plants have been constructed. However, due to climate dependence of renewable energies, the failure to supply reliable electricity to communities have been registered (Energypedia, 2018).

In this regard, as electricity from the national grid is not sufficient to compensate these energy fluctuations for rural communities, and as electricity from renewable energies is intermittent, the combination of two or more renewable energies (hybrid power system) is a way of overcoming intermittency in energy generation. The design and structure of a sustainable hybrid power system should consider optimal techno-economical energy sources locally available in an area to supplement the existing energy sources, and energy consumption the system would have to support.

This work sought the feasibility of upgrading the capacity of the existing Kigwena micro-hydropower plant with supplementary energy sources. These supplementary energy sources would compensate the micro-hydropower plant by increasing the generation capacity to satisfy the electrical load demand and overcome the intermittency in energy supply.

1.2. Problem statement

The power sector in Burundi which mainly relies on hydropower is characterized by a very low level of electrification (installed capacity of 35.8 MW). About 10 % of the population have access to electricity, and even more, are facing a planned electrical load shedding on a daily basis especially during dry seasons (Ministry of Energy and Mining, 2012).

Rural areas are characterized by dispersed population which most depends on traditional biomass as energy source and are more often not close to the grid infrastructure. Hence, ABER started constructing micro-hydropower plants in rural areas to satisfy their energy demand. However, these plants which rely on climatic conditions are facing power cutoffs in supply on a daily basis mainly during dry seasons (Hamududu & Killingtveit, 2012).

For this case study of Kigwena micro-hydropower plant, the electricity production drops due to the general reduction in the level of water. In addition to this, the electricity generated is not enough to satisfy the demand during peak hours even when working at its maximum production capacity (Energypedia, 2018).

1.3. Justification of the research

The low rate of electricity access, of about 10 %, is mainly benefited by people living in Bujumbura city and even more, are facing power shortages and electrical shedding. In the meantime, the transmission network of the national grid has a low efficiency with the estimated losses of 24 % of total energy supply (Bamber, Guinn, & Gereffi, 2014).

As a response, specially made for rural communities, distributed generation system was initiated by ABER as an alternative to centralized generation networks with the target of improving the living conditions of the population as well as to facilitate fighting against poverty. ABER was involved in the construction of five micro-hydropower plants which are Kigwena, Butezi, Kayongozi, Ryarusera and Nyabikere for rural electrification.

However, the general reduction in the level of water, especially in dry seasons and the breakdown of hydropower plants are the source of drop in electricity production in Burundi, mainly depending on hydropower at 98 %. In the droughts of 2009 and 2011, the country has registered a drop of about 40 % of its electricity production which made its economy to be dramatically affected (REEEP, 2012).

Table 1.1 presents the recorded production levels (from 2002 to 2006) of different micro-hydropower plants managed by ABER where there was a production drop of 19 % in 2006 by comparing with production in 2005.

Table 1. 1: Production levels of micro hydropower plants of ABER (MWh) in 2002 - 2006

MHP plants	**2002**	**2003**	**2004**	**2005**	**2006**
Kigwena	out of service	81	30	out of service	out of service
Murore	12.7	18	3	2	12.2
Nyabikere	37.5	64	81	92	9.3
Ryarusera	2.86	12	2	out of service	12.27
Butezi	64.29	98	39	112	133.24
Total	117.4	273	155	206	166.86
(%)	3.00 %	132.50 %	- 43 %	32.90 %	- 19 %

This main dependence on one source of energy (hydropower) makes the country to be vulnerable to climate extremes. Therefore, this main source can be compensated by integrating it with other techno-economical viable energy sources in a study area. Thus, hybrid power system would be a solution to these energy issues in Burundi.

1.4. Objectives of the study

1.4.1. Main objective

This study aimed to identify a simple, reliable, viable and cost-effective hybrid system that would reduce the electricity production intermittency, especially power cutoffs for consumers supplied by Kigwena micro-hydropower plant. The system should be scalable, monitored and can be implemented in other localities.

1.4.2. Specific objectives

The specific objectives of this research were:

- To analyse the load for Kigwena community
- To investigate the available energy resources potential in Kigwena
- To design and simulate an off/on grid hybrid system with the available energy resources
- To evaluate the economic and technical feasibility of the suitable system depending on the supplementary power supply in need to satisfy the daily energy demand.

1.5. Research questions

The main research question of this study was :

- How can energy production fluctuations from micro-hydropower plants be optimized to contribute to electricity supply reliability and access in rural areas?

To tackle this main question, the following sub-questions were addressed:

- How does the change of the flowrate of the river affect the energy supply?
- Will an alternative supplementary source of energy based on power supply deficiency enhance electricity reliability to the community?

1.7. Thesis outline

The thesis is prearranged in five chapters. The general introduction with the background information of the thesis on “Study of a hybrid development in optimization of micro hydropower plant: case of Kigwena in Burundi” is described in chapter one. Apart from this, problem statement, justification of the research, objective of the study research questions and assumptions are contained within.

The literature review is under chapter two and it covers the introduction on state of energy demand and access in the world, as well as in Burundi. Furthermore, it includes the hybrid power systems overview, the side of its technical aspect, the integration of hydropower in a hybrid system and research gap in different studies for the case of Burundi.

Chapter three describes the methodology used to meet the aim of the study and responds to the research questions. Chapter four presents the results obtained and discusses the results of the hybrid system simulated using Homer. Finally, the chapter five draws the conclusion and recommendation made out the whole work.

CHAPTER TWO: LITERATURE REVIEW

2.1. Introduction

The access to affordable, reliable, sustainable, and modern energy for all is proven to be a key for achieving other sustainable development goals as indicated in Sustainable Development Goal 7 (United Nations, 2015) . Nonetheless, energy access, environmental pollution and population growth are the most pressing issues challenging the world nowadays. The situation of universal energy access in Africa is alarming. The worst case is Sub-Saharan region where 633 million people are estimated to lack of electricity access, and other 792 million people have no choice to cook with traditional biomass. Furthermore, in this region, it is expected that the number of people with unimproved energy facilities will increase through 2030 even though efforts are being conjugated to reduce the electricity access rate (Morrissey, 2017).

The United Nations General Assembly of December 2012 emphasized that access to modern energy for developing countries is crucial to the achievement of international agreed development goals (World Bank, 2013).

A large proportion of the population of the world lacks access to modern energy and are mostly concentrated in developing countries in isolated areas. Inclusive economic growth is a key to poverty reduction and energy access was found to be a major factor (World Bank, 2013). The hybrid power system HPS was found as an excellent solution for remote areas where the grid extension is challenged by economic feasibility (Dawoud & Lin, 2015).

For the case of Burundi, although it is described with a low electricity consumption, the national electricity production capacities are insufficient to meet domestic needs (figure 2.1). The target of meeting a high rate of electrification cannot be achieved without a sustainable harnessing of the available energy resources.

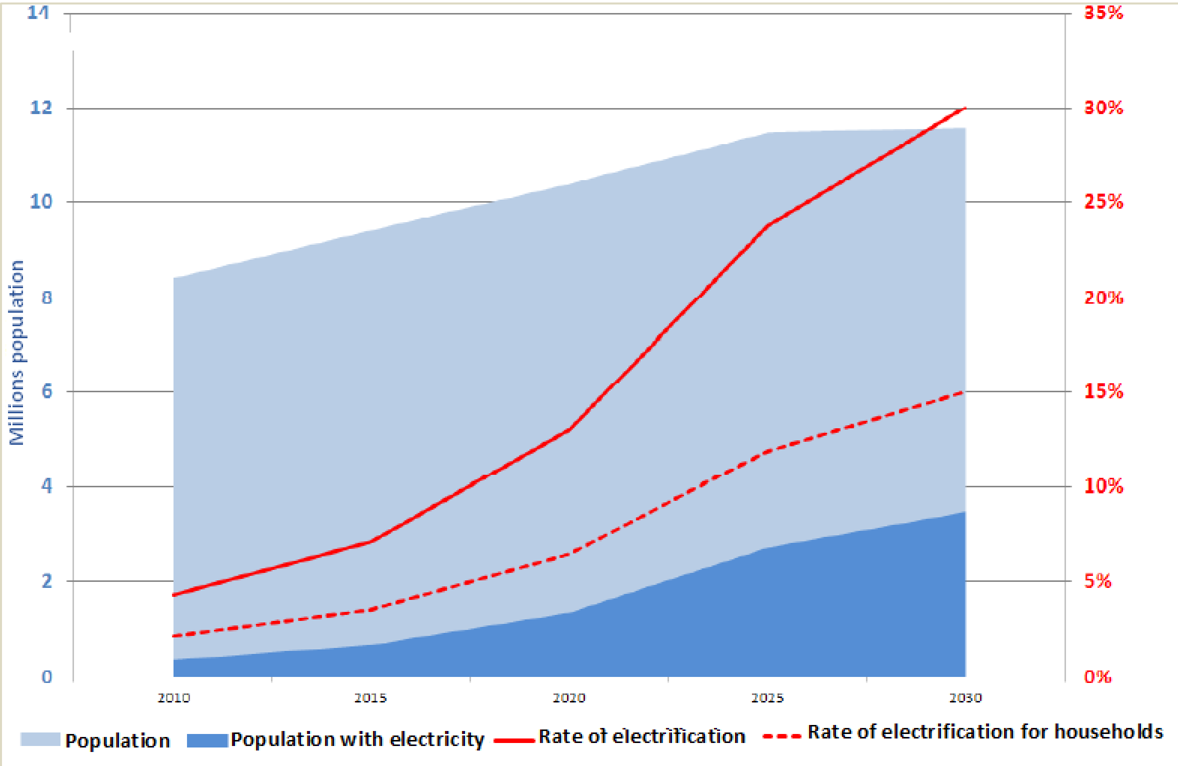


Figure 2. 1: Target for population electrification rate 2010 – 20130 (MEM, 2013)

2.1. Hybrid power systems overview

2.1.1. Recent studies on hybrid power system

The HPS is seen to be a common solution for rural areas electrification (Dawoud, Lin, & Okba, 2018). This technology is expected to be the future for developing countries and is predicted to supply electricity more than one billion people lacking access to electricity. This energy sources combination can improve the power reliability (Dawoud, Lin, & Okba, 2018).

Usually, in HPS, one of the energy sources is a conventional powered by a diesel engine, while the other(s) would be renewables such as solar photovoltaic, wind or hydro. However, different studies have been conducted where the focus was the combination of renewable sources without a conventional source as a back-up. An off-grid hybrid power system of solar PV, wind and hydro energy sources was studied for a remote area in Nepal and concluded that this integration of different sources in a mini-grid increase the power quality and its reliability (Bhandari et al., 2014). A feasibility study for an off-grid hybrid system of small hydro, photovoltaic (PV) and wind for rural electrification was conducted and found that the combination would be a solution for reliable electricity in rural areas in Ethiopia (Bekele & Tadesse, 2012). A hybrid of PV and wind energy system were found a solution to improve the reliability of an isolated micro-grid for rural electrification in Egypt (Dawoud & Lin, 2015). Hybridization of a micro-hydropower and PV system was found to be the best solution solve issues related to rural electrification for a village in Cameroon (Kenfack, Pascal, Tamo, & Mayer, 2009).

The HPS optimization is used to minimize the system cost while the system reliability is maintained. Different factors are here considered. Those factors include the type and capacity of the power system, the size of the system components, the minimum system capital cost, the operation and maintenance cost as well as reduction of the fuel consumption (Dawoud et al., 2018). Different types of HPS, methods and tools have been used for techno-economic analysis when designing an optimal HPS. However, HOMER (Hybrid Optimization Model for Electric Renewables) is a friendly software that has been used for many HPS studies for grid-connected or stand-alone systems (Negi & Mathew, 2014).

For rural electrification in Egypt, a micro-grid of a hybrid PV and wind energy system has been proposed and HOMER software was used for an optimal hybrid design (Dawoud & Lin, 2015). Multi-metaheuristic techniques were used for optimal designing of a grid-connected hybrid system of wind, solar PV and gas turbine with battery storage (Mekhamer, Abdelaziz, & Algabalawy, 2017). An off-grid hybrid study of small hydro, solar PV and wind system for rural electrification in Ethiopia has been analyzed using HOMER energy software (Bekele & Tadesse, 2012). A proposed study of hybridization wind and solar energy in Sri Lank has been modelled for its techno-economic analysis using HOMER software(Udayakanthi, 2015).

The use of diesel engines seems not to be a sustainable solution for the case of Burundi since the country relies on importation of fuels and this with high volatility in prices as it is shown in Figure 2.2.

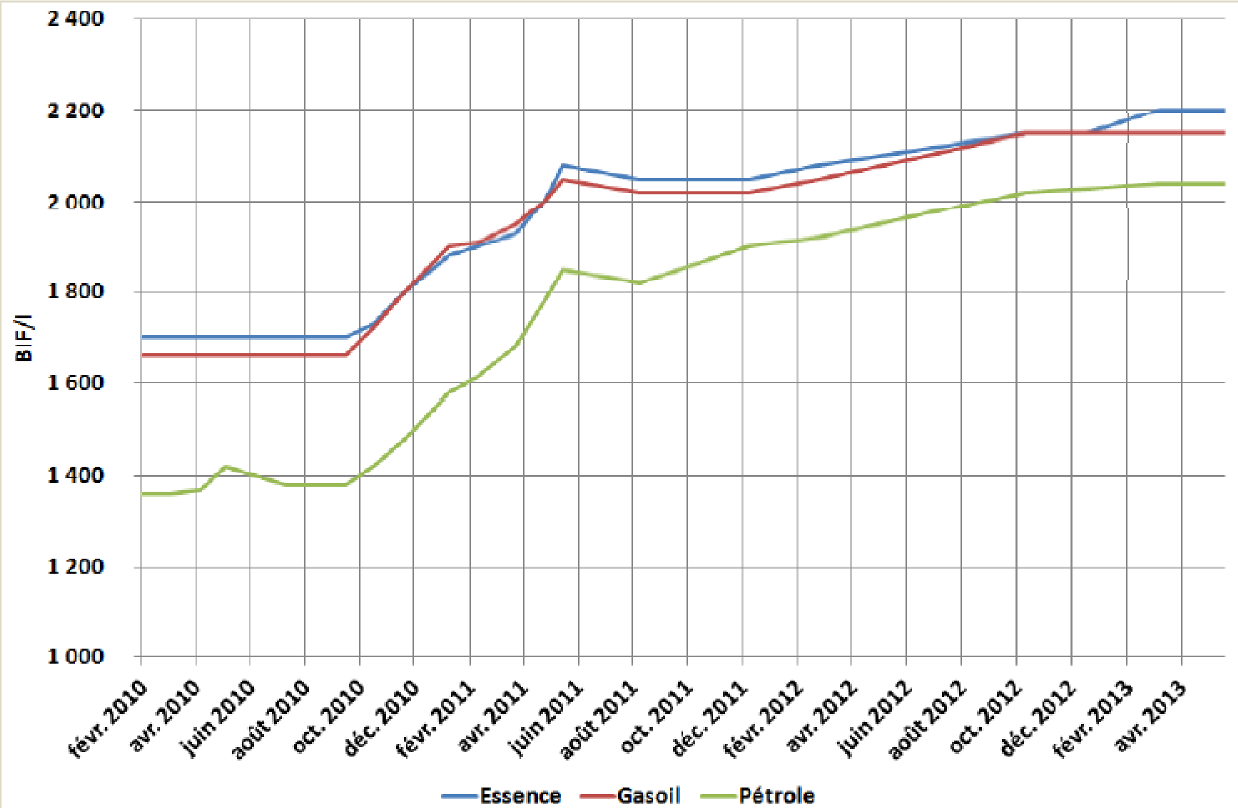


Figure 2. 2: Evaluation of fuels prices since 2010 (MEM, 2013)

2.1.2. Technical aspect of hybrid Power System

2.1.2.1. Synchronization

The synchronization of two voltage sources is the process of reaching the lowest possible difference between their voltage parameters. Consequently, since two AC voltage sources are identified by three variables which are magnitude, phase angle and frequency they are more difficult to synchronize than two DC voltage sources (Ngani, Minaglou, Jaeger, & Sorger, 2017).

There is a recent interest in synchronization AC power sources to the grid voltage which has become more interesting with the spread of renewable energy ((Jaalam, Rahim, Bakar, Tan, & Haidar, 2016), (Anjali, Geetha, & Asst, 2017), (Jean Marie Vianney, Mnati, & Den, 2017), (Rizqiawan, Hadi, & Fujita, 2019), (Adzic, Vlado, Boris, Nikola, & Katic, 2013), (J Mahdi, A. Al-Anbarri, & A. Hameed, 2018)).

The power that renewable energy sources deliver must obligatorily feed into the grid at frequencies closely matching that of the grid power. With hybrid power system, the main challenges are encountered when there is a combination of many powers sharing the same load (Iftikhar & Sarwar

Awan, 2017). The waveforms of the different sources in hybrid power systems must be synchronized. Precisely, these sources have to match in voltage, frequency, phase, and phase sequence.

Many techniques for synchronization exist. The widely used method is the Phase-locked Loop (PLL) method. This method allows to track the grid frequency and is commonly used for synchronization of power electronic converters with the basic structure shown in Figure 2.3 (Ngani et al., 2017).

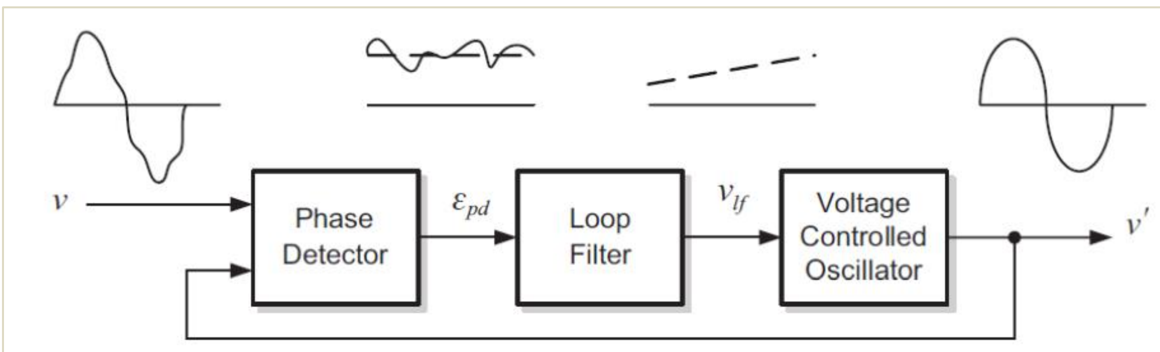


Figure 2. 3: Basic configuration of a PLL technique

A synchronization with the PLL method was proposed in modelling a hybrid system of wind and PV connected with the grid. The method was found to be able to reduce the harmonics and match the grid frequency during voltage unbalances (Nair, Karthika, & Manju, 2015).

A promised scheme for synchronization has to fulfill some conditions that are (TEJA, 2013):

- proficient detection of the phase angle of the utility signal;
- tracking of the phase and frequency variations;
- rejection of harmonics and any disturbance.

A grid-connected power inverter that adapts the magnitude, frequency and phase angle of the micro-grid voltage was a case in synchronization the power of a wind farm to utility grid characterized by frequency and voltage variations. This enabled smooth and fast synchronization (Rekik, Abdelkafi, & Krichen, 2015).

Therefore, the schemes used in grid-connected mode obey the synchronization conditions matching to the grid. An inverter in a grid-connected mode has to track the grid frequency. For a grid-tied photovoltaic system, the required key factors for an efficient and effective system are Maximum Power Point Tracking (MPPT), Grid synchronization, Islanding, DC-link voltage control and Current control.

2.1.2.2. Efficient power transmission and distribution

For efficiency and power quality improvement, a technical aspect proposed by Soham Ghosh includes reduction of losses due to power transmission and distribution. In his study, he highlighted that data collection regarding existing loads, operating conditions, forecast of expected loads are some of the strategical measures (Ghosh, 2012).

Despite the fact that U.S.A power transmission and distribution is ranked among the most efficient in World, losses in their system are about 6 % of total electricity generation (Warwick, Hardy, Hoffman, & Homer, 2016). The average of losses between 6 to 11 % is ranged for advanced countries in the World (Ghosh, 2012**).** The transmission losses due to outdated technology in Burundi was assessed to be 24 % of total supply in 2012, a percentage that represented a daily loss ranging from 20 to 30 MW (Penny, Andrew, & Gereffi, 2014).

In addition to the low generation capacity, Burundi is facing high energy transmission and distribution losses. To minimize the losses between generating facility and load, distributed generation is an alternative solution to centralized electricity generation networks. Nevertheless, it is crucial to interconnect distributed generation networks with one another to make it more reliable to consumers (MISHRA, 2013**).** The combination of several energy sources in hybrid systems was found to be a solution for remote area electrification (Dawoud et al., 2018).

2.1.3. Hydropower generation integrated into a hybrid power system

Hydropower is classified as one of the oldest energy techniques of converting mechanical energy into electrical energy. Small hydropower is known to be environmentally friendly, flexible in operation and requires small investment with a short return period. For those reasons, it has become the point of attraction for private sectors (Mehra, Alvi, & Rajasekhar, 2007).

There is no consensus in the World on the classification of hydropower plants according to installed capacity. They can be classified as large, small, mini, micro and pico-hydropower plants. Mini, micro and pico-hydropower plants could be regarded as small hydropower plants. However, they have specific technical characteristics and deserve their own definition.

Table 2.1 highlights the classification according to the installed capacity ((Sharma & Singh, 2013), (Dave, Parmar, & Parmar, 2015)). Nevertheless, different countries and organizations have different definitions.

Table 1.1: Hydropower classification according to installed capacity

Terminology	Capacity limits	Unit
Large	> 100	MW
Medium	15 - 100	MW
Small	1 - 15	MW
Mini	0.1 - 1	MW
Micro	5 - 100	kW
Pico	< 5	kW

Small hydropower is considered to be one of the viable alternatives for rural electrification. It is seen as an option to electricity deficit for rural and remote areas of developing countries which, apart from financial benefits, is also known for easy implementation to communities served (Dave et al., 2015).

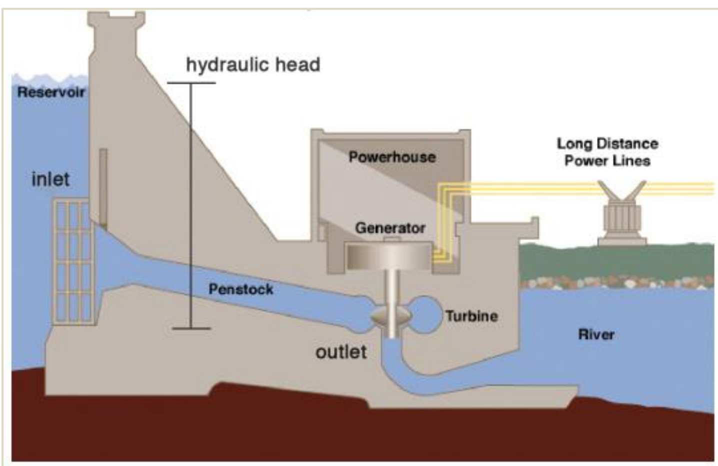


Figure 2. 4: View of a hydropower with a reservoir

Hydropower plants can be classified in different ways according to their characteristics.

- ✓ Impoundment plants: they are the most common type of hydroelectric power plants and are usually large hydropower schemes and use a dam to store river water in a reservoir.
- ✓ Run-of-river plants**:** this type of plant generally does not have storage system. By means of a diversion weir, water is diverted from the river and given to the transmission canal or sometimes tunnel.

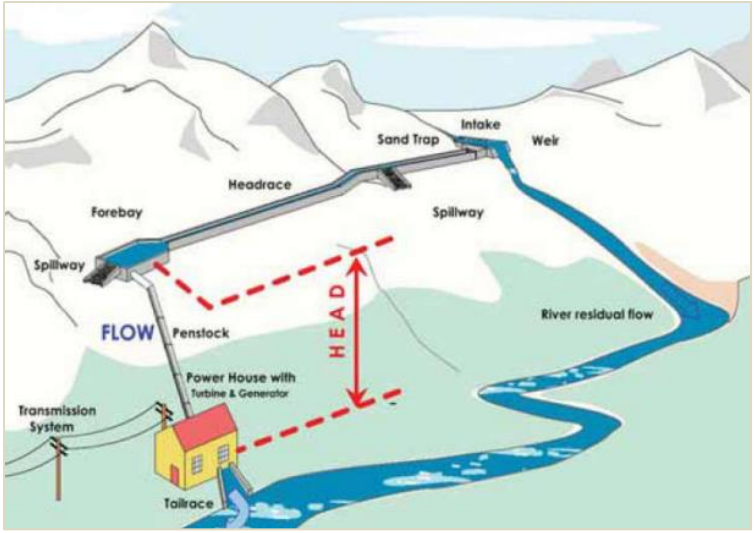


Figure 2. 5: Schematic diagram of Run off river micro hydropower plant

- ✓ Pumped-storage plants**:** in contrast to conventional hydropower plants, this type of plants reuse water and store electrical energy as potential energy. They pump water to an upper reservoir at times of surplus energy on an electrical supply grid-typically, at night.

Hence, as energy consumption in the world is expected to increase intensely, energy sources combined together would be a solution to cover the growing energy demand. Many studies for the combination of hydropower and other renewable energies in a hybrid system have been conducted. A study of a hybrid system combining micro-hydropower and Solar PV was found to be able to continually supply the energy to the load of Bunnasopit school in Thailand (Iemsomboon, Pati, & Bhumkittipich, 2013). Various feasibility studies and researches on hybrid power systems combining hydropower and other sources of renewable energy have been conducted in different locations: small hydro, PV, wind hybrid for off-grid rural electrification in Ethiopia ((Bekele & Tadesse, 2012); micro-hydro and PV hybrid in Thailand (Iemsomboon et al., 2013); study on connecting many hydro-power plants for effeiciency improvement (Markus et al., 2017) ; hybrid system of PV, wind, micro-hydro and Diesel in Indian (Lal, Dash, & Akella, 2011), a pico-hydropower and PV hybrid in Cameroon (Nfah & Ngundam, 2009); micro-hydro and PV hybrid design for developing countries (Kenfack et al., 2009).

2.2. Researches for hydropower efficiency improvement

Various researches have been done so as to improve the performance of micro-hydropower (MHP) system by increasing the efficiency and to promote low-cost technologies especially for developing countries which need to supply electricity in rural areas.

Several small hydropower plants connected alongside a river were proposed as a solution to increase the efficiency and to promote low-cost technologies especially for developing countries which need to the supply electricity in rural areas.

Several small hydropower plants connected alongside a river were proposed as a solution to increase the efficiency of generating capacity and this would reduce the downtimes and operating costs. With this research, there is a possibility of connecting together small hydropower plants, private and independent plants and an increase in overall energy production of 2 to 5 % was predicted (Markus et al., 2017)**.**

The blade cross-section of a turbine was found to be more performant when it is shaped in full v. This study was conducted on a simplified pico-hydro system. The rotational speed of the alternator shaft and the voltage obtained were measured and found the best with 1678.95 rpm and 212.1 V for a full v-shaped cross-section (Edeoja, Ibrahim, & Tuleun, 2016).

With the purpose of sustainable development design, a small hydropower plant was evaluated. The assessment carried out on Francis turbine concluded that the highest losses of output power is obtained for the lowest water head combined with the lowest flow rate and this translates the largest financial loss (Walczak, 2018).

Ion & Marinescu (2011) proposed a single control structure for an autonomous micro-hydro power plant to ensure both the voltage and frequency regulation of an isolated induction generator. They performed simulations and experiments on the proposed configuration so as to validate the reliability under a static and dynamic load (Ion & Marinescu, 2011).

However, as hydropower, like other renewable energy sources, is intermittent (seasonal dependent) and conditioned by available river flowrates, its output power is fluctuant and has an impact on a supplied load. Figure 2.6) highlights how the turbine shaft torque and output power varies in function of the rotating speed.

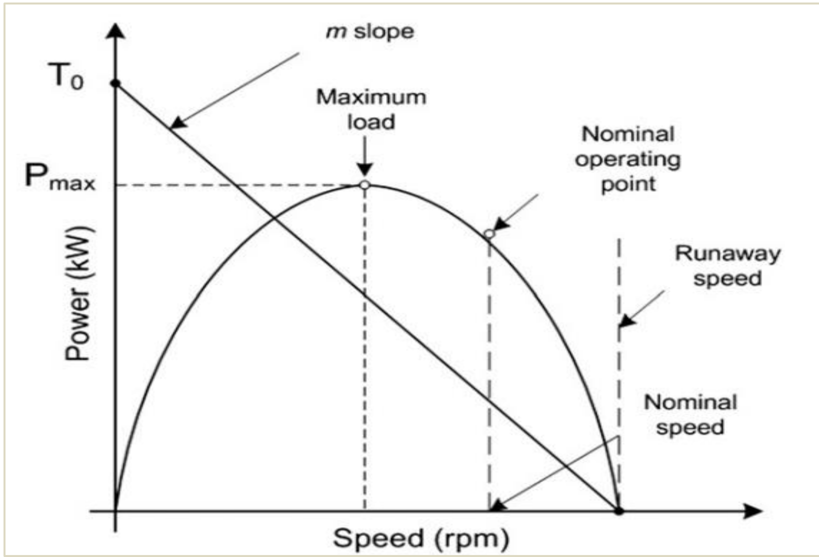


Figure 2. 6: Hydraulic turbine torque and power dependence on speed (Ion & Marinescu, 2011)

Furthermore, the level of river flowrate has an impact on turbine efficiency (Barelli, Liucci, Ottaviano, & Valigi, 2013). Figure 2.7 shows how turbine efficiency varies with river flowrate.

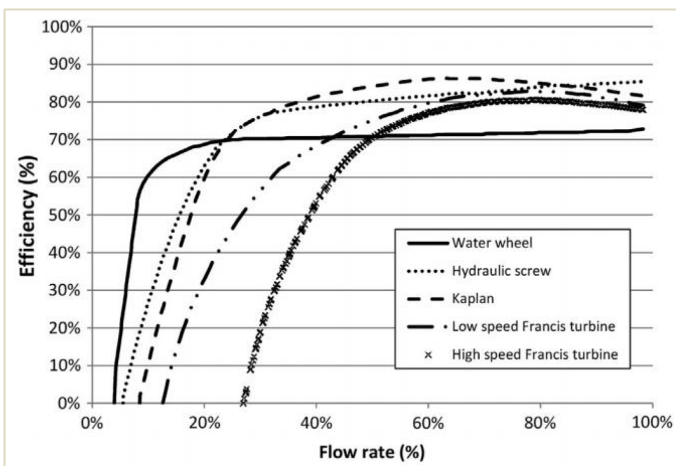


Figure 2. 7: Impact of flowrate on Efficiency (Barelli, Liucci, Ottaviano, & Valigi, 2013)

2.3. Analysis of the value chain of Burundian power sector

The value chain of power infrastructure is composed of generation, transmission, distribution and trading. The efficiency of electricity value chain plays a big role in the power sector as this affects electricity supplied to consumers. The key objectives of upgrading electricity value chain in Burundi today are as result of the increasing capabilities to expand access to electricity at the community level, and to facilitate access to a more reliable source of electricity for industrial growth (Ministry of Energy and Mining, 2013)**.**

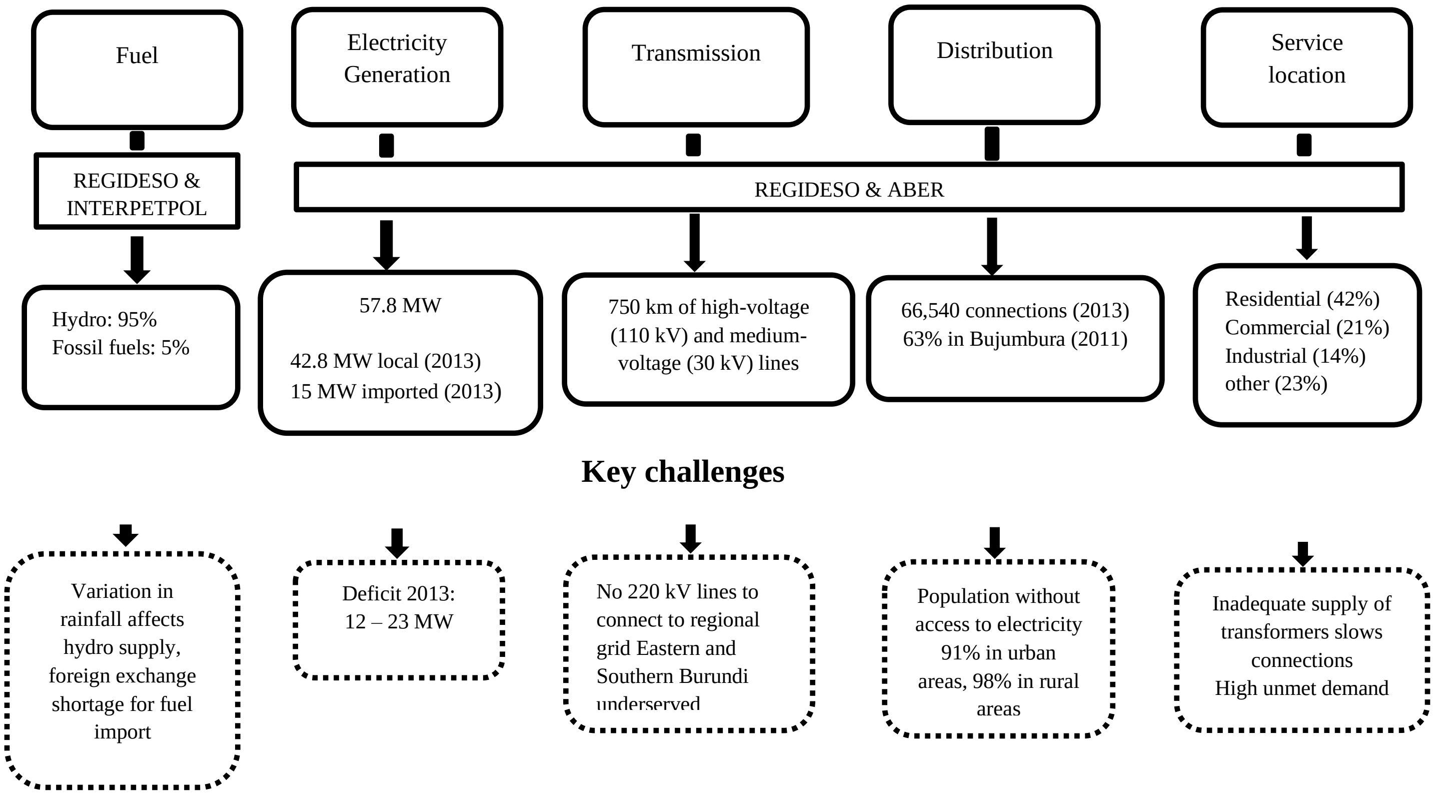


Figure 2. 8: Burundi in the Electricity Value Chain and key challenges (Penny et al., 2014)

For this, because of this deficiency in power generation, rural electrification from the main grid is still an unsolved problem. The program initiated by ABER for rural electrification is challenged by intermittency character of renewable energies. Therefore, any reliable solution to this gap would bring a change in the Burundian energy sector. Furthermore, the existing network is not adequate to effectively develop connections between the national grid and regional power lines, restraining the probable engagement in energy trade to meet the energy demand of the country.

2.4. Research gap

Most research that has been done in Burundi shows that electricity supply mainly depends on hydropower generation. It is noticeable that the power supply of this country is not reliable during the whole year, particularly in dry seasons. The intermittency of stream-flows in most parts of the country is due to climate change and this has a direct negative impact on the power supply of the country (Bodegom & Satijn, 2015). Furthermore, most research in this country ((Mashauri & Michael, 2005); (Hartvigsson, 2012); (Ministry of Energy and Mining, 2013)) has concentrated on the possibility of small hydropower plants development as main option to reliable electricity supply. Therefore, this study assesses the possibility of best hybrid power system that can be applied to support the insufficient power generation of micro-hydropower plants. Therefore, as this country is endowed with different renewable energy resources (Ministry of Energy and Mining, 2012), this study would pave way for developing similar studies for reliable rural electrification in other locations of the country. This study is also the first in its kind in Burundi as it deals with hybridization of an existing micro-hydropower.

CHAPTER THREE: RESEARCH METHODOLOGY

3.1. Introduction

This chapter presents the methods used to attain the aim of the thesis and to obtain the pertinent results and conclusions. Mainly, the focus is on the methods used to evaluate the power gap of the village, identify the performance Kigwena power plant and thus, to upgrade the capacity of the plant to meet the electrical load demand. The data obtained are presented in details. The methods of data analysis and those used to design the system configuration are also presented. HOMER software is then used in such a way that it allows the combination of different energy sources as input and make optimization for the combined system. Figure 3.1 below highlights the methodology suggested for the system.

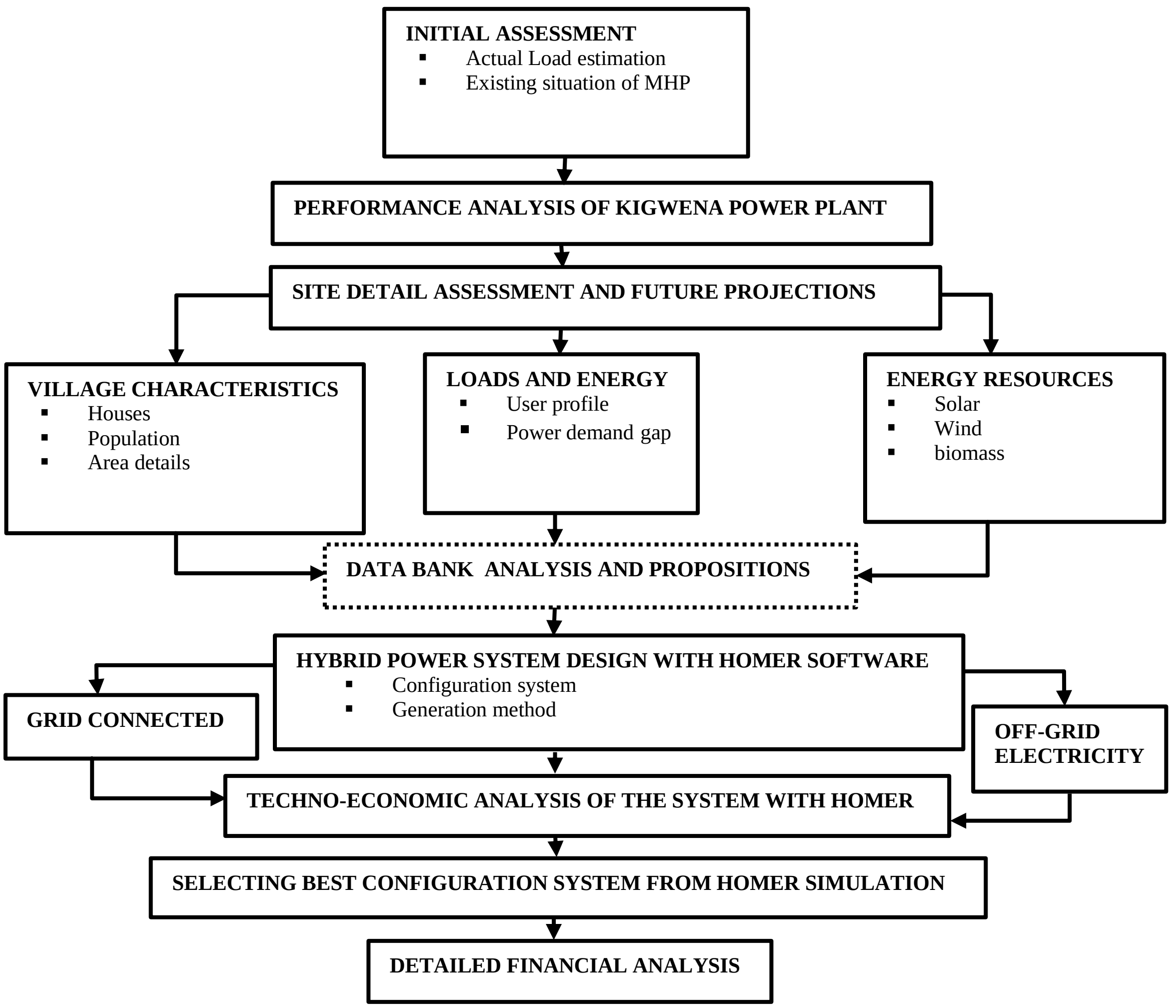


Figure 3. 1: Functional diagram of the model

3.2. Data collection and treatment

3.2.1. Study area description

The case study is located in South - Western Burundi, in the province and community of Rumonge. It is enclosed in Cabara and Karonda villages in Kigwena zone, exactly 4 km from the National Road 3. Rumonge is a new province that includes four communes namely Muhuta, Bugarama, Buyengero, and Burambi. The site is situated at 4°08'47.10" South and 29°32'34.02" East, and at an elevation of about 1011.632 m. The site is close to the utility grid and to a very small village accessible by road where the reconnaissance survey was conducted. The targeted village is supplied by Kigwena micro-hydropower and its total load is now beyond the plant capacity due to small businesses increasing and new lifestyle.

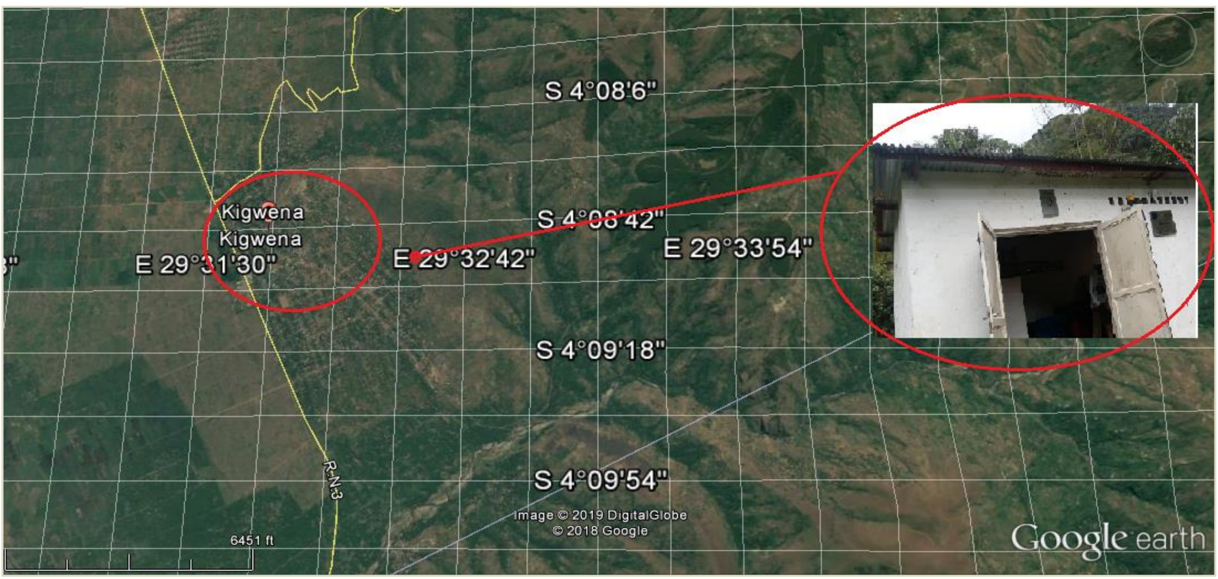


Figure 3. 2: Geographic allocation map of the village powered by Kigwena micro hydropower plant

From the reconnaissance study, the river flowrate is not enough to sustain the plant the whole year, and the plant takes advantage of having a river with enough hydraulic head (gross head of 141 m). Since other available renewable resources exist throughout the year at this specific location, there is a possibility of upgrading its capacity. There is no constructed pond and also, almost all the river is diverted towards the penstock.

Figure 3. 3: Photo of the weir diversion

3.2.2. Electrical load of the village

3.2.2.1. Assessment of electrical load of the village

The village has an estimated capacity of 3,648 villagers (according to the survey). The micro-hydro power plant was constructed by ABER as an initiative to provide electricity to the village.

The installed capacity of the plant is 100 kVA. However, due to low river discharge the power output of this plant has never reached its maximum capacity even if the village peak load is higher than it. Therefore, as this plant is not sufficient to supply the whole village load, the users are constrained to disconnect some of their loads.

3.2.2.2. Estimation of electrical load demand of the village

A survey was conducted in the study area in order to evaluate the load demand gap of the village. For this, a future projection is indispensable to predict the expected load in the future and then find out an optimal and viable solution for the future.

Figure 3. 4: Photo of the village powered by Kigwena micro hydropower plant

According to James Holland Jones (Jones, 2006), the population forecast can be estimated using the following relationship.

$$P_t = P_0 \ (1 + r)^n \tag{3.1}$$

Where P_0 is the size of the initial population, P_t is the population at the forecast year, r Population growth rate and n is the number of years between the forecast year t and initial year.

In this village, the load is mainly composed of bulbs for lighting, radio and television, flour and palm oil mills, medical centre, primary and secondary schools load. According to the survey, there are 456 households. The assumption was made and this considered 8 people in each household.

Therefore, a survey helped to determine the total electrical load considering the eventual expansion of the village. Hence, some appliances like iron and TV were considered to be only used by high income households. Furthermore, 9 classrooms were considered for primary schools and 4 classrooms were considered for secondary schools.

3.3. Performance assessment of Kigwena micro-hydropower plant

This micro-hydropower plant is based on run-off of the river structure, hence the effect on the environment is insignificant since the noise from the turbine-generator group is lower to be qualified noise pollution.

Micro-hydro power plants are evaluated based on their power output, voltage fluctuations and user satisfaction. This assessment has mainly focused on the power output of the plant in order to evaluate the generating capacity of the plant and from that, deducing electrical load demand gap for users.

3.3.1. Characteristics of electromechanical equipment of the plant

3.3.1.1. Turbine

The installed turbine is a horizontal shaft Ossberger cross-flow turbine with the following parameters.

Table 3. 1: Installed turbine at Kigwena power plant

Parameter	Unit	Description
P = 91.3	CV	Hydraulic power
N = 1500	min^{-1}	turbine speed
H =131.7	m	Nominal Head
Q_{max} = 65.0	l/sec	Maximum discharge

3.3.1.2. Generator

The generator in operation is a three-phase synchronous generator of type MJT 250 MA4 B34 operating at 50 Hz frequency and having the following electrical parameters (Table 3.2). This operating generator is self-exciting, by means of a brushless type excitation system.

Table 3. 2: Electrical parameters of operating alternator

Parameter	Unit	Description
S = 100	kVA	Apparent power
U = 400	V	Three phase voltage system
f = 50	Hz	Frequency
I = 2.2	A	Excitation current
V = 18	V	Excitation voltage

Figure 3.5 highlights the group turbo-generator installation in the plant.

Figure 3. 5: View of the mounted turbo-alternator group of Kigwena plant

3.3.2. Performance evaluation of the plant

The performance evaluation of this MHP consists of inspecting the output and input values at different points of electromechanical components of the plant. The available data are used for evaluation. Recording of power outputs and frequencies at different times of the day is also done. Figure 3.6 gives a description of the assessment.

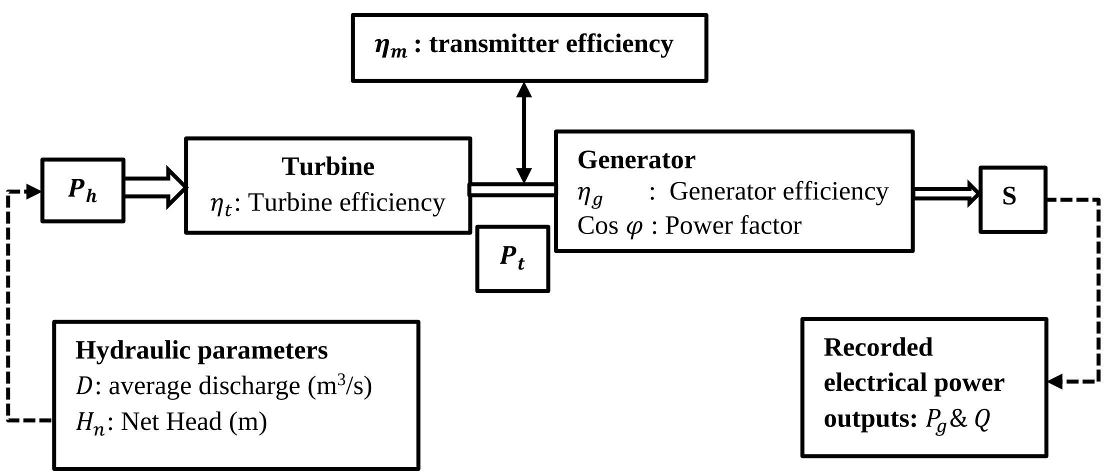


Figure 3. 6: Assessment of a micro hydropower performance

The electrical power output of generator is given by equation (3.2).

$$P_g = P_t \ \eta_g \ \eta_m \tag{3.2}$$

The power out of the turbine shaft can be written as follows (equation 3.3):

$$P_t = \eta_t \; P_h \tag{3.3}$$

The hydraulic power (available power at the turbine inlet) can be formulated as:

$$P_h = \rho \;\; g \; H_n \; D \tag{3.4}$$

The plant overall efficiency is given by equation (3.5):

$$\eta_0 = \frac{P_g}{P_h} = \eta_t \; \eta_g \; \eta_m \tag{3.5}$$

Finally, the turbine efficiency is found equal to equation (3.6):

$$\eta_t = \frac{\eta_0}{\eta_g \; \eta_m} \tag{3.6}$$

3.3.3. Streamflow assessment

There are unlimited methods used for river flow rate optimum estimation to predict a hydropower potential. The science of hydrology is more involved, especially for ungauged rivers where water discharges for a long period are not available. This study may consider the rainfall and streamflow, determining the catchment areas, drainage basins determination, losses due to evapotranspiration (European Small Hydropower Association, 2004)**.**

The variation of water discharge along the whole year and the available head is a key for water potential estimation. In the common case, the river flowrate estimation is performed by hydraulic institutions in a country by installing a gauging station in the river under consideration. If this was the case, the data for streamflow time series would have repeatedly be collected over many years. Unfortunately, this case study is dealing with ungauged river and only 2 months were evaluated by ABER before the rehabilitation of the plant (indicated in Table 3.3).

Table 3. 3: River flowrates data from ABER

Discharge	Value	Year	Description
D_1	85 l/s	Feb-2015	Monthly average discharge measured in February 2015
D_2	32 l/s	Sep-2016	Monthly average discharge measured in February 2016
D_{nom}	65 l/s	Mar-2017	Rated discharge of the turbine installed in 2017

This data is not enough to predict the energy potential of hydropower. European Small Hydropower Association highlighted that for the case where stream-flow series are not available, the discharges are to be measured at least one year. Unfortunately, the time constraint did not allow to perform those measurements.

However, as HOMER software uses optimization method when combining two or more energy sources and requires 12 inputs as monthly data for each source, this has led to the use of estimation techniques.

The estimation techniques mentioned above could be imprecise and not match the observed output power as this study works on an existing power plant. The proposition was to use the real data obtained when the plant is in operation mode as the aim is to upgrade its capacity. For that reason, as the power at the generator output can be given by equations 3.2, 3.7 and 3.8, it is possible to deduce the turbine output power.

$$Generator\ (kVA) = \frac{(Turbine\ output\ in\ kW) * (Generator\ efficiency)}{Generator\ power\ factor} \quad (3.7)$$

$$S = \left[P^2 + Q^2\right]^{1/2} \quad (3.8)$$

Where S $[kVA]$ is the apparent power, P $[kW]$ active power and Q $[kVAr]$ reactive power at the generator output.

The values of P and Q are recorded every 2 hours. Figure (3.7) is a view of the generator output at the study area.

Figure 3. 7: Photo of the generator output at Kigwena power plant checked at 1:30 pm on 16/04/2018

The data recorded throughout the year 2018 was used in this study after calculating their daily and monthly mean values.

The estimated water discharge at the entrance of the turbine is found using the equations (3.4), (3.7) and (3.8). The calculations were developed with the assumption that the river flowrates were not extremely impacting the turbine efficiency (Figure 3.8).

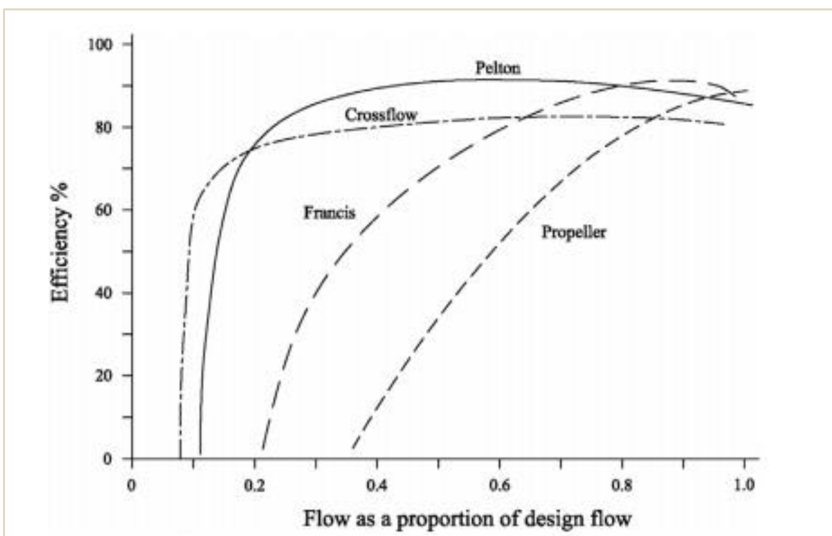


Figure 3. 8: Turbine efficiency according to water flows (Elbatran, Yaakob, Ahmed, & Shabara, 2015).

3.3.4. Plant utilization factor

A measure of the extent of the use of a generating power plant is called plant utilization factor. For the economical purpose, this factor is expected to be greater than 25 % for a feasible project. It measures the effective utilization of the total installed capacity of the plant (Patil Dinkar & D.V, 2015)**.** It is defined as the ratio of the peak load and the rated capacity of the plant.

$$Plant\ utilization\ factor = \frac{Peak\ Load}{Plant\ capacity} \tag{3.9}$$

3.4. Alternative energy resources assessment in the study area

3.4.1. Assessment solar energy potential

The input data required by HOMER software must be a series of either monthly insolation in a specific location. Unfortunately, the data available from Burundi Geographical Institute (IGEBU) does not include this case study location. However, a series of empirical equations (equations 3.10 to 3.14) enables to estimate data for monthly insolation ((John & Beckman, 2013), (G.Bekele & G. Tadesse, 2012))

$$H = H_0 \left(a + b \frac{n}{N} \right) \tag{3.10}$$

Where H is the monthly average daily radiation on horizontal surface (J/m^2); H_0 the monthly average daily extra-terrestrial radiation on a horizontal surface (J/m^2); N monthly average of maximum possible daily hours of bright sunshine; n monthly average daily hours of bright sunshine; a and b are empirical constants depending on location estimated to a = 0.30; b = 0.51 for this study (John & Beckman, 2013).

The monthly average daily extra-terrestrial insolation H_0 on horizontal surface is found using the following equation (3.11).

$$H_0 = \frac{24 * 3600\, G_{SC}}{\pi} \left[1 + 0.033 * \cos\left(\frac{360\, n_d}{365} \right) \right] + \left(\cos\varphi\ \cos\delta\ \sin\omega_S + \frac{\pi\ \omega_S}{180} \sin\varphi\ \sin\delta \right) \tag{3.11}$$

Where n_d is the day in the year; G_{sc} the solar constant (G_{sc} = 1367 W/m^2); φ the latitude of the location (4.08°); δ the declination angle (in degrees) given by the relation (3.12) and ω_s is the sunset hour angle (in degrees) given by the relation (3.13).

$$\delta = 23.45\ \sin\left(360 \frac{248 + n_d}{365} \right) \tag{3.12}$$

$$\omega_S = \cos^{-1}\left(-\tan\varphi\ \ \tan\delta \right) \tag{3.13}$$

The day length, N, is number of hours between sunrise and sunset given by (3.14) equation.

$$N = \frac{2}{15}\omega_S \qquad (3.14)$$

3.4.2. Assessment of wind energy potential

The monthly average wind speed data is obtained from IGEBU for a period of four years (2015 – 2018). This data is collected by the station located in Nyanza-Lac area considered by IGEBU having the same climatic conditions as Kigwena.

Table 3. 4: Wind speed data for the study area from IGEBU (at 10 m)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	**Average**
0.23	0.29	0.29	0.26	0.41	0.64	0.75	0.85	0.90	0.85	0.60	0.38	**0.54**

Therefore, as this was not enough and not specific to the present study area, NASA data is also used for comparison purpose. Additionally, the data from IGEBU is measured at 10 m height which is too low for assessing wind turbine performance. For that reason, the following equation is used to extrapolate the collected data to the hub centre of the selected wind turbine (John & Beckman, 2013)**.**

$$\frac{V(Z_1)}{V(Z_2)} = \left[\frac{Z_1}{Z_2}\right]^{\alpha} \qquad (3.15)$$

Where Z is the height $V(Z)$ is the wind speed at the height Z . The value of the exponent α is a function of these factors (terrain, wind speed, temperature, surface roughness, time of day, and season) and is generally taken 1/7 (0.14) when the detailed information is not available.

3.4.3. Assessment biomass resources potential

Biomass refers to all organic matter that is derived from plants and animals. Biomass resources include agricultural crops and their residues, wood and wood wastes, municipal solid waste, animal residues, food processing residues, aquatic plants and algae (Hensley, Gu, & Ben, 2011)**.**

Generally, estimation of biomass potential can be categorized into theoretical potential, technical potential, economic potential, implementation potential and sustainable potential (Rettenmaier, Schorb, & Koppen, 2010).

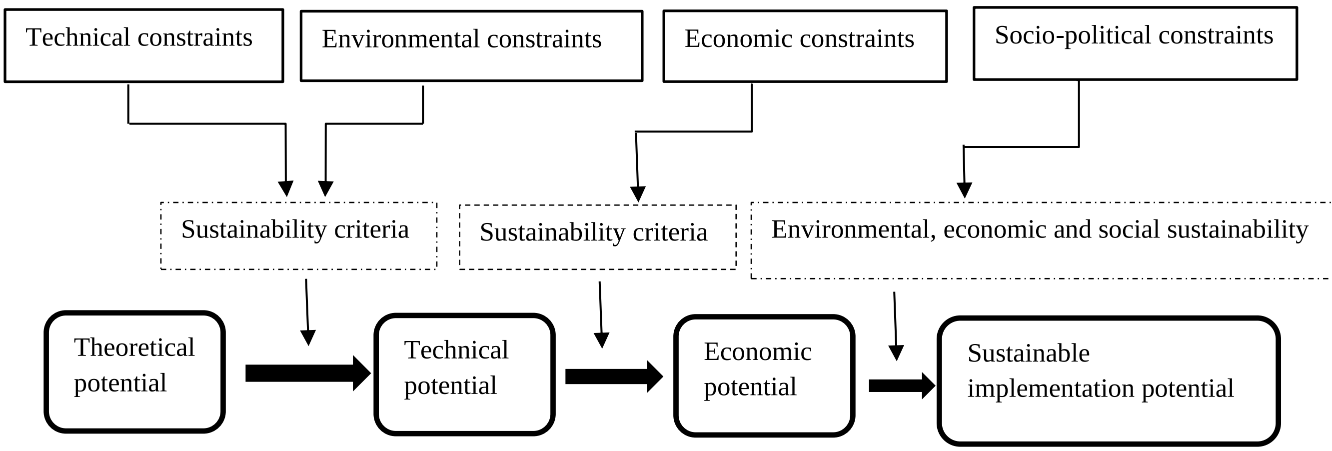


Figure 3. 9: Sustainable biomass potential assessment (Rettenmaier et al., 2010*).*

This energy resource was difficult to quantify in terms of electricity generation by following the different steps in Figure 3.9 because of time constraints as this assessment needs to be followed for a long period of time. Furthermore, the biomass is mainly composed of crops residues which cannot be sustainable for a daily electricity generation. Therefore, it was excluded in the different options to upgrade the hydropower plant capacity.

3.5. Modelling of a hybrid power system

3.5.1. Introduction

There is a need to meet a power gap demand of Kigwena community. A hybrid power system which is the combination of two or more energy sources was proposed as a suitable solution to upgrade the capacity of Kigwena micro-hydropower plant that has become unable to meet the power demand.

Therefore, the potential energy sources (solar and wind) assessed in the area were tested in the combination to the existing hydropower plant and analysed in order to select a suitable technology for optimal design. HOMER software requires input data such as electric load, renewable resources, component types, component details costs, lifetime of components, economic parameters (nominal discount rate, expected inflation rate, project lifespan, system fixed capital cost and capacity shortage penalty), system constraints (maximum annual capacity shortage, minimum renewable energy fraction, operating reserve) and emission penalties to perform simulation and optimization of the proposed hybrid power system.

3.5.2. Hybrid power system components and cost estimation

3.5.2.1. Solar PV technology

This technology is a conversion of sunlight into DC current using a solar PV panel. The power of solar PV array to be installed is dependent on solar insolation and the daily load demand. HOMER calculates the power output (P_0) of the PV array using the following equation (Homer Energy, 2016):

$$P_0 = c_{pv} \, D_{pv} \left(\frac{\bar{I}_T}{I_{T,STC}} \right) \left[1 + \alpha_p (T_C - T_{C,STC}) \right] \tag{3.16}$$

$$T_C = T_a + I_T \left(\frac{T_{C,NOCT} - T_{a,NOCT}}{I_{T,NOCT}} \right) \left[1 - \frac{\eta_C}{\tau \, \mu} \right] \tag{3.17}$$

Where c_{pv} is the rate capacity of the PV module in (kW) under standard test conditions (STC); D_{pv} the PV derating factor (%); $\bar{I}_T$ solar radiation incident on the module surface (kW/m^2); I_T is the radiation hitting the PV modules [kW/m^2]; α_p is the temperature coefficient of power (% / ℃); T_C is the PV cell temperature in ℃; T_a is ambient temperature; η_C is the efficiency of electrical conversion of the PV modules [%]; τ is solar transmittance of any cover over the PV array [%] and μ is the solar absorptance of the PV array [%].

For cost analysis, a 1 kW solar panel installation are approximate to between $US\$ \, 1800$ and $US\$ \, 3000$ as well as replacement costs (Bekele & Tadesse, 2012). The lifetime of solar PV array is estimated to 25 years.

3.5.2.2. Wind turbine technology

The power output from a wind turbine (WT) is dependent on wind speed. In technology, the WT generator converts mechanical energy into electrical energy. The power developed can be expressed by equation (3.18).

$$P_{WT}(t) = \begin{cases} 0, & V \leq V_{in} ; V \geq V_{Cout} \\ A + BV + CV^2, & V_{in} \leq V \geq V_r \\ P_r, & V_r \leq V \geq V_{Cout} \end{cases} \tag{3.18}$$

Where A, B and C are wind power characteristic curve parameters given for each wind turbine; P_r is a rated power of a WT; V_r, V_{in}, V_{Cout} are rated, cut-in and cut-out wind speed respectively.

The power output expected from a wind turbine depending on wind speed under standard conditions of temperature and pressure can be predicted using the power curve of a wind turbine.

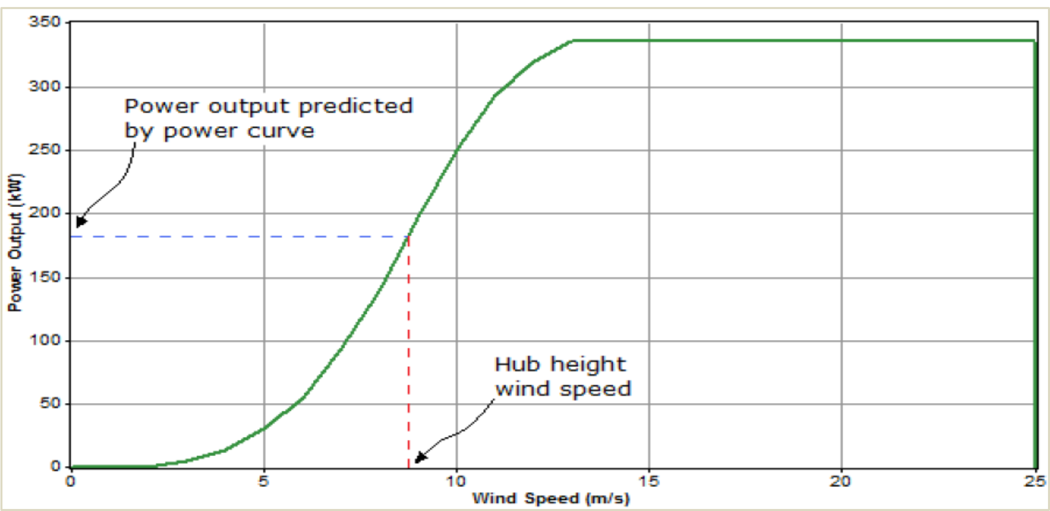


Figure 3. 10: Power curve of Wind turbine (Homer Energy, 2016)

3.5.2.3. Hydro turbine technology

A crossflow Ossberger turbine is an operational turbine in Kigwena power plant. Its rated flowrate is 65 l/s. An estimated yearly average river flowrate was taken as a design flow to input in Homer software. The permanency of flowrate was estimated at 80 %.

Since all the costs related to Kigwena power plant were not available, the cost estimation was made in accordance to other researches already conducted about micro-power plant implementation. A unit cost is ranged from $US\$$ 1500 to \$ $2500/kW$ as an estimate of an initial capital cost for small hydropower plants with recent technologies (Kimera, Okou, & Sebitosi, 2014). This cost was demonstrated with a case study in an Indian village where a capital cost of

$US\$$ 42,000 was estimated to implement a small hydropower plant of 30 kW while the replacement and O&M costs were reflected to reach $US\$$ 35,000 and $US\$$ 4,000, respectively (Sen & Bhattacharyya, 2014).

3.5.2.4. Energy storage

Power management is one of the major issues in micro-grids where variations of the loads and generations are significant in the system (Ambia, Al-durra, Caruana, & Muyeen, n.d.). The storage is imperative to smooth the output power from them. Energy storage aims to balance the load demand and energy generation.

Taking in consideration of energy storage and with regard to the study area description, the following strategies were considered to be evaluated for this case study (Figure 3.11). The choice of this is taken with respect to the renewable energy resources in the study area and that village is close to national utility grid.

The storage should be large enough to store sufficient energy to enable a smooth transition of the power load demand especially during the peak load time, at night and cloudy days. According to www.alibaba.com, a deep cycle rechargeable 1 kWh solar battery is estimated to have a cost between 100 and US \$ 500.

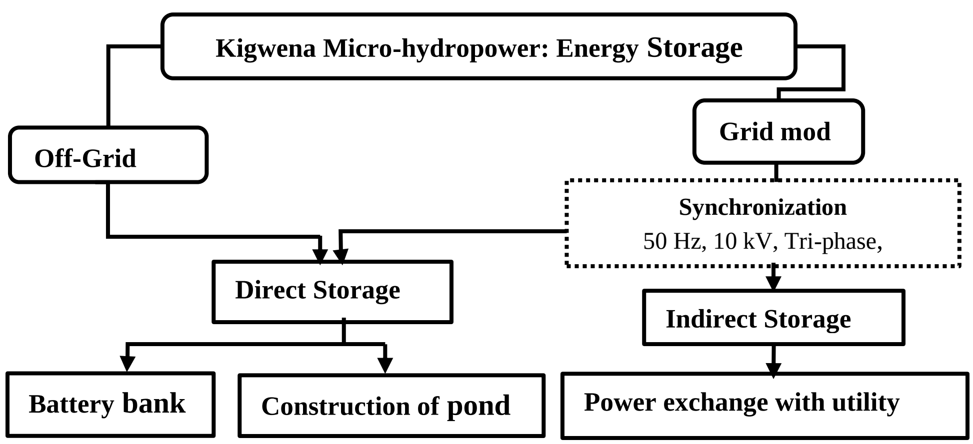


Figure 3. 11: Strategies of energy storage for Kigwena electrical load.

The conceptual schematic of the system was suggested in a such a way that the electrical system should be always secured (Figure 3.12).

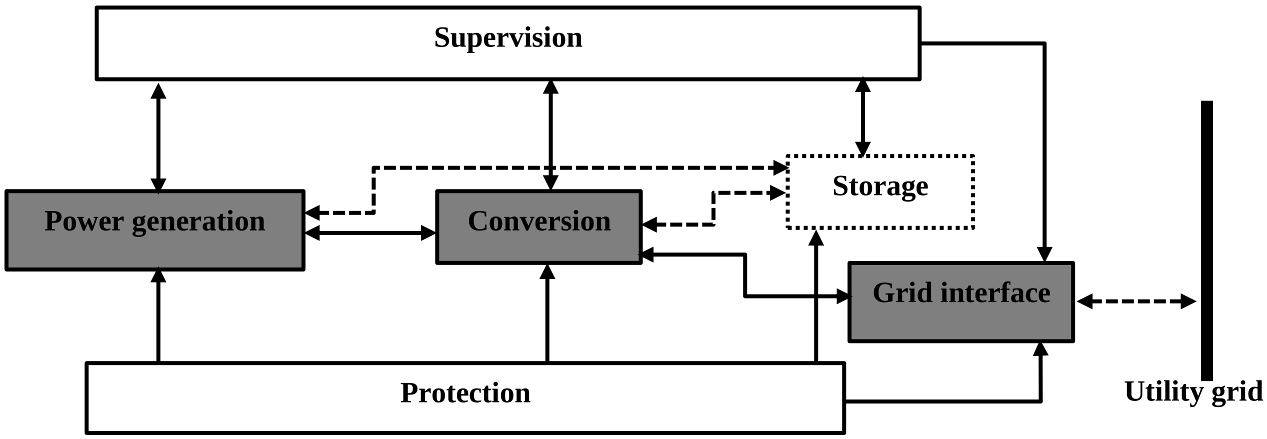


Figure 3. 12: Configuration of the system with storage option

For a grid connected system and net-generation calculated monthly, the total annual energy charge is calculated in the following way:

i. If the net-metering system is not applied, then:

$$C_{grid,energy} = \sum_{i}^{rates} \sum_{j}^{12} E_{gridpurchases,\ i,j} * C_{power\ ,i} - \sum_{i}^{rates} \sum_{j}^{12} E_{gridsales,\ i,j} * C_{sellback\ ,i} \tag{3.19}$$

ii. If the net-metering system is applied, it follows:

$$C_{grid,energy} = \sum_{i}^{rates} \sum_{j}^{12} \left\{ \begin{array}{l} E_{net\ gridpurchases,\ i,j} * C_{power\ ,i}\ if\ E_{net\ gridpurchases,\ i,j} \geq 0 \\ \\ E_{net\ gridpurchases,\ i,j} * C_{sellback\ ,i}\ if\ E_{net\ gridpurchases,\ i,j} < 0 \end{array} \right\} \tag{3.20}$$

Where $E_{net\ gridpurchases}$ is the net grid purchases, the difference between purchases and sales in month j when the rate i applies $[kWh]$; $E_{gridsales,\ i,j}$ the amount of energy sold to the grid in month j when the rate i applies $[kWh]$; $C_{power\ ,i}$ is the grid power price for rate i $[\$/kWh]$ and $C_{sellback\ ,i}$ is the sellback rate for rate i $[\$/kWh]$.

According to the Utility of Water and Electricity Distribution in Burundi (REGIDESO), the current tariffs for electricity range from 41 BuF/kWh for low energy consumers to 127 BuF/kWh for consumption over 750 kWh per two months. The ABER tariffs also vary from 56 BuF/kWh to 72 BuF/kWh. Note that BuF is a Burundian currency is equivalent to 1800 BuF for $US\$$ 1 as of 2019.

3.5.2.5. Power electronic

The DC voltage from solar PV and battery is converted into AC current using step-up tri-phase inverter. The input power and voltage of the inverter have to be adapted to the supply source (and though, to the load). Thus, it is common to oversize the inverter due to the eventual system expansion (Leonics, 2013). Therefore, an oversizing of 25 % can be taken for the inverter power.

$$P_i = 1.25 \; P_{Load} \tag{3.21}$$

Where P_{Load} is the power of all the loads running at the same time.

For a 1 kW system the installation and replacement costs are taken as $300 and $300, respectively (www.alibaba.com). Lifetime of a unit is considered to be 15 years with an efficiency of 90%.

3.5.3. Economic analysis of the system

The lifespan of the project is estimated for 25 years. For this economic analysis, two major economic output metrics which are Net Present Cost (NPC) and Levelized Cost of Energy (LCOE) were regarded for analysis, discussion, feasibility and implementation of the best option technically viable. The NPC of the system considers all costs that the system incurs over its lifetime, minus the present value of all the revenue that the system earns over its lifetime. HOMER software calculates those parameters using equations from 3.22 to 3.24 (Lambert et al., 2006). The NPC of the project is given by equation 3.22.

$$C_{NPC} = \frac{C_{ann,\ tot}}{CRF(i,\ R_{proj})} \tag{3.22}$$

Where $C_{ann,\ tot}$ is the total annualized cost, i the discount rate, R_{proj} the project lifetime, and $CRF(i,\ n)$ is the capital recovery factor which is given by equation 3.23.

$$CRF(i,\ n) = \frac{(1+i)^n}{(1+i)^n - 1} \tag{3.23}$$

Where i is the discount rate and n the number of years (lifetime of the project). The discount rate in Burundi was averaged at 10.18 % (from 2007 to 2018) (Trading Economics, 2019) and averaged inflation rate (from 2014 to 2017) amounted about 16.64 % (Statista, 2019).

The levelized cost of energy is calculated using equation 3.24.

$$COE = \frac{C_{ann,\ tot}}{E_{prim}\ E_{def}\ E_{grid,sales}} \tag{3.24}$$

Where E_{prim} and E_{def} are the total amounts of primary and deferrable load, respectively and $E_{grid,sales}$ is the amount of energy sold to the grid per year.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1. Different options of a Hybrid micro-grid model for Kigwena community

Figure 4.1 shows the general structure of energy resources in the study area feasible for optimization to the existing micro-hydropower plant.

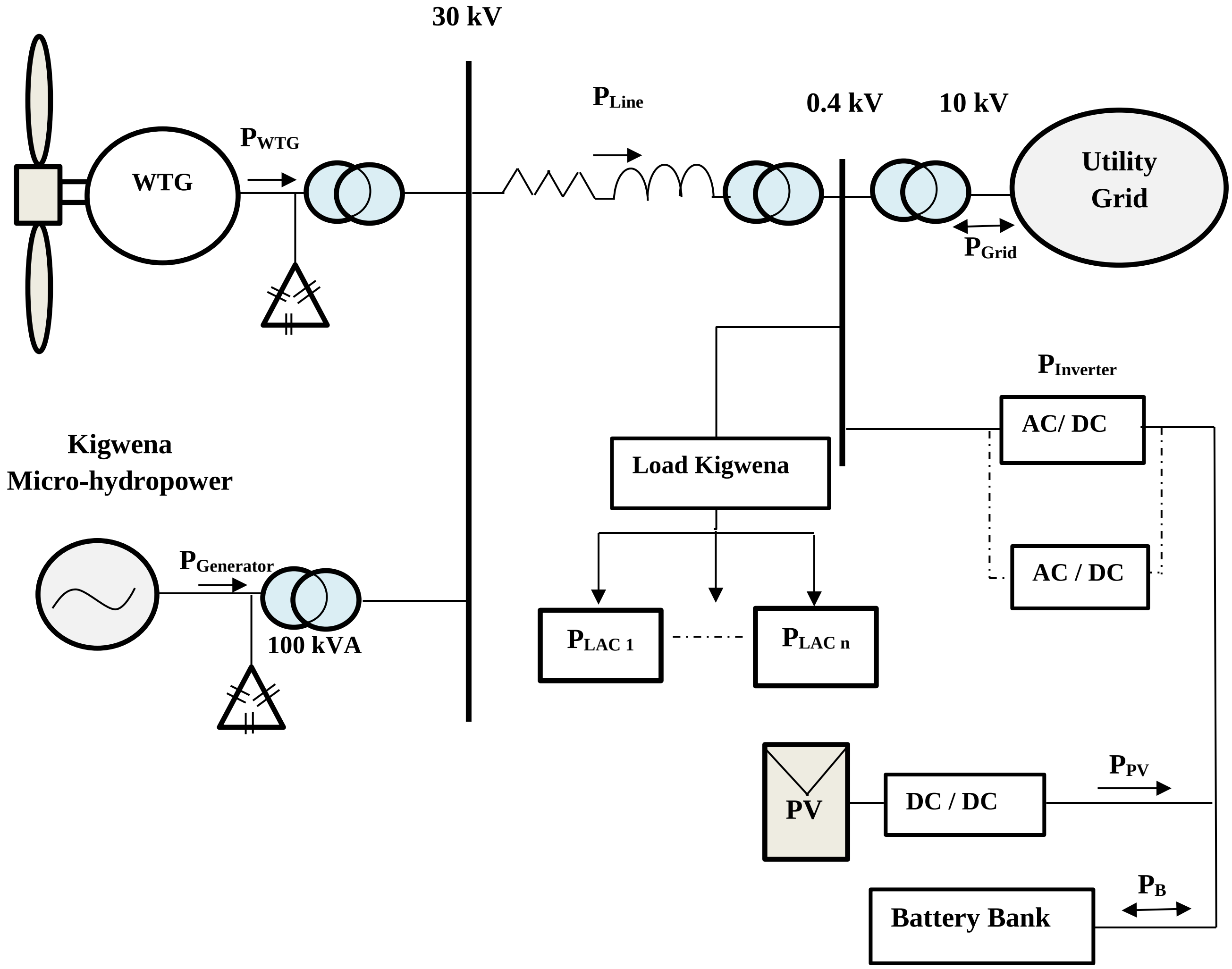


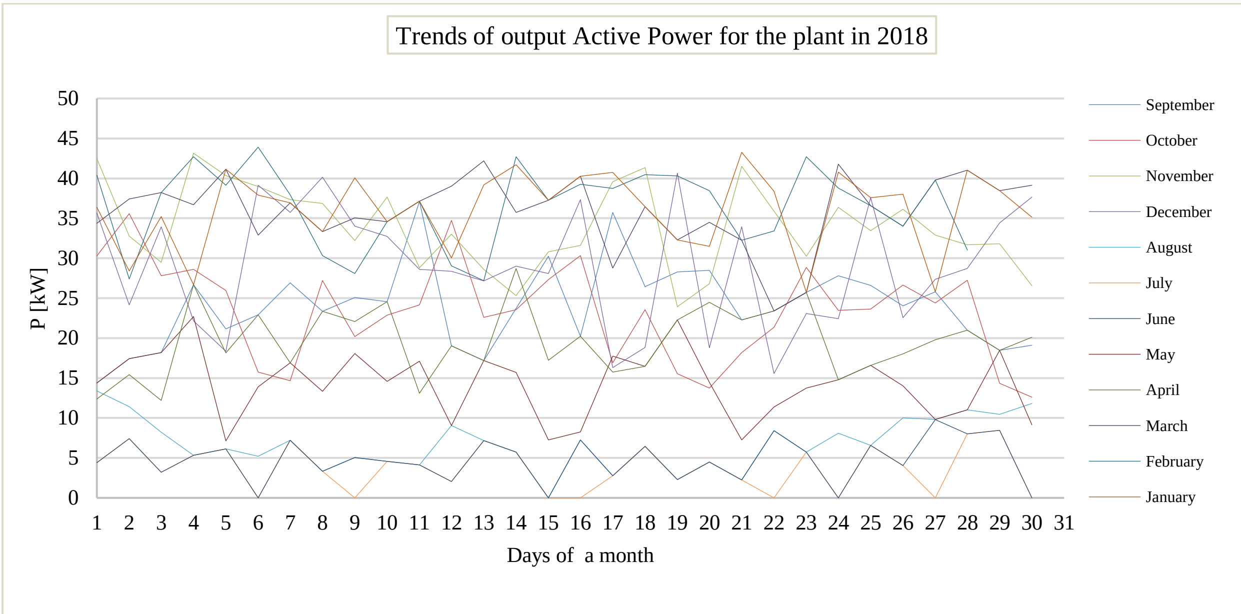
Figure 4. 1: Different options of a Hybrid micro-grid model for Kigwena community

Therefore, these options were evaluated in this study with the aim of choosing the best combination technically and financially suitable to meet the power gap demand of the village.

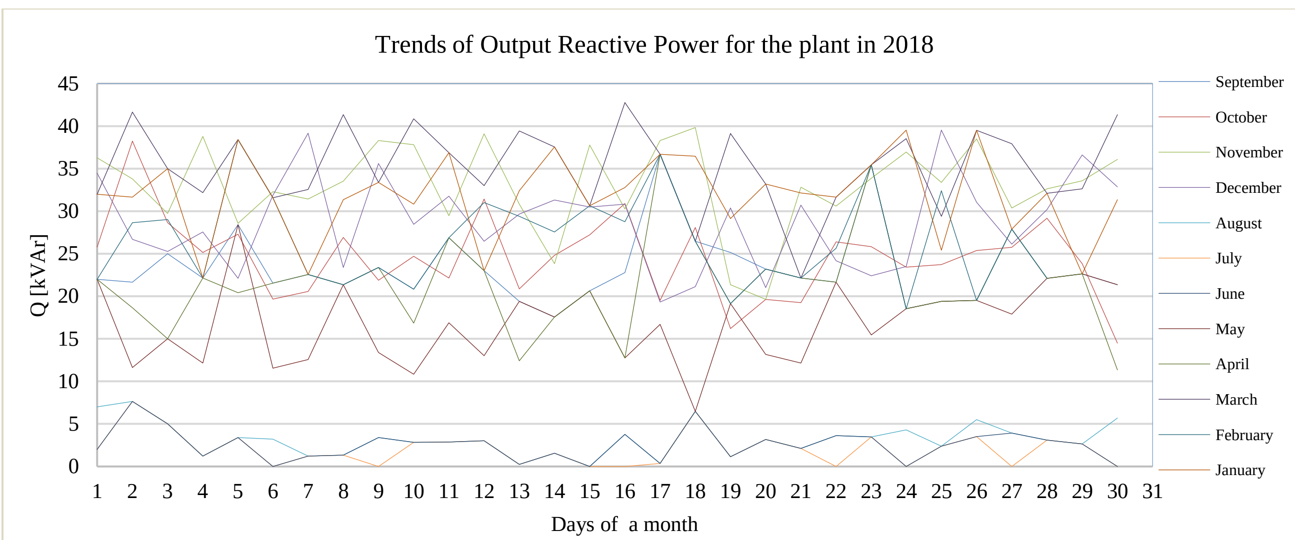
4.2. Performance evaluation of Kigwena hydropower plant

The power plant was rehabilitated in 2017 to improve its performance. The outputs of the power plant are recorded daily every two hours all along the whole year 2018 and the patterns are given in Figure 4.2.

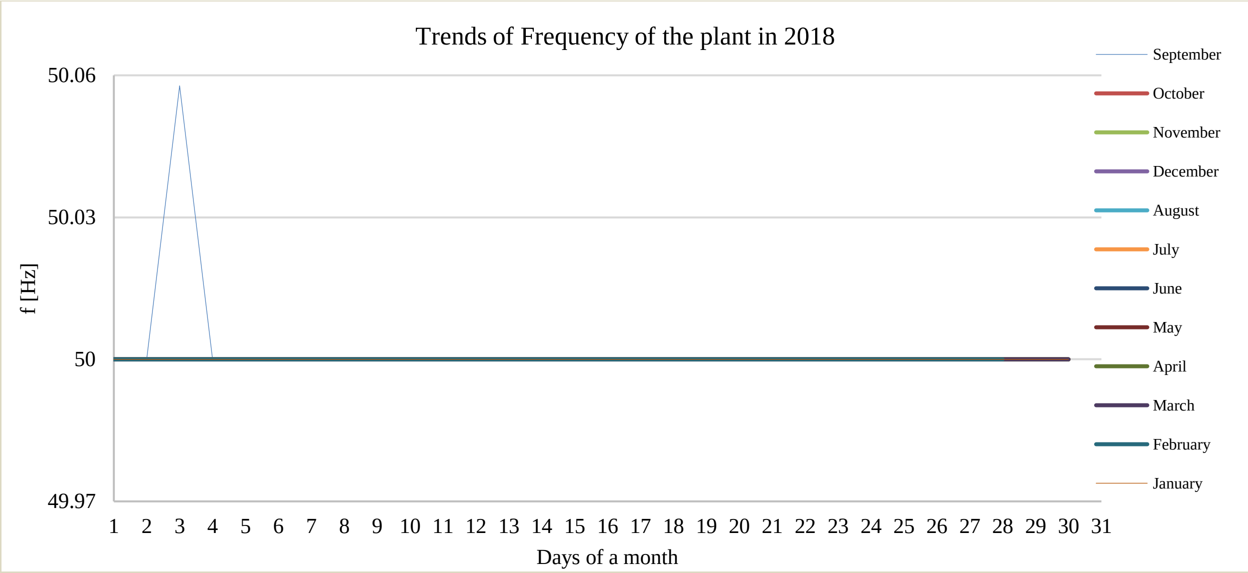
The graphs below (Figure 4.2) show the pattern figure of the generator outputs that can relate the fluctuations in the power production.



(a)



(b)



(c)

Figure 4. 2: Generator output: (a) Active power (b) Reactive power (c) Frequency

Figure 4.2 (c) shows that the frequency is almost stable throughout the whole year and this can explain that the control method in use is able to stabilize the frequency variations. Thus, the governor and other controls are efficient and AC generator constantly rotates at constant angular speed.

Considering the maximum power that has been recorded at the generator output as the peak load, the plant utilization factor is 50.7 %.

The Ossberger crossflow turbine developed for small hydropower is made for heads between 2.5 and 200 m and can operate with very low river flowrates which is not the case for some other turbines (Ossberger, 2019). A minimum flow ratio of 7.5 % was estimated using figure 3.8.

Table 3.7 shows the estimated water flowrates supplying the turbine at Kigwena power plant considering a constant turbine efficiency of 75 %, generator efficiency of 97 % and hydraulic efficiency of 85 %. The power factor of the generator is 0.8.

Table 4. 1: Estimation of water discharge D of Kigwena power plant in the year 2018

Year 2018	P [kW]	Q [kVAr]	S [kVA]	P_h [kW]	D [l/s]
January	36.05	31.85	48.10	40.50	50.75
February	36.49	26.55	45.13	38.00	47.62
March	35.88	35.88	50.74	42.73	53.54
April	19.65	21.45	29.09	24.49	30.69
May	14.28	16.85	22.08	18.60	23.30
June	4.74	2.52	5.37	4.52	5.66
July	3.72	2.03	4.24	3.57	4.47
August	6.78	3.19	7.49	6.31	7.90
September	24.05	23.38	33.54	28.24	35.39
October	23.40	24.57	33.93	28.57	35.80
November	33.92	32.99	47.32	39.85	49.93
December	29.09	28.81	40.94	34.47	43.19

The approximated flow rates of the river along the whole year 2018 is then generated as it is shown in the Figure 4.3.

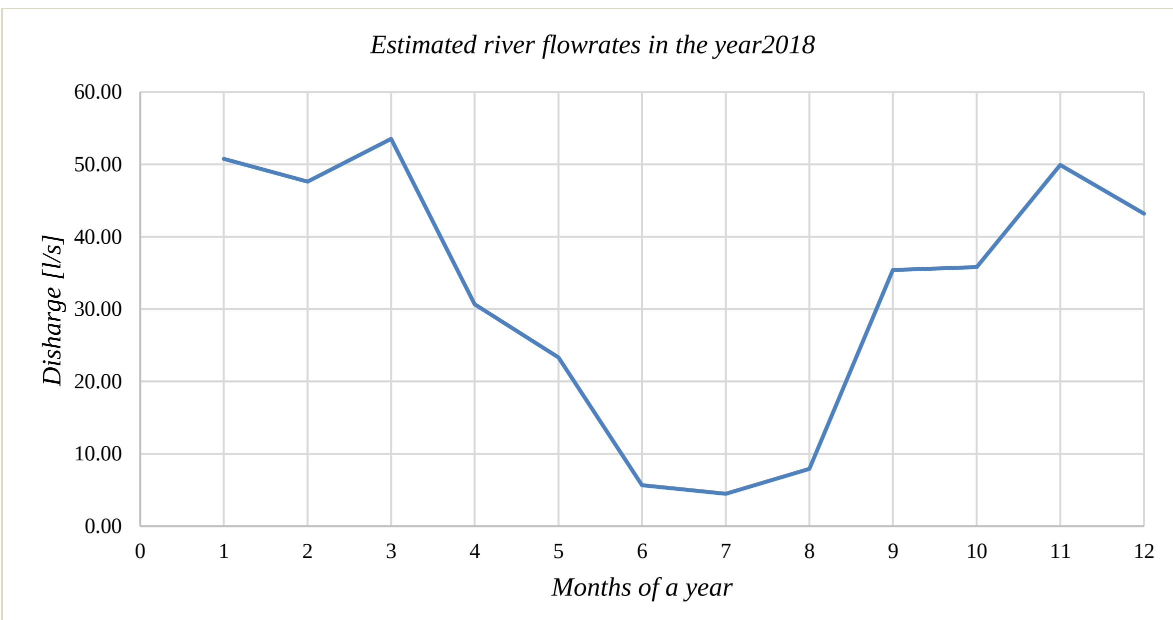


Figure 4. 3: Approximated flow rate of Nzibwe River at Kigwena power plant

The monthly estimated river flowrates are the input data to Homer when dealing with hydropower. Figure 4.4 shows the variation of hydropower resource along the year (run-off-the-river for this case) for Kigwena micro-hydropower plant with the annual average of 32.25 l/s. This residual flow is neglected and considered to be 0.01 l/s as almost the river is diverted towards the penstock (see Figure 3.3).

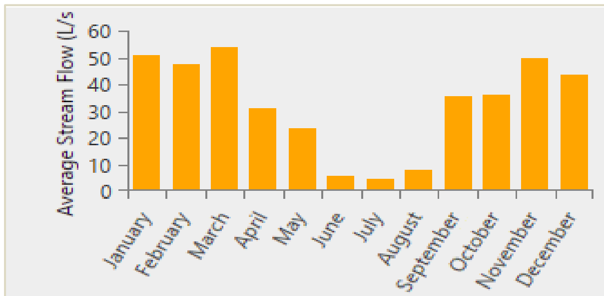


Figure 4. 4: Monthly streamflow variation

4.3. Load profile for Kigwena community and projections

4.3.1. Power demand and energy consumption

The population of Kigwena village was considered to have a growth rate of 3.25, the same rate of growth as for the whole country estimated in 2017 (The World Factbook, 2019). The projections from 2019 to 2040 (number of years considered as the lifespan of solar PV panels) are shown in Table 4.2.

Table 4. 2: Population estimation of Kigwena village

Year	Population	High income households	Low income households
Initial year (2019)	3,648	152	304
Forecast year (2030)	7,069	295	589

The socio-economic data (state of the house and income levels) were used as a hypothesis to determine high- and low-income households in order to estimate the electrical load of a house. This agrees with Miner et al. (2017) who found out that there is a relationship between income levels and conditions of the house (Miner et al., 2017). According to a conducted survey on households living conditions in Burundi, BUF 41,054 per adult per month was taken as the national basic needs poverty line (Belghith, Tom, Beko, & Tsimpo, 2016). Then, 152 houses were observed as belonging to high income households and other 304 houses as belonging to low income households. The same proportion was used to do projections for the future (Table 4.2). Table 4.3 shows actual and projected frequency distribution of infrastructure for the village.

Table 4. 3: Frequency distribution of infrastructure for the village

Category	Actual (Base year 2019)	Future (Target year 2040)
Households	456	884
Primary school	1	2
Secondary school	1	2
Community church	2	3
Medical center	1	1
Administration posts	1	3
Small business	20	50
Palm oil mill	2	4
Flour mill	1	2

The estimated daily load demand for Kigwena community is given in appendix 1. It is clear that the supplementary power supply source is needed to compensate the deficiency (Figure 4.2 and Figure 4.5).

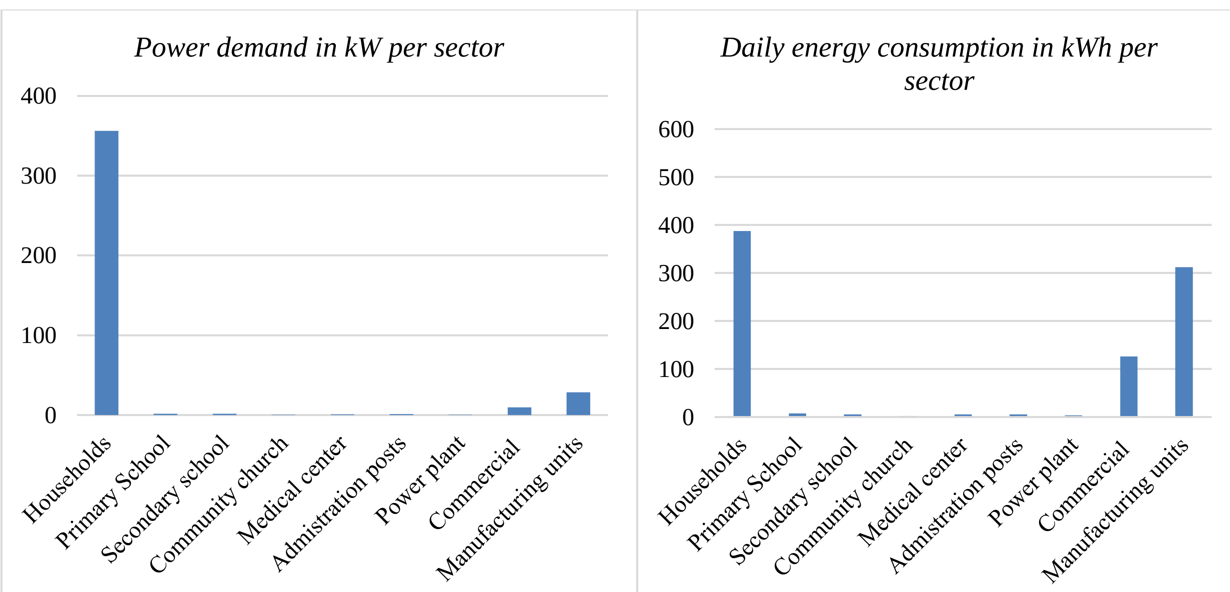


Figure 4. 5: Power demand and daily energy consumption of the village

In that village, due to high production of palm oil, it can be noticed that small manufacturing units are the main consumers of electricity following the households (Figure 4.5).

4.3.2. Electrical load schedule

The electrical load of the village and its use time were estimated during the survey (Appendix 1). The load was estimated to have the same behavior throughout the whole year. Table 4.4 shows the estimated load schedule for the study area.

Table 4. 4: Estimated load schedule of Kigwena village

Schedule	Load (kW)	Schedule	Load (kW)
00:00 - 01:00	4.94	12:00 - 13:00	36.11
01:00 - 02:00	4.94	13:00 - 14:00	36.11
02:00 - 03:00	4.94	14:00 - 15:00	36.11
03:00 - 04:00	4.94	15:00 - 16:00	36.08
04:00 - 05:00	4.94	16:00 - 17:00	36.08
05:00 - 06:00	4.94	17:00 -18:00	36.11
06:00 - 07:00	7.72	18:00 - 19:00	190.44
07:00 - 08:00	7.46	19:00 - 20:00	50.21
08:00 - 09:00	37.68	20:00 - 21:00	48.53
09:00 - 10:00	38.69	21:00 - 22:00	48.90
10:00 -11:00	39.22	22:00 - 23:00	4.84
11:00 - 12:00	38.54	23:00 - 00:00	4.84

4.4. Alternative energy resources assessment in the study area

4.4.1. Insolation data

Using the equations (3.10 to 3.14), the estimated insolation of the study area is given in Table 4.5.

Table 4. 5: Estimated insolation data for the study area

Mid of the month	n_d	δ (°)	ω_s (°)	N (hours)	n	H_0 (kWh/m2/day)	n/N	H (kW/m²/day)	NASA (kW/m²/day)
15-Jan	15	-23.05	88.26	11.77	9.90	9.90	0.84	7.22	4.57
14-Feb	45	-22.17	88.34	11.78	10.10	9.97	0.86	7.35	4.94
15-Mar	74	-15.82	88.84	11.85	8.40	10.36	0.71	6.85	4.99
15-Apr	105	-4.81	89.66	11.95	8.00	10.73	0.67	6.88	4.92
15-May	135	7.15	90.51	12.07	8.10	10.68	0.67	6.86	4.90
15-Jun	166	17.52	91.29	12.17	7.30	10.26	0.60	6.22	5.05
15-Jul	196	22.93	91.73	12.23	5.80	9.91	0.47	5.37	5.27
15-Aug	227	22.24	91.67	12.22	4.90	9.96	0.40	5.02	5.38
15-Sep	258	15.36	91.12	12.15	7.90	10.38	0.65	6.56	5.25
15-Oct	288	4.61	90.33	12.04	9.10	10.73	0.76	7.35	4.72
15-Nov	319	-7.72	89.45	11.93	9.50	10.67	0.80	7.53	4.41
15-Dec	349	-17.65	88.70	11.83	9.70	10.26	0.82	7.37	4.49
Average								**6.72**	**4.91**

Global horizontal irradiation is mostly considered as a climate reference for a considered area. Direct components of GTI (or GHI) indicate how different PV technologies may perform. The last two columns of Table 4.5 respectively show insolation data obtained from empirical equations and from NASA in (kWh/m²/day). As there was no direct measured data from IGEBU, the worst scenario was considered (data from NASA source) to be used in this study. The data from this source is estimated from monthly averaged values over a period of 22 years from July 1983 until June 2005. Figure 4.6 illustrates the daily radiation in kWh/m²/day and the clearness index considered for Kigwena village.

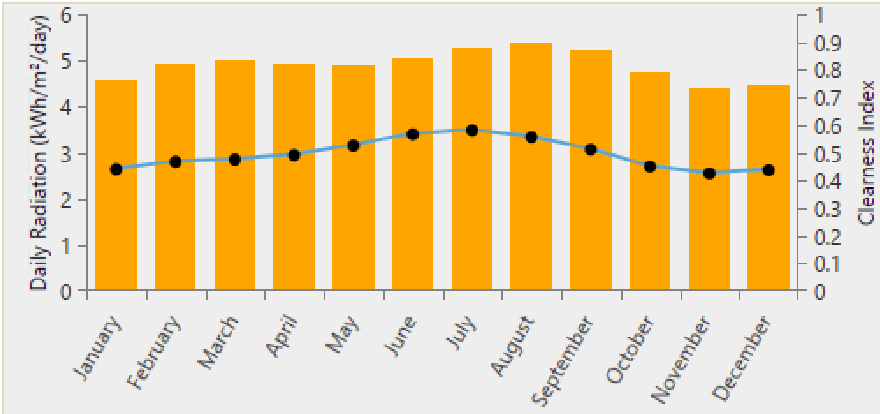


Figure 4. 6: Daily Radiation and Clearness Index of the Study Area

The clearness index is a measure of the clearness of the atmosphere. It is the fraction of the solar radiation that is transmitted through the atmosphere to strike the surface of the Earth. It is a dimensionless number between 0 and 1, defined as the surface radiation divided by the extra-terrestrial radiation. The clearness index has a high value under clear, sunny conditions, and a low value under cloudy conditions.

From Figure 4.6, August is the sunniest month of the year at which the normal sun-powered irradiance for the month is 5.38 $kWh/m^2/day$; November is the month with the lowest irradiance which is approximately equal to 4.41 $kWh/m^2/day$. May to September have been identified as the months with high GHI; but also, with higher variability. The clearness index rises from April to September. From October to March, the clearness index remains relatively the same with the values (0.439; 0.466; 0.474; 0.449; 0.424; 0.437) respectively.

4.4.2. Wind speed data

The table 4.6 recapitulates the wind speed obtained at the heights 10 m and 50 m using equation 3.15.

Table 4. 6: Wind speed estimation at the study area

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	**Average**
NASA													
50 m	2.48	2.53	2.49	2.97	3.90	4.29	4.25	4.09	3.44	2.75	2.42	2.17	**3.15**
10 m	1.98	2.02	1.99	2.37	3.11	3.42	3.39	3.26	2.75	2.20	1.93	1.73	**2.51**
IGEBU													
10 m	0.23	0.29	0.29	0.26	0.41	0.64	0.75	0.85	0.90	0.85	0.60	0.38	**0.54**
50 m	0.29	0.36	0.36	0.32	0.52	0.80	0.94	1.07	1.13	1.07	0.75	0.47	**0.68**

The data from IGEBU was considered to be used in this study as it directly reflects the study area specifications. The wind speed in Kigwena (using data from IGEBU), was found to have an annual average of 0.67 m/s a value estimated when the hub centre of the selected wind turbine is at 50 m of height. The high speed is found in September with 1.13 m /s.

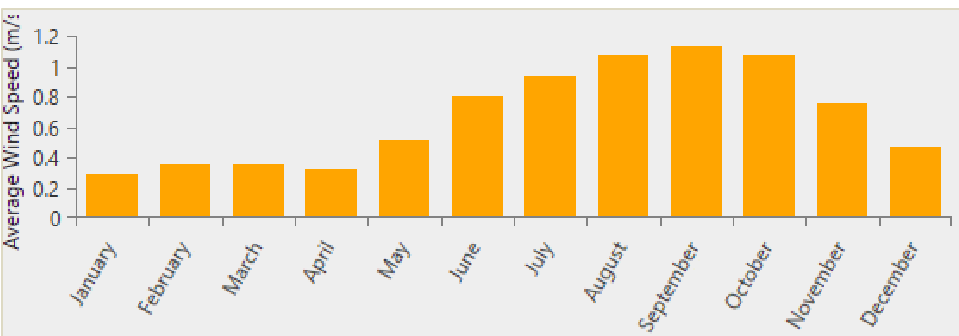


Figure 4. 7: Wind speed pattern in Kigwena

4.5. Power demand gap of the village

The output power from the installed generator at Kigwena micro-hydropower display an annually behavior shown in Figure 4.8.

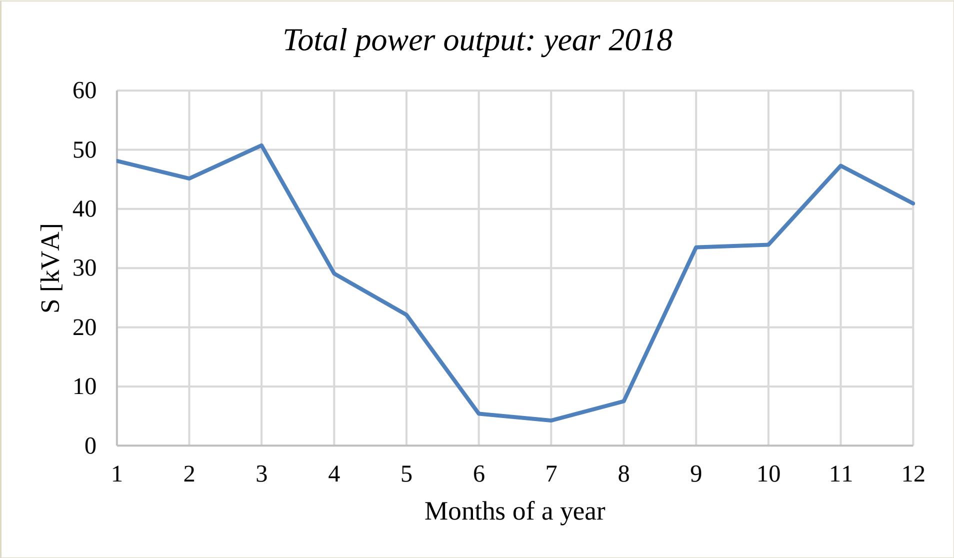


Figure 4. 8: Power output curve of Kigwena Micro-hydropower for the year 2018

A descriptive statistical analysis of the power was conducted to check the status of power output of the plant. The table below shows the descriptive statistics of the findings.

Table 4. 7: Statistical analysis of Kigwena power output for the year 2018

Output power in kVA	
Mean	30.66
Standard Error	4.98
Median	33.73
Standard Deviation	17.24
Sample Variance	297.21
Kurtosis	- 1.22
Skewness	- 0.54
Range	46.50
Minimum	4.24
Maximum	50.74
Sum	367.97
Count	12.00
Confidence Level (95.0%)	10.95

From the Table 4.7, the power supply needed to compensate the deficiency was deducted. With a peak load of 190.44 kW, there is a need of 159.75 kW to satisfy the load for the forecasted year 2040, considering the average power output of the existing hydropower plant.

4.6. Modeling of a hybrid power system

4.6.1. Load profile of the village

The electrical load for the community is a function of time. Consequently, there is an unpredicted change of energy demand every hour to hour, season to season and day to day and working days to weekend depending on the activities of the community. Therefore, the day to day with a variability of 10 % was used in this study to represent a realistic load pattern for the day. Random variability was set for the variation of the daily load from month to month. The time step for the simulation of the data was set to 60 minutes by default. The variation range for each time step was set to 20 % of the load according to the default settings of HOMER.

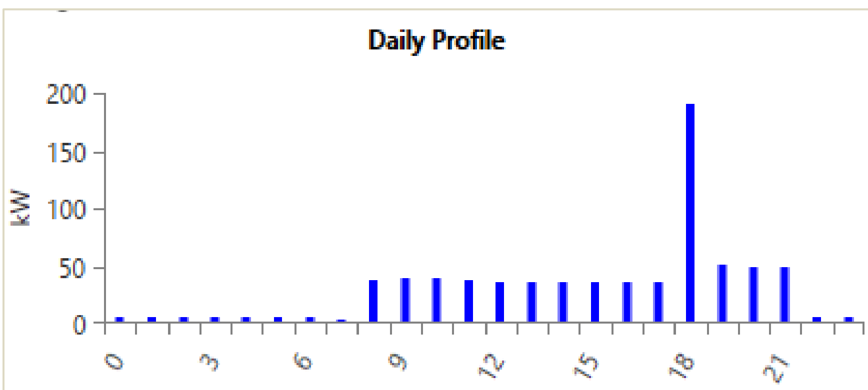


Figure 4. 9: A trend of a daily load Profile for Kigwena community

From the baseline data supplied to HOMER (Table 4.4), the hourly load profile of the site for a typical day (1 January) is shown in figure 4.9 from where scaled average energy consumption per day, scaled daily peak demand and daily average demand are found to be approximately 757.74 kWh, 190.44 kW, and 31.57 kW, respectively.

The 10 % of random variability increased the community daily electric load peak load. The load demand profile for the village is mostly AC load with scaled annual average of 757.74 kWh and a peak load of 323.88 kW which are presented in figure 4.10. From this figure, it can be observed that the maximum load ranges between 249.07 kW and 323.88 kW monthly with the lowest in June and highest in November and the daily peak is seen to vary from 178.23 kW to 206.06 kW, whereas the average load is almost the same in all the months.

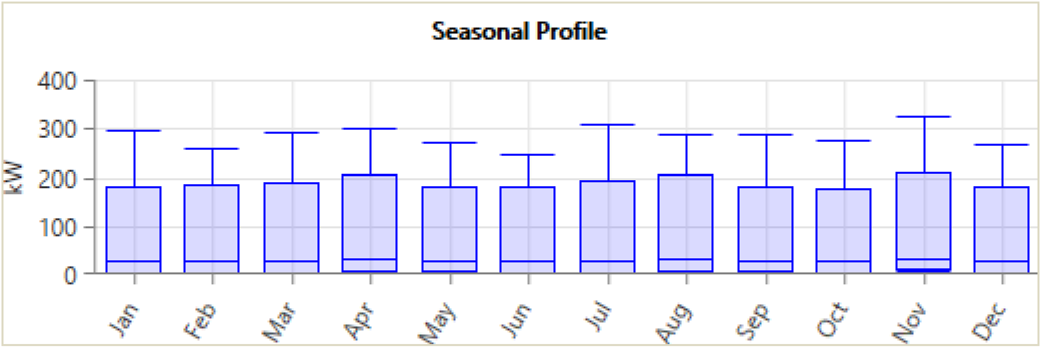


Figure 4. 10: Monthly load profile of the study area

Figure 4.11 shows the predicted variation in AC load over the whole year. While Figure 4.12 shows a diurnal variation of the load profile. It can be noticed from Figure 4.11 that most of the community load falls under the value of 35 kW which justify the average load for the whole year in the community of 31.57 kW.

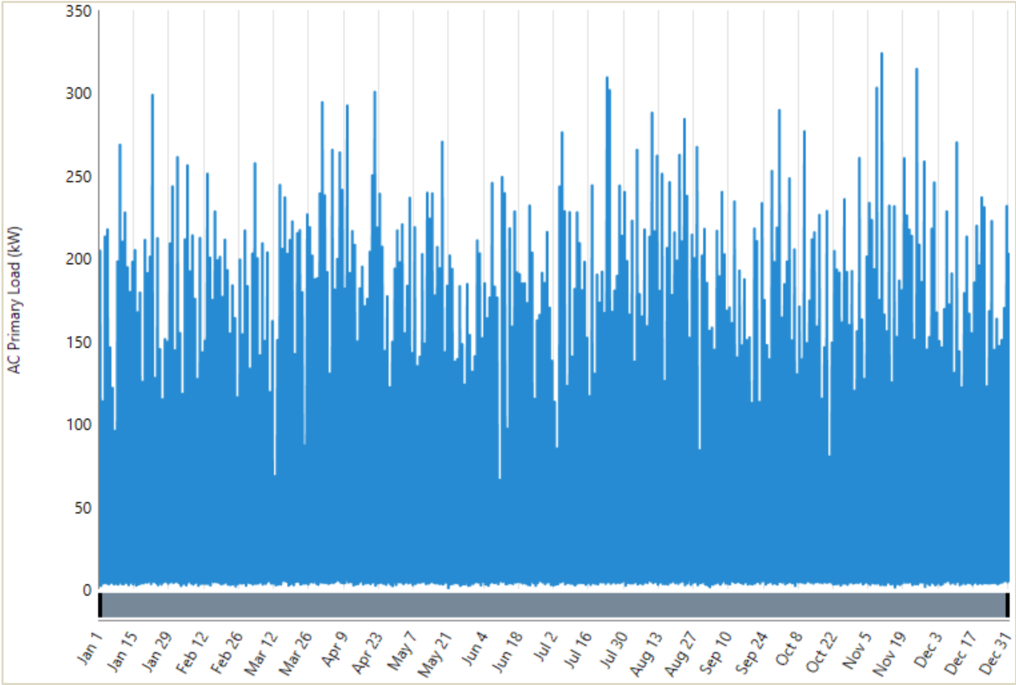


Figure 4. 11: Load variation for the whole year

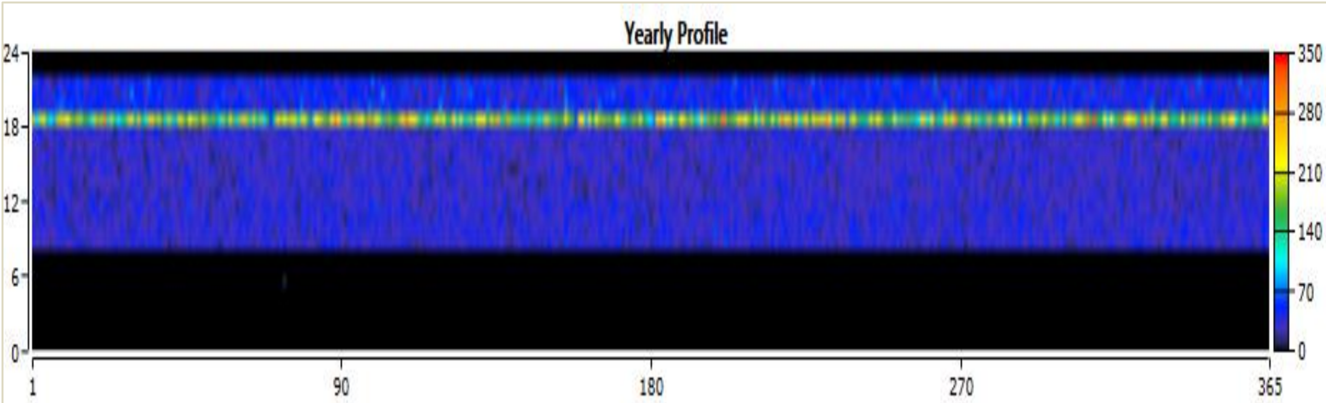


Figure 4. 12: Diurnal variation of primary load profile

4.6.2. Options to meet the power gap demand

The energy storage strategies proposed with head pond construction in Figure 3.11 was not a technically feasible solution due to the topographical location of the study area, and due to that almost all the river is diverted towards the penstock (Figure 3.3). Therefore, construction of head pond was not considered in different options of energy storage in this study.

Different options to meet the power gap demand for Kigwena village were setup as shown in Figure 4.13. All energy resources assessed in this study area were input to HOMER as well as different options of energy storage to smooth the power output of the system. As the study was dealing with an AC load, DC power from solar PV and batteries is to be converted in AC power. Additionally, the AC power delivered by different sources is to be matched to the utility grid power characteristics (synchronization). Figure 4.13 shows the configuration of all the proposed options to be tested.

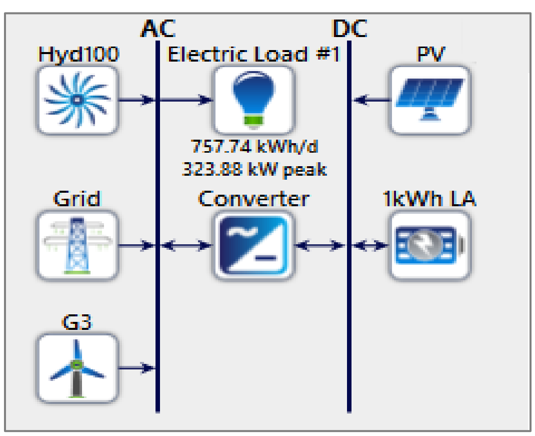


Figure 4. 13: A generated grid-connected hybrid power setup

4.7. Optimization results for the different options

After all the possible options were simulated, different configurations were displayed by HOMER and these are sorted by their NPC and LCOE. In each option, the lowest NPC and LCOE configuration is displayed. The results of the best categorized optimum system configurations are presented in Figure 4.14.

Export...

Optimization Results

Left Double Click on a particular system to see its detailed Simulation Results.

Architecture							Cost				System
PV (kW)	G3	1kWh LA	Grid (kW)	Hyd100 (kW)	Converter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)
74.6			999,999	31.1	50.9	CC	$0.0333	$732,432	$9,411	$196,221	71.9
73.1		1	999,999	31.1	50.3	CC	$0.0335	$734,174	$9,487	$193,642	71.7
74.4	1		999,999	31.1	50.2	CC	$0.0346	$760,850	$9,604	$213,667	71.9
76.8	1	1	999,999	31.1	51.8	CC	$0.0344	$762,599	$9,548	$218,636	72.2
			999,999	31.1		CC	$0.0425	$808,764	$13,377	$46,650	53.2
		1	999,999	31.1	0.161	CC	$0.0426	$810,573	$13,402	$46,998	53.2
	1		999,999	31.1		CC	$0.0440	$837,176	$13,559	$64,650	53.2
	1	2	999,999	31.1	2.48	CC	$0.0442	$842,068	$13,622	$65,995	53.2

Figure 4. 14: Categorized optimum system configurations results

From the Figure 4.14, it is clear that a system made of 31.1 kW micro-hydropower, 74.6 kW PV modules with 50.9 kW inverter with 999,999 kW from the utility grid to smooth the system power output is the cheapest configuration option. This option reflects a COE of $USD\ 0.0334/kWh$ and its NPC value is $USD\ 732{,}432$.

According to simulated results in Figure 4.14, the wind technology is not an economically suitable option in the study area. Additionally, from the available wind speed (data collected from: IGEBU), the site is not technically advisable for wind farm project and this can be highlighted by the power curves of different wind turbines options given by HOMER software. Figure 4.15 is one of the several simulated turbines (Appendix 2).

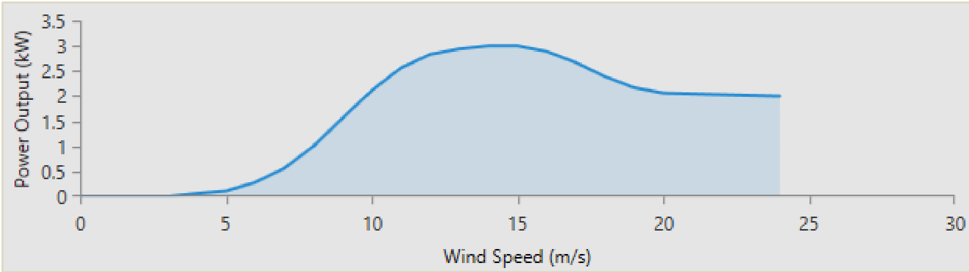


Figure 4. 15: Power curve for 3 kW Generic wind turbine at 50 m of hub-height

Figure 4.15 shows that the power output is almost 0 kW as soon as the wind speed is below 5 m/s, the speed which is observed for this case study.

4.7.1. Generation and consumption of electrical energy of the hybrid system

Figure 4.16 shows the monthly average energy production of the optimal hybrid system option composed of the utility grid, existing micro-hydropower and solar PV system. The expected annual energy production from the system is 393,500 kWh which almost half of it (45.2 % of annual production) is contributed by the existing micro-hydropower. Furthermore, the utility grid has a meaningful contribution in this configuration where the energy excess generation is directly fed into the grid (grid sales) and taken back to feed the community load in order to smooth its energy consumption (grid purchases) when there is power generation deficiency from the system. The Table 4.8 presents the resultants of annual power generation and consumption.

Table 4. 8: Annual energy production and consumption for the simulated system

Production	kWh/yr	%	Consumption	kWh/yr	%
Generic flat plate PV	107,184	27.2	AC Primary Load	276,575	71.6
Hydro	177,848	45.2	DC Primary Load	0	0
Grid Purchases	108,467	27.6	Grid Sales	109,821	28.4
Total	393,500	100	Total	386,396	100

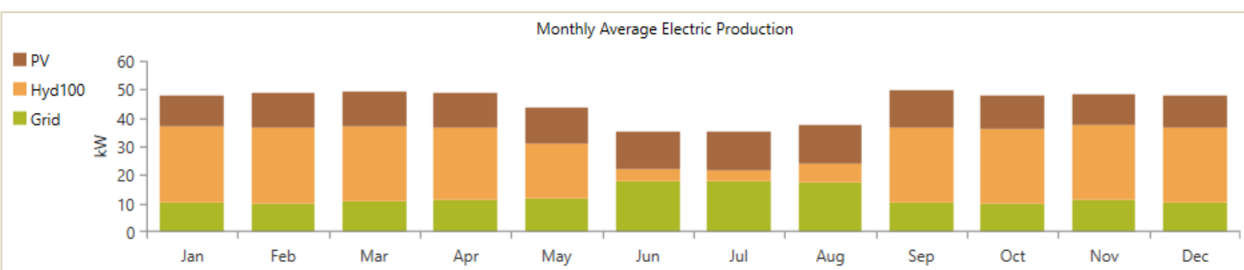


Figure 4. 16: Monthly energy production and system architecture of the most feasible system configuration

Figure 4.16 shows how the micro-power plant plays a big role in this combination, especially during the first four and the last four months of the year. This is a consequence of high river flowrates during these periods of the year (Figure 4.3). For the months of June, July and August, the hydropower contribution reduces, solar PV and grid contributes a lot in the power supply system.

4.7.2. Excess electricity and unmet electricity load

Table 4.9 presents the yearly excess of electricity produced compared with the yearly unmet total electricity to supply Kigwena village by the optimal system simulated. From the results in Table 4.9, the proposed system is able to meet the peak load of the community without any capacity shortage and without unmet load.

Table 4. 9: Annual total of excess electricity from the system

Quantity	kWh/yr	%
Excess Electricity	1,837	0.467
Unmet Electric Load	0	0
Capacity Shortage	0	0

The unmet electric load happens when electricity supply cannot meet the electricity demand. It is the amount of electricity the power system is unable to supply. For the table above (Table 4.9), it is easier to notice the performance of the proposed hybrid system to meet the power demand of the village. The electrical load demand is met along the whole year and a yearly excess of electricity of 1,837 kWh/year is produced from the power generation system.

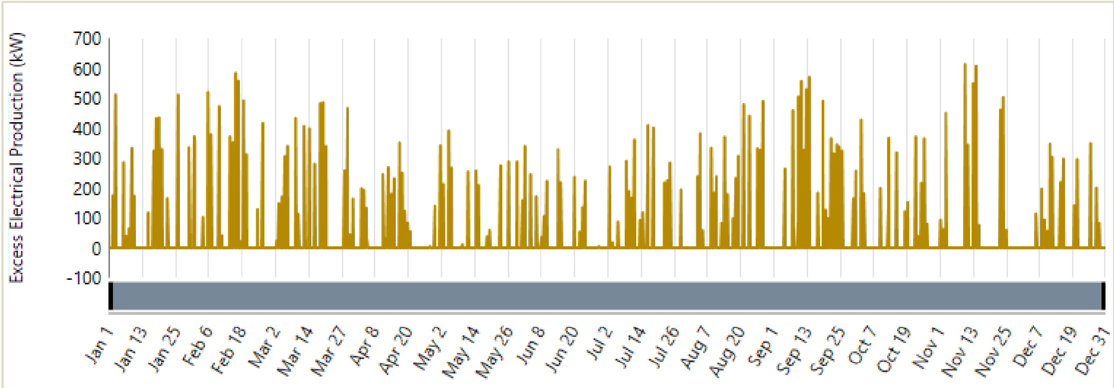


Figure 4. 17: Monthly excess of electricity production

The LCOE of $USD\ 0.0334/kWh$ seems to be low compared to the existing tariff. This can be explained by the fact that there is excess of electricity injected in the utility grid and that the grid power price and grid sellback price were considered as $USD\ 0.071/kWh$ and $USD\ 0.030/kWh$ respectively.

4.8. Performance analysis of the hybrid system components

4.8.1. Optimal performance of PV array

The annual PV output variation is shown in Figure 4.18 while the Table 4.10 presents the predicted performance indicators and power output for the PV component of the optimal simulated system.

Table 4. 10: Performance indicator for a model PV component of the hybrid system

Quantity	Value	Units	Quantity	Value	Units
Rated Capacity	74.6	kW	Minimum Output	0	kW
Mean Output	12.2	kW	Maximum Output	70.5	kW
Mean Output	294	kWh/d	PV Penetration	38.8	%
Capacity Factor	16.4	%	Hours of Operation	4,380	hrs/yr
Total Production	107,184	kWh/yr	Levelized Cost	0.0290	$/kWh

The PV array has a rated capacity of 74.6 kWp, a mean output of 294 kWh/day and a capacity factor of 16.4 %. The PV array output divided by the average primary electric load, known as PV penetration is found to be 38.8 %. The 4,380 hours/year are expected for this PV array. The estimated LCOE from the PV is $US\$\ 0.0290/kWh$ (Table 4.16).

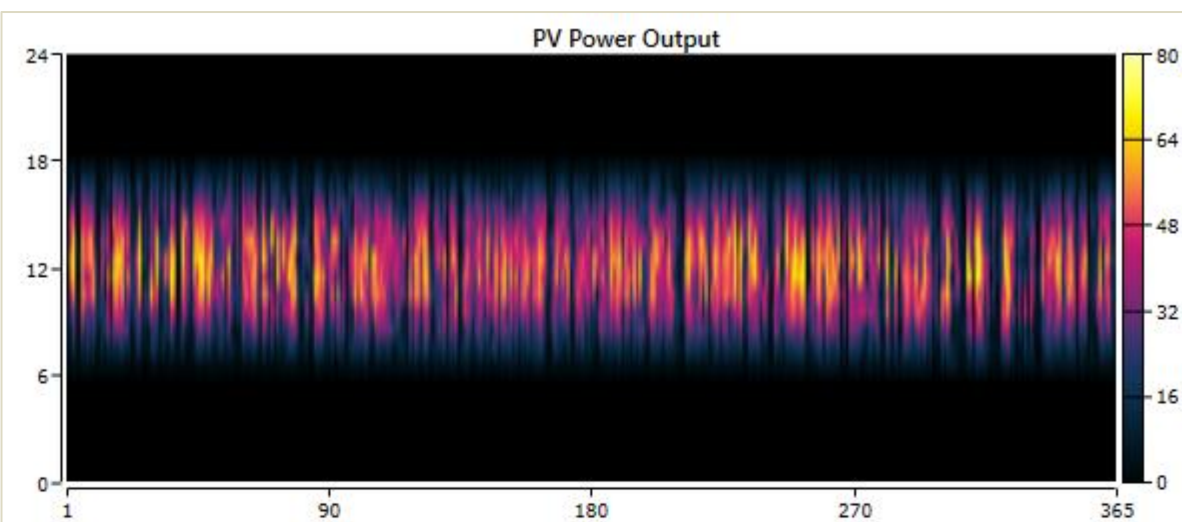


Figure 4. 18: Daily operation and performance of PV power output

From Figure 4.18, the PV power production starts around 6:00 am in the morning and ends at 18:00 in the evening with a peak electricity production during noon. The performance of PV array production is expected to be the same throughout the day, week, month and year.

4.8.2. Optimal performance of utility grid

The utility grid was used as indirect energy storage. The overproduction from the generation system is fed into the utility grid whereas the grid serves to smooth the power supply of the system during its low generation. Table 4.11 presents the monthly energy sold to and purchased from the grid along the whole year.

Table 4. 11: Monthly energy sold to and purchased from the grid

Month	Energy purchased (kWh)	Energy sold (kWh)	Net energy purchased (kWh)	Peak demand (kW)	Energy charge ($)	Demand charge ($)
January	6718.041	11295.88	- 4577.84	234.6872	$138.10	$0
February	7851.059	12010.05	- 4158.99	267.8477	$197.12	$0
March	8010.883	11443.5	- 3432.62	275.3003	$225.47	$0
April	8764.078	8783.945	- 19.8669	251.2402	$358.73	$0
May	12675.45	2018.315	10657.13	244.4121	$839.41	$0
June	13265.45	1954.098	11311.35	305.623	$883.22	$0
July	13057.2	2745.063	10312.14	281.4571	$844.71	$0
August	7407.284	12328.14	- 4920.86	263.0917	$156.07	$0

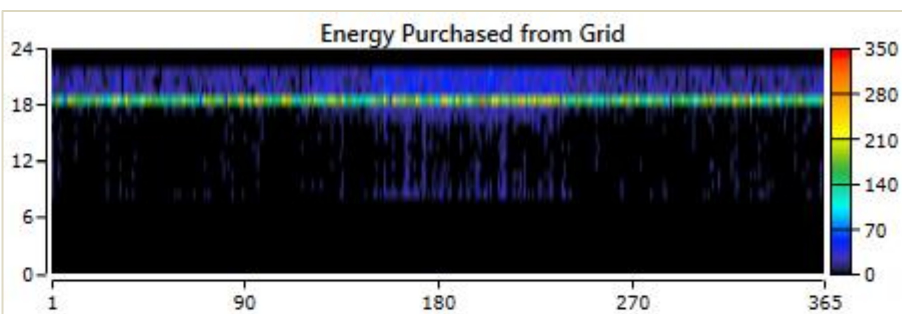


Figure 4. 19: Daily energy purchased from the grid all along the year

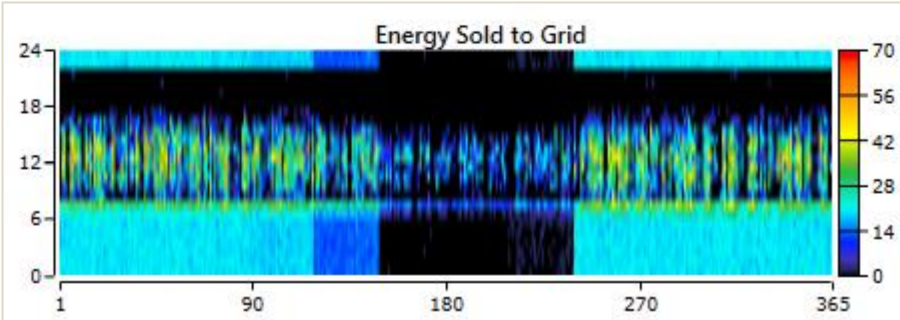


Figure 4. 20: Daily energy sold to the grid all along the year

Figure 4.19 shwaws that energy is most purchased from the grid from 18:00 to 21:00 with a huge consumption around 18:00. This is because the peak load for the village is at that time. The overproduction is huge from 00:00 to 8:00 and after this time, there is also small amount of energy consumed by the grid up to 17:00. From 22:00 to 24:00, there is energy fed into the grid. It can also be noticed that the energy excess from the hybrid system becomes very less in the middle of the year (Figure 4.20) and this can be explained by the reduction of river flowrates in that period of the year (Figure 4.3).

4.8.3. Optimal performance and operation of system converter

The DC power from PV array is converted to AC power by using an inverter of 50.9 kW capacity and 22.4 % capacity factor. Its annual operation is expected to be 4,380 hours/year with energy in and out estimated to be 105,348 kWh/year and 100,080 kWh/year respectively, which reflect energy losses due to inverter efficiency of 5,267 kWh/year (Table 4.12).

Table 4. 12: Yearly operation and performance of inverter

Quantity	Inverter	Rectifier	Units
Capacity	50.9	50.9	kW
Mean Output	11.4	0	kW
Minimum Output	0	0	kW
Maximum Output	50.9	0	kW
Capacity Factor	22.4	0	%

Quantity	Inverter	Rectifier	Units
Hours of Operation	4,380	0	hrs/yr
Energy Out	100,080	0	kWh/yr
Energy In	105,348	0	kWh/yr
Losses	5,267	0	kWh/yr

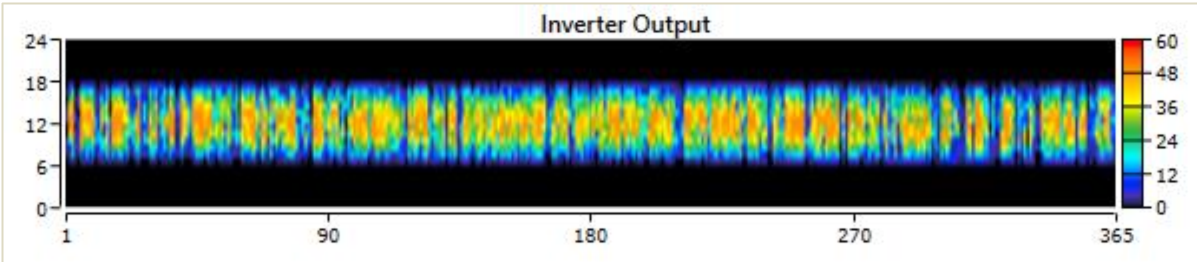


Figure 4. 21: Daily performance of inverter

Figure 4.21 highlights that the inverter functions from 6:00 – 18:00 with a maximum output during noon time. These are the hours of the day when the PV panels generate DC electricity which is converted into AC electricity to power the AC electrical loads.

4.8.4. Optimal performance of hydropower

Table 4.13 shows the hydropower output results. The modelled hydropower operates at a capacitor factor of 65.3 % with a nominal capacity of 31.1 kW. The minimum and maximum outputs are 3.68 kW and 26.4 kW respectively. The hydropower operates the full year (8,760 hours/year) with an average power output of 20.3 kW and 65.3 % of capacity factor. This yields to annual energy production of 117,848 kWh/year with an estimated LCOE of $US\$\,0.0271/kWh$. Figure 4.22 shows the average daily power output from the hydropower along the whole year.

Table 4. 13: Yearly operation and performance indicators of modelled hydropower

Quantity	Value	Units
Nominal Capacity	31.1	kW
Mean output	20.3	kW
Capacity factor	65.3	%
Total Production	177,848	kWh/yr

Quantity	Value	Units
Minimum output	3.68	kW
Maximum output	26.4	kW
Hydro penetration	64.3	%
Hours of operation	8,760	hrs/yr
Levelized Cost	0.0271	$/kWh

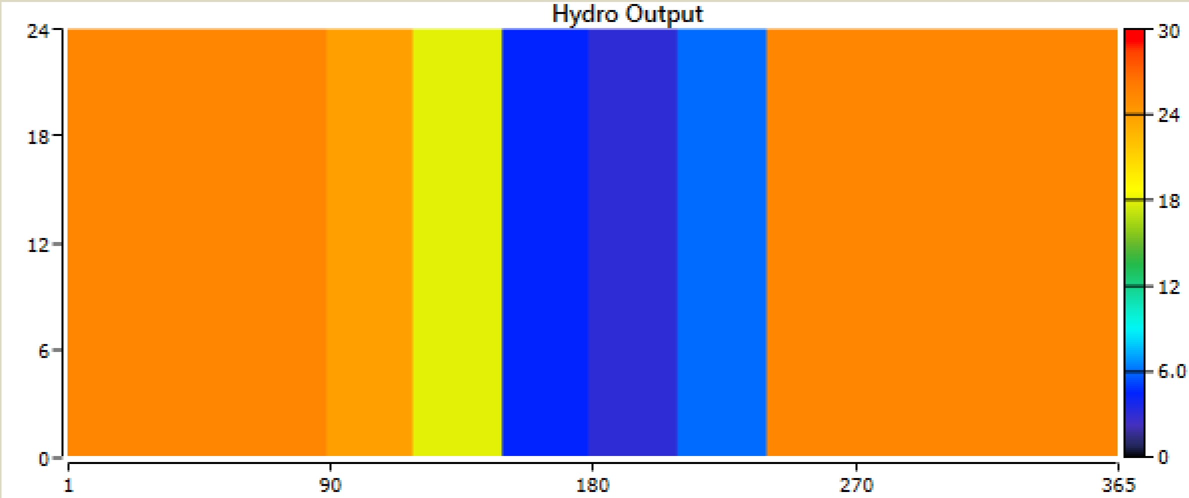


Figure 4. 22: Daily power output from the hydropower

4.8.5. Cost summary and yearly cash-flow of the optimum combination

Figure 4.23 presents the Net Present Cost of the hybrid system components. The optimal hybrid power system has an overall NPC of $US\$$ 732,432. Out of the total NPC, hydropower has the highest NPC of $US\$$ 274,546.14 representing 37.5 %, followed by the grid ($US\$$ 251,058.92) representing 34.3 %, solar PV array 176,800.52. Least NPC of the components representing 4 % is for an inverter with $US\$$ 30,026.15.

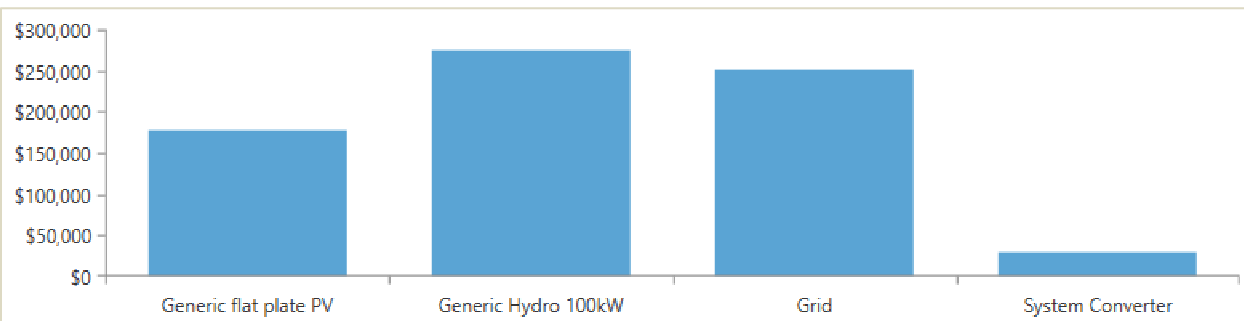


Figure 4. 23: Cost summary by net present cost of the components

Table 4.14 shows the cost summary of the hybrid system along its lifetime. The yearly cash flow summary by cost type over the project lifetime is also presented in Figure 4.24. From that figure, it can be seen that after 15 years, a replacement of a component is imperative. That component is an inverter as other components have 25 years of lifetime.

Table 4. 14: Cost summary of the hybrid power generation system

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Generic flat plate PV	$134,293.59	$0.00	$42,506.93	$0.00	$0.00	$176,800.52
Generic Hydro 100kW	$46,650.00	$0.00	$227,896.14	$0.00	$0.00	$274,546.14
Grid	$0.00	$0.00	$251,058.92	$0.00	$0.00	$251,058.92
System Converter	$15,277.32	$35,910.24	$0.00	$0.00	($21,161.40)	$30,026.15
System	$196,220.91	$35,910.24	$521,461.99	$0.00	($21,161.40)	$732,431.73

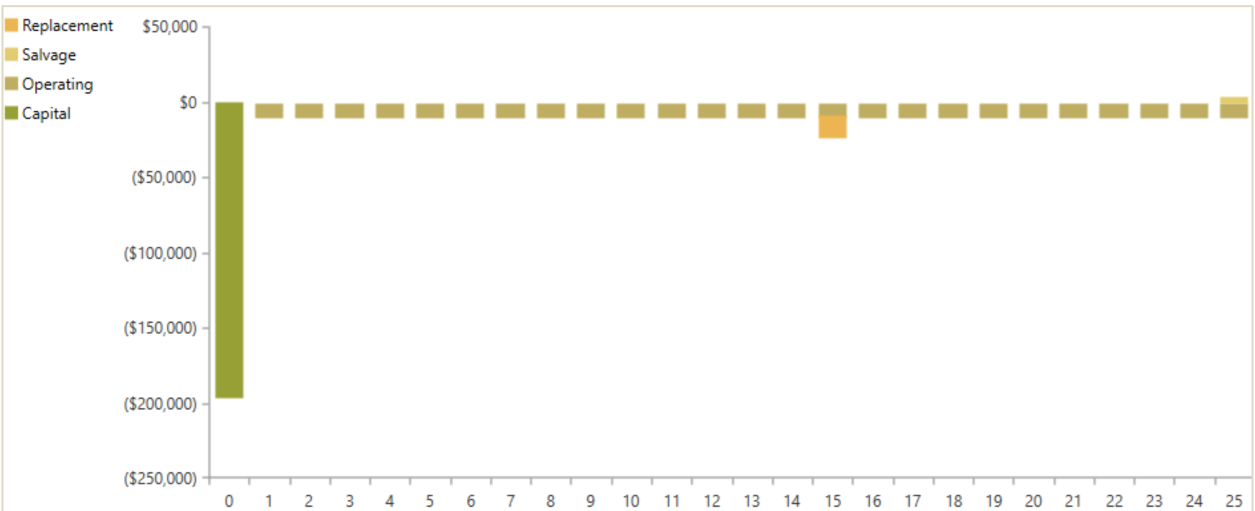


Figure 4. 24: Yearly cash flow summaries by cost type over the project lifetime (with nominal cashflow)

The salvage cost is then obtained after 25 years. The salvage cost of *US*$ 21,161.40 comes from the inverter as shown in yearly cash flow by component with discounted cashflow (Figure 4.25).

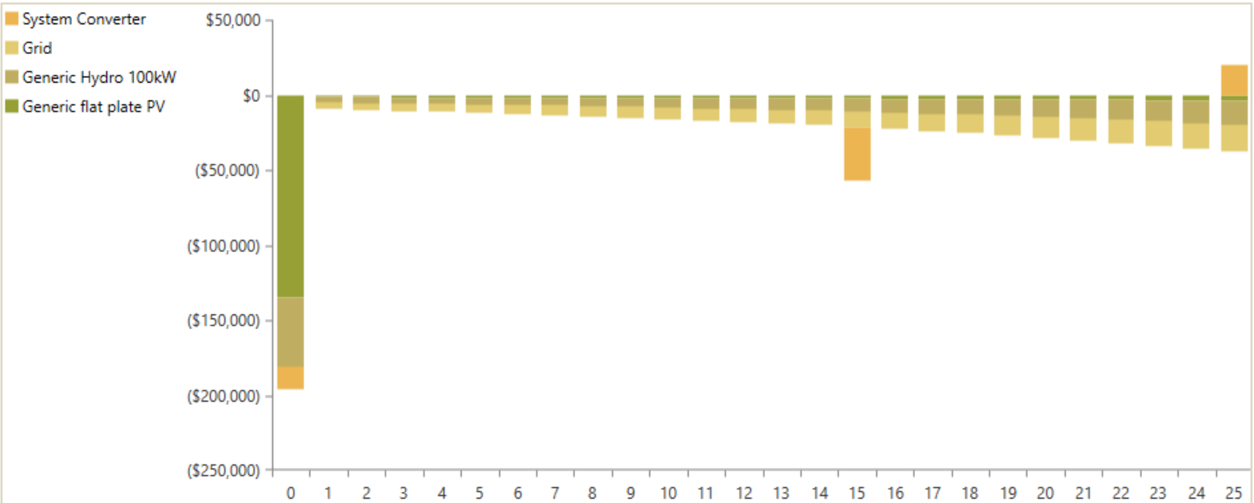


Figure 4. 25: Yearly cash flow summaries by component over the project lifetime (with discounted cashflow)

4.9. Emissions analysis

Solar PV and hydropower do not emit pollutants into the atmosphere. This optimal hybrid power system is only made of renewable energy sources. The results obtained regarding the environmental impact are displayed in Table 4.15.

Table 4. 15: Emissions analysis for the optimum hybrid system

Quantity	Value	Units
Carbon Dioxide	-856	kg/yr
Carbon Monoxide	0	kg/yr
Unburned Hydrocarbons	0	kg/yr
Particulate Matter	0	kg/yr
Sulfur Dioxide	-3.71	kg/yr
Nitrogen Oxides	-1.81	kg/yr

This part of emission analysis is essential in the prediction of the future benefits of air pollution reduction from using the proposed system. The results are given in the form of the amount of carbon dioxide emissions reduced which is shown in the form of kg/year emission not emitted (conservation equivalent). Therefore, from that table, for 25 years of lifetime, the system would reduce the amount of carbon dioxide emission by 856 kg/year, sulphur dioxide emission by 3.71 kg/year and nitrogen oxides emission by 1.81 kg/year.

4.10. Sensitivity analysis

For the variables which their values are uncertain, it is advisable to enter multiple values in a certain reasonable range. This helps to specify the impact of that value on the output results. An input variable for which multiple values are specified is called a sensitivity variable. Sensitivity analysis helps in exploring the effect of the changes in the available resource and economic condition. In this study, due to the fact that Burundi inflation rate has been fluctuating substantially, it has been considered as a sensitivity parameter. The sensitivity values entered for that variable are: 16.64 %, 18 %, 20 % and 23 %. The results obtained are presented in Figure 4.26.

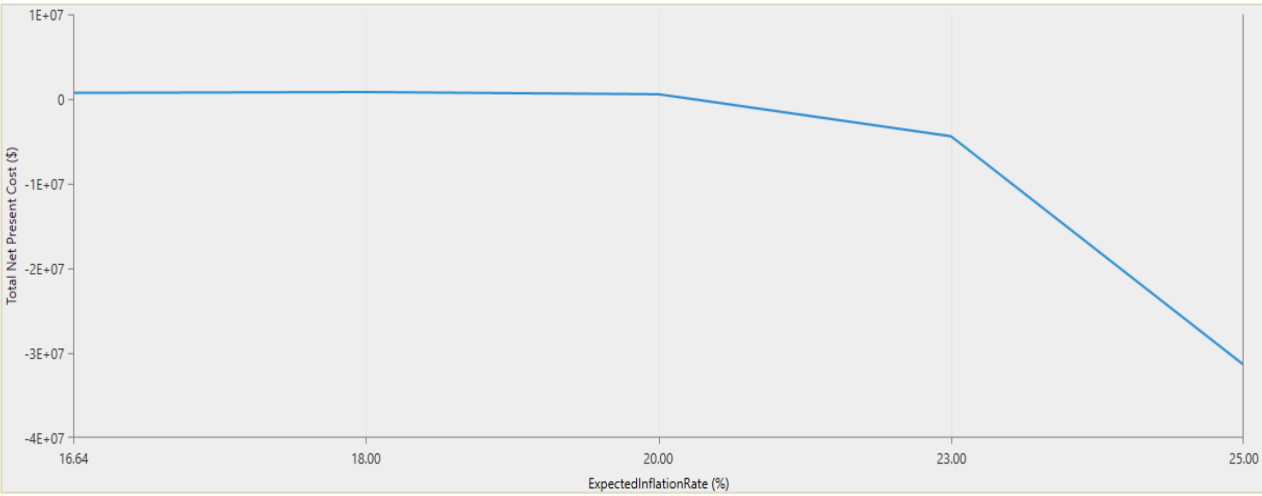


Figure 4. 26: Change of Total NPV with expected inflation rate

Figure 4.26 shows that the inflation rate above 20 % would make the project economically not viable although it was tested to be technically feasible.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

In this study, a reliable and cost-effective hybrid system for capacity supply increasing of Kigwena micro-hydropower was carried out. Three major tasks have been treated in proposing a techno-economical option to meet the power demand gap for Kigwena village: electrical load demand and gap of Kigwena village; performance assessment of Kigwena micro-hydropower and assessment of energy resources available in the study area.

Available energy resources in Kigwena village were evaluated using empirical equations and GIS data for global solar radiation. The worst scenario was considered in this study (data from NASA source) as there was no direct measured data from IGEBU and therefore, the data from this source was estimated at monthly averaged values over a period of 22 years from July 1983 until June 2005. An annual average of 4.91 kWh/m^2 was considered for Kigwena village. The wind technology was found to be not a techno-economically suitable option in the study area due to the low available wind speed with an estimated annual average of 0.67 m/s, a value estimated when the hub centre of the selected wind turbine is at 50 m of height. The high speed was found in September with 1.13 m /s. The daily recorded power outputs from Kigwena hydropower were used to estimate the monthly river flow rate with an annual average estimated to be 32.25 l/s. The estimated monthly hydro flowrate showed huge variations in intensity at times, thus making it less reliable as a continuous source of energy for power generation. Biomass resource was excluded in the different options to upgrade the hydropower plant capacity as it is mainly composed of crops residues which cannot be sustainable for a daily electricity generation.

The electrical load of the village mainly composed of lighting for households, small manufacturing units (palm oil and flour mills) and the commercial was assessed and predicted in the future according to the rate of population growth. The total community of about 6,636 people was predicted in 2040 and estimated to have a primary peak demand of 190.44 kW.

Different options with the assessed energy resources in the study area were evaluated in order to compensate the power fluctuations for Kigwena micro-hydropower. The combination of several renewable energies was found to be a way to overcome this intermittency of hydropower generation. A techno-economic feasible combination of hydropower, wind and solar PV with two options for energy storage strategies directly in battery or indirectly with utility grid was simulated using Homer software. Hence, in overall optimization results, different configurations with their total NPC and LCOE obtained, the most optimum combination was of solar PV, hydropower and utility grid with the lowest LCOE of $US\$\ 0.0334\ /kWh$. This cost is within the range in comparison to the current electricity tariff in Burundi ranging from $US\$\ 0.023/\ kWh$ to $US\$\ 0.072/kWh$.

The suggested system is totally composed of renewable energies. Furthermore, the existing hydropower is a run-off-river type which is friendly to the environment. The proposed system responds to the persistent energy shortage for the village while promoting clean energy development. This solution of increasing energy access is subjected to change the lifestyle of rural communities in Burundi.

This work concludes that Burundi needs to invest in renewable energy such as micro-hydropower plants and solar PV plants in order to meet the growing energy demand. This is because, Burundi has a huge potential in hydroelectric power and solar energy. Furthermore, as renewable energy are intermittent sources of energy, their combinations in hybrid systems would help to overcome the weakness of one to another.

5.2. Recommendations

Considering that most of rural communities in Burundi do not have access to electricity and that most of hydropower plants implemented by ABER are characterized by insufficient power supply, the following recommendations are proposed:

- The government has to harmonize the energy policies and regulations by targeting the key issues of the environment at the national level as well as regional.
- This country has to prioritize the harnessing of available energy resources. The government, non-governmental organizations and private sectors should make combined efforts to improve the quality of life of the communities living in rural areas.
- The capacity building of human resources through trainings in energy sector would handle the scarcity of technical and management skills which affect the prospects for developing the country's energy resources, and would also enable the scope for effective policy-making and the planning and operations of energy producing, marketing, and consuming institutions.
- The government has to be committed to improve the existing hydropower plants infrastructures in order to increase the total capacity and put a lot of effort in implementing the solar PV modules in rural areas that are located far away from the grid. Any off-grid system should be encouraged in order to decentralize the production of electricity to meet the domestic demand. Furthermore, exploiting diverse types of renewable energy sources in hybrid systems would offer a possibility for higher reliability in energy supply. Subsequently, this thesis might be a beginning stage for further work on future researches.
- Researchers willing to develop this work for new sites for the remaining unreliable small hydropower plants should use data directly collected from the site. Data for solar irradiation and wind speed from the study sites should be used for future studies to improve the accuracy of the results.

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APPENDICES

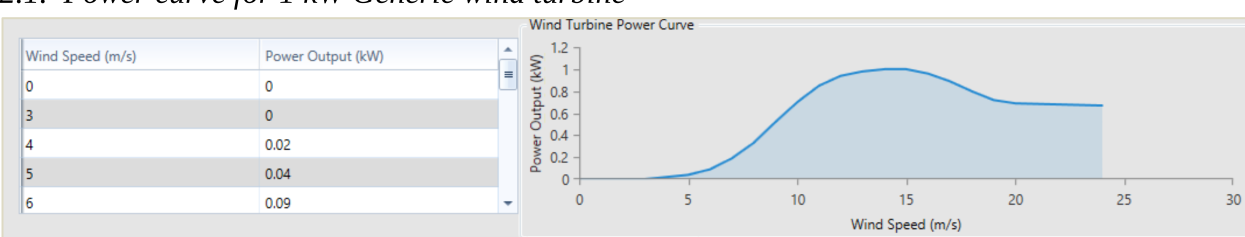
Appendix 1: Estimated electrical load demand of Kigwena village

Sector	Appliances	Units	Power / Unit [kW]	Tot. Power [kW]	Use hours [h]	Use duration	Daily energy consumption [kWh]
Households	Light Bulb	4,420	0.01	44.18	6	18:00-22:00	265.07
	19" colour TV	147	0.04	11.78	3	19:00-22:00	35.34
	Radio	147	0.015	4.42	2	06:00-08:00	8.84
	Iron	147	1	294.52	0.25	18:00-19:00	73.63
	Cell phone charger	295	0.005	1.47	3	18:00-21:00	4.42
Primary School	Indoor lighting	36	0.022	0.79	2	06:00-08:00	1.58
	Outdoor lighting	18	0.022	0.40	12	18:00-06:00	4.75
	Photocopy machine	1	0.2	0.20	1	08:00-09:00	0.20
	Desktop Computer	4	0.1	0.40	3	09:00-12:00	1.20
	Ink-jet printer	1	0.04	0.04	0.25	10:00-11:00	0.01
Secondary school	Indoor lighting	16	0.022	0.35	2	06:00-08:00	0.70
	Outdoor lighting	8	0.022	0.18	12	18:00-06:00	2.11
	Photocopy machine	1	0.2	0.20	2	08:00-10:00	0.40
	Desktop Computer	8	0.1	0.80	3	09:00-12:00	2.40
	Ink-jet printer	1	0.02	0.02	2	10:00-12:00	0.04
Community church	Indoor lighting	18	0.022	0.40	2	06:00-08:00	0.79
	Outdoor lighting	6	0.022	0.13	12	18:00-06:00	1.58
	Megaphone	12	0.006	0.07	1	09:00-10:00	0.07

Medical center	Refrigerator	1	0.18	0.18	24	00:00-23:00	4.32
	Microscope binocular	2	0.02	0.04	2	09:00-11:00	0.08
	Small radio	1	0.03	0.03	6	12:00-18:00	0.18
	Lighting	12	0.04	0.48	2	10:00-12:00	0.96
Administration posts	Indoor lighting	9	0.01	0.08	1	06:00-07:00	0.08
	Outdoor lighting	9	0.01	0.08	12	18:00-06:00	0.96
	Photocopy machine	3	0.2	0.60	3	08:00-11:00	1.80
	Desktop Computer	6	0.1	0.60	4	08:00-12:00	2.40
	Ink-jet printer	3	0.02	0.06	2	10:00-12:00	0.12
Power plant	Indoor lighting	3	0.04	0.12	12	18:00-06:00	1.44
	Outdoor lighting	5	0.04	0.20	11	19:00-06:00	2.20
Commercial	Street light	20	0.1	2.00	12	18:00-06:00	24.00
	Fridge	15	0.1	1.50	24	00:00-23:00	36.00
	Small business	40	0.15	6.00	11	08:00-19:00	66.00
Manufacturing units	Palm oil mill	3	8	24.00	11	08:00-19:00	264.00
	Flour mill	2	2.2	4.40	11	08:00-19:00	48.40
Total				**400.72**			**856.09**

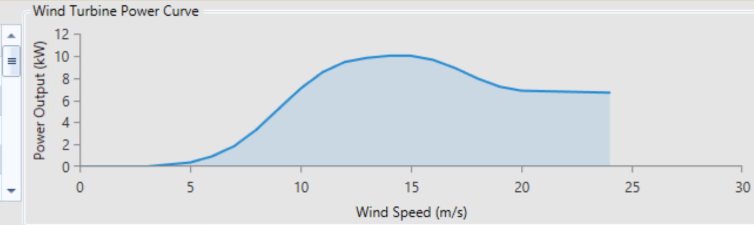
Appendix 2: Power curve for wind turbine at 50 m of hub-height

2.1. Power curve for 1 kW Generic wind turbine



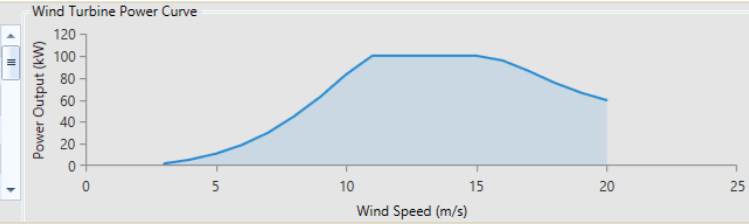
2.2. Power curve for 10 kW Generic wind turbine

Wind Speed (m/s)	Power Output (kW)
0	0
3	0
4	0.19
5	0.37
6	0.93



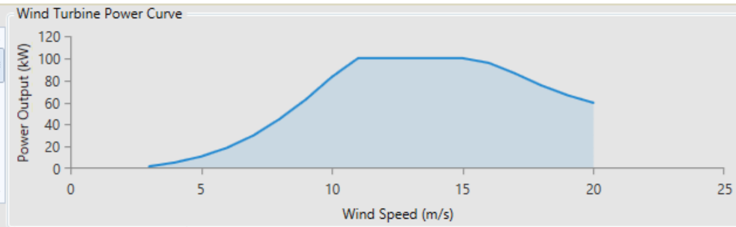
2.3. Power curve for 100 kW XANT M-21 wind turbine

Wind Speed (m/s)	Power Output (kW)
3	2.0
4	5.6
5	11.0
6	19.0
7	30.1



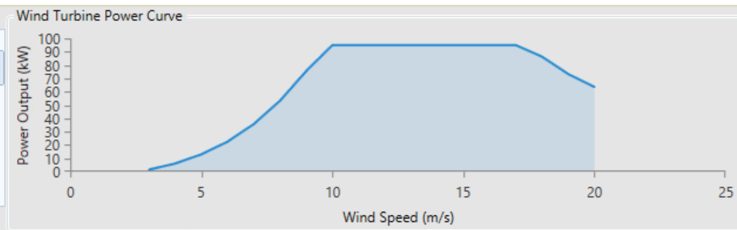
2.4. Power curve for 100 kW XANT M-21- ETR wind turbine

Wind Speed (m/s)	Power Output (kW)
3	2
4	5.6
5	11
6	19
7	30.1



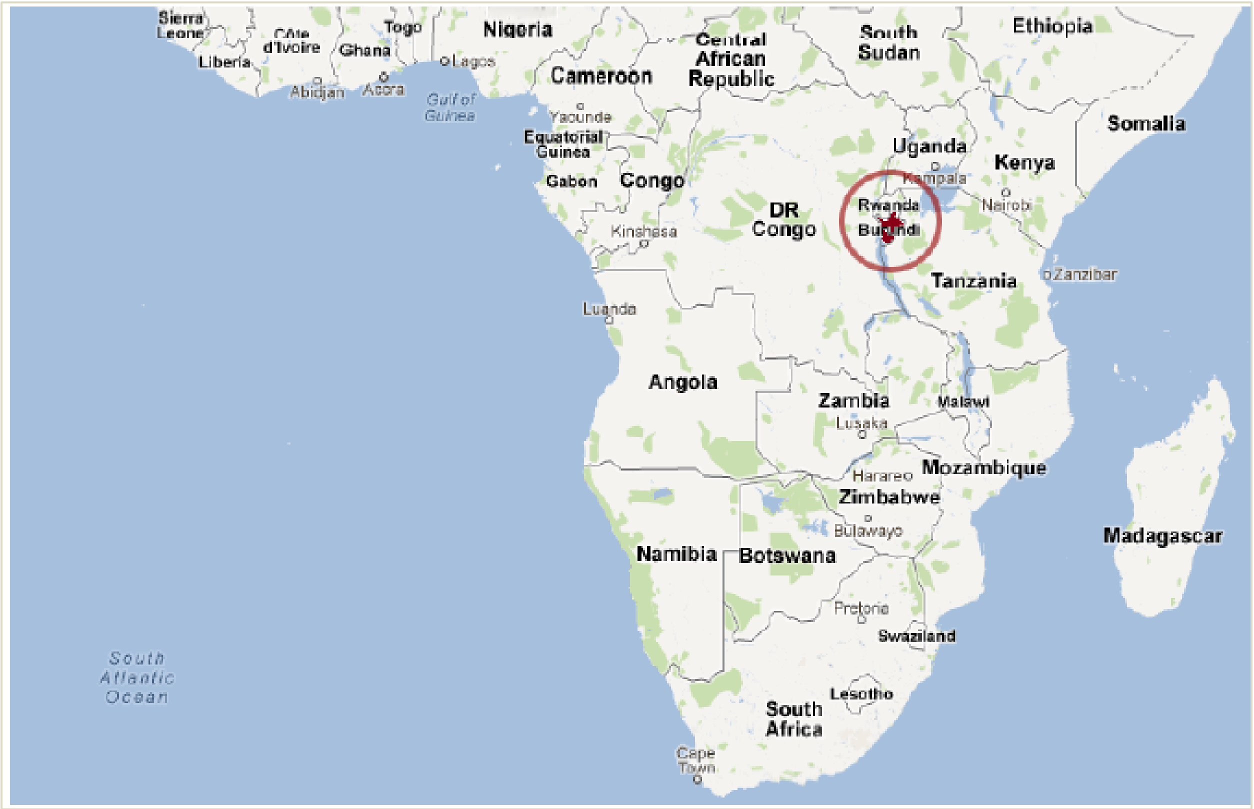
2.5. Power curve for 95 kW XANT M-24 wind turbine

Wind Speed (m/s)	Power Output (kW)
3	1.5
4	6.1
5	13
6	22.5
7	35.7



Appendix 3: Burundi National utility grid

Appendix 4: Burundi location



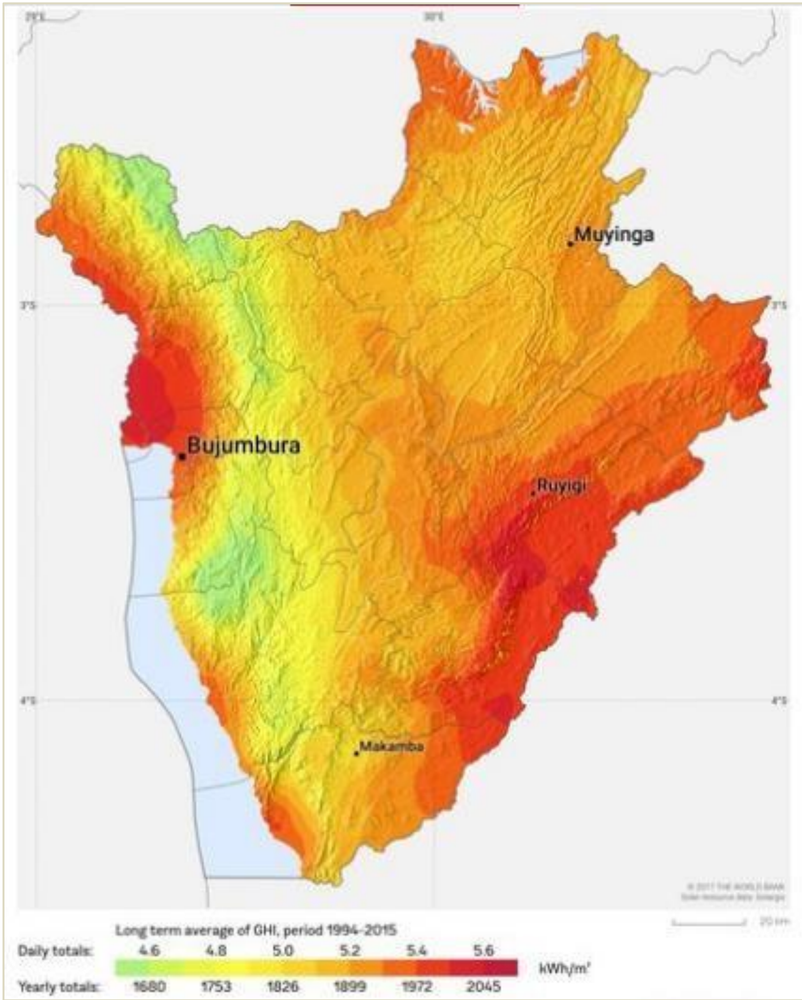
Appendix 5: State of Power plants in Burundi (from 2002 – 2008)

Production plants	Installed capacity (MW)	Electricity production (GWh) 2002	2003	2004	2005	2006	2007	2008
Domestic supply								
Regideso stations								
Bujumbura thermal plant	5,50							
Rwegura	18,00	68,08	48,71	42,32	49,27	35,82	59,89	55,33
Mugere	8,00	44,37	44,47	38,24	42,89	51,22	47,35	42,37
Ruvyironza	1,27	2,84	3,61	1,16	2,33	-	2,55	1,99
Nyemenga	1,44	5,43	4,47	3,85	3,42	4,39	1,60	1,54
Gikonge	0,85	1,28	1,05	0,97	0,82	-		1,52
Kayenzi	0,85	1,23	1,05	0,96	0,59	0,51		0,24
Marangara	0,24	0,89	1,05	0,73	0,63	0,75		0,40
Buhiga	0,24				0,63	0,19		
Total national production	36,39	124,13	104,42	88,23	100,58	92,89	111,40	103,40
Remote DGHER plants	0,47	0,64	7,98	1,51	23,40	6,19		
Private plants	0,65							
Total domestic capacity	37,51	124,77	112,39	89,74	123,98	99,08	111,40	103,40
Imported supply								
Rusizi I	28,00	27,65	26,13	29,43	20,96	16,74	25,13	24,13
Rusizi II	12,30	12,25	30,89	44,68	49,96	42,08	52,28	72,03
Total imports	40,30	39,90	57,03	74,10	70,92	58,82	77,41	96,16
Total supply	77,81	164,67	169,42	163,85	194,89	157,90	188,80	199,56
Memo item:								
Share of imports in total (%)	51,8	24,2	33,7	45,2	36,4	37,3	41,0	48,2
Capacity utilization (%)								
Domestic capacity		38,0	34,2	27,3	37,7	30,2	33,9	31,5
Import capacity								
Rusizi I		11,3	10,7	12,0	8,5	6,8	10,2	9,8
Rusizi II		11,4	28,7	41,5	46,4	39,1	48,5	66,9
Average for imports		11,3	16,2	21,0	20,1	16,7	21,9	27,2
Average for total capacity		24,2	24,9	24,0	28,6	23,2	27,7	29,3

Appendix 6: Electricity demand and electrification rates in Burundi

Indicator	2007	2010	2015	2020	2025	2030	Growth rate (% p.a.)	
							2007-10	2010-30
Electrification program								
Total number of households ('000)								
Urban	146	177	233	301	384	490	6,7	5,2
Rural	1 430	1 538	1 723	1 920	2 124	2 328	2,5	2,1
Total	1 576	1 715	1 957	2 221	2 508	2 818	2,8	2,5
Electrification rates (%)								
Urban	20,9	19,0	40,0	85,0	85,0	85,0	(3,2)	7,8
Rural	0,2	0,2	3,0	15,0	24,0	34,0	-	29,3
Average	2,1	2,1	7,4	24,5	33,3	42,9	-	16,3
Households with electricity ('000)								
Urban	31	34	93	256	326	416	3,1	13,4
Rural	3	3	52	288	510	792	-	32,2
Total	34	37	145	544	836	1 208	2,9	19,0
Electricity consumption								
Consumption per household (kWh)								
Urban	2 457	2 400	2 706	2 988	3 299	3 642	(0,8)	2,1
Rural	250	250	271	299	330	364	-	1,9
Total electricity consumption (GWh)								
Households	75,2	81,5	266,7	849,9	1 244,6	1 805,1	2,7	16,8
Business sector	51,8	55,0	109,8	211,4	407,0	783,6	2,0	14,2
Mining sector	-	-	-	650,0	650,0	650,0	-	-
Government	15,9	16,4	19,0	22,1	25,6	29,6	1,1	3,0
Total	142,9	152,9	395,5	1 733,4	2 327,1	3 268,3	2,3	16,5
System losses								
Percentage of production (%)	24,4	22,0	16,0	12,5	10,0	10,0	(3,4)	(3,9)
Total losses (GWh)	45,9	43,1	75,3	247,6	258,6	363,1	(2,1)	11,2
Total supply (GWh)	188,8	196,0	470,8	1 981,0	2 585,7	3 631,5	1,3	15,7
Generation capacity								
Required capacity	36	37	90	377	492	691	1,0	15,8

Appendix 7: Global solar radiation in Burundi



Appendix 8: Burundi hydropower potential