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DESIGN OF HOME ELECTRICITY SUPPLY SYSTEM USING SOLAR PV AND ITS INTEGRATION TO THE NATIONAL GRID: A CASE STUDY OF MASAKA VILLAGE

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CERTIFICATE

This is to certify that this thesis entitled **"Design of Home Electricity Supply System Using Solar PV and its Integration to the National Grid: A Case Study of Masaka village"**, is a record of the original work done by Mr. Ernest NSHIMIYIMANA (Reg. No: PAUWES/2016/MEE05) in partial fulfillment of the requirement for the award of a Master of Science Degree in Energy Engineering at the Pan African University Institute of Water and Energy Sciences, (including Climate Change**)**. He has incorporated all observations, suggestions and comments made by the thesis supervisor.

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DECLARATION

I, Ernest NSHIMIYIMANA 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.

Signed: **13-09-2018**

Ernest NSHIMIYIMANA **Date**

DEDICATION

This work is dedicated to my family whose words of encouragement and push for tenacity ring in my ears, I dedicate this thesis to my supervisor for guiding and inspiring me from the beginning till this far and on, my classmates for their daily cooperation, companies which allowed me to have access to quantitative and qualitative data used in this project, friends and everyone who supported me in another way, whether mentally, physically and emotionally.

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ABSTRACT

In spite of the way that non-renewable energy sources are found in relatively small number of places, they are consumed worldwide. On the other hand, the sustainable power source is accessible everywhere throughout the world; however, it is so far used just by little a portion of the total world population. Currently, because of an increased awareness of the environmental impact of fossil fuels and advancement in renewable energy technology, there is a rise in the use of renewable energy as an alternate source of energy. Due to a rapid increase in household biomass energy consumption which has been occurring recently in Rwanda particularly in urban and semi-urban households due to the energy crisis in Rwanda, solar energy is promoted and widely adopted at the domestic level. This insufficient electricity is affecting industrial growth and projected markets extension in the country. Therefore, different measures must be applied to ensure the future national growth projections. This work presents a study that examined the possibility of supplying electricity to Masaka village households by using a grid-connected solar PV system. Rwanda has a geographical advantage by virtue to its position approximately two degrees below the equator and in the region where the sufficient solar radiation for PV generation system can be accurately forecasted. Data for solar insolation and domestic load from the case study was collected and then analyzed so as to design a typical solar photovoltaic system. Information gathered have demonstrated that Masaka village receives a monthly average solar insolation of 4.8 kWh/m^2/day for the most time of the year. The selected middle-class family has the average peak power of 5.93 kWp while the total daily energy consumption is 8.3 kWh. RETScreen Expert package was used to size and simulate the photovoltaic system suitable for the selected house. Considering the daily energy consumption for the household and different loses, a 3 kW PV system was sized where the surplus electricity during off-peak demand could be exported to the grid and be imported when there is a low production for the system. In order to reach this project's goal, a cost-benefit analysis was performed to determine if the investment would be financially worthwhile. The results reveal that solar energy is viable in this selected village with an initial investment of $ 11,489 and a payback period of 8.1years. The designed system will be capable of satisfying the needs of the selected household and injecting the surplus power to the grid.

Keywords: *Renewable Energy, Grid-connected, solar PV systems, and RETScreen software*.

RÉSUMÉ

En dépit du fait que les sources d'énergie non renouvelables se trouvent dans un nombre relativement restreint de lieux, elles sont consommées dans le monde entier. D'autre part, la source d'énergie durable est accessible partout dans le monde ; cependant, il est jusqu'à présent utilisé juste un peu par une partie de la population mondiale totale. Actuellement, en raison de la prise de conscience accrue de l'impact environnemental des combustibles fossiles et de l'avancement de la technologie des énergies renouvelables, il y a une augmentation de l'utilisation des énergies renouvelables comme source d'énergie alternative. En raison de l'augmentation rapide de la consommation d'énergie de la biomasse des ménages qui a récemment eu lieu au Rwanda, particulièrement dans les ménages urbains et semi-urbains en raison de la crise énergétique au Rwanda, l'énergie solaire est encouragée et largement adoptée au niveau national. Cette électricité insuffisante affecte la croissance industrielle et l'extension prévue des marchés dans le pays. Par conséquent, différentes mesures doivent être appliquées pour garantir les projections de croissance nationales futures. Ce travail présente une étude qui a examiné la possibilité de fournir de l'électricité aux ménages du village de Masaka en utilisant un système photovoltaïque solaire connecté au réseau. Le Rwanda a un avantage géographique en raison de sa position à environ deux degrés au-dessous de l'équateur et dans la région où le rayonnement solaire suffisant pour le système de génération de PV peut être prévu avec précision. Les données relatives à l'insolation solaire et à la charge domestique tirées de l'étude de cas ont été recueillies puis analysées afin de concevoir un système solaire photovoltaïque type. L'information recueillie a démontré que le village de Masaka reçoit une moyenne mensuelle d'ensoleillement de 4,8 kWh / m2 / jour pour la majeure partie de l'année. La famille de la classe moyenne sélectionnée a la puissance de pointe moyenne de 5,93 kWc alors que la consommation d'énergie quotidienne totale est de 8,3 kWh. Le logiciel RETScreen Expert a été utilisé pour dimensionner et simuler le système photovoltaïque adapté à la maison sélectionnée. Compte tenu de la consommation d'énergie quotidienne du ménage et des pertes, un système photovoltaïque de 3 kW a été dimensionné pour que l'électricité excédentaire en période de pointe puisse être exportée vers le réseau et importée lorsque la production du système est faible. Afin d'atteindre l'objectif de ce projet, une analyse coûts-avantages a été effectuée pour déterminer si l'investissement serait rentable. Les résultats révèlent que l'énergie solaire est viable dans ce village sélectionné avec un investissement initial de 11 489

$ et une période de récupération de 8,1 ans. Le système conçu sera capable de satisfaire les besoins du ménage sélectionné et d'injecter le surplus d'énergie dans le réseau.

***Mots clés**: Énergies renouvelables, réseaux connectés, systèmes PV solaires et logiciel RETScreen*

CONTENTS

LIST OF ABBREVIATIONS AND ACRONYMS

DER:	Distributed Energy Resources
EDCL:	Energy Development Corporation Limited
ESMAP:	Energy Sector Management Assistance Program
EDPRS:	Economic Development and Poverty Reduction Strategy
GHG:	Greenhouse Gases
NASA:	National Aeronautics and Space Administration
NREL:	National Renewable Energy Laboratory
MININFRA:	Ministry of Infrastructure
MPP:	Maximum Power Point
MPPT:	Maximum Power Point Tracking
PPA:	Power Purchase Agreements
PLL:	Phase-Locked Loop
PT:	Theoretical Power
RMA:	Rwanda Meteorology Agency

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Chapter 1. INTRODUCTION

Rwanda's energy sector plays a big role to its development in many areas like urbanization, industrialization and many other sectors. The government of Rwanda has devised different strategies to improve the energy sector. Though new power plants are being implemented, Rwanda energy capacity is still insufficient to cover the daily energy needs of people (African Development Bank Group, 2013; MININFRA, 2016). Design of Home Electricity Supply System using Solar PV and its integration to the national grid can be one of the means to increase the capacity of energy required to serve the country.

Solar energy is the most favorable of the renewable energy sources in view of its apparent limitless potential (Nwabineli, 2015). It is important that Rwandan technologies for electrification be based on renewable energy sources because Africa is vulnerable to climate change (Boko et al. 2007) and the continent has more solar radiation than any other continent on earth according to the World Sunshine Map. It has the greatest potential for solar power projects with a larger part of the continent getting about $300W/m^2$ of solar radiation annually(Ebenezer Nyarko, 2013). The most pursued renewable energy technology is solar photovoltaic as it is environmentally friendly, low maintenance, possibility of expandability. Photovoltaic technology does not require any fuel and is noise free and pollution free (Zeman, 2006). The message here is that electrification using renewable energy should come hand in hand with development.

Renewable energy is a term that is roughly used to describe any form of electric energy generated from resources other than fossil and nuclear fuels. Renewable energy resources include hydropower, wind, solar, wave and tide, geothermal and hydrogen. The Sun is the source of all these renewable energies with exception of geothermal and tidal energy (Timmons *et al*., 2014). Using this kind of energy resources lead to much less pollution generation than using fossil fuels technologies and are constantly replenished and thus called renewable.

This project presents a design of home solar system connected to the grid (net metering) and its benefits such as increasing energy efficiency to the consumers by reducing the amount of money they spend on energy from the utility company. In point of facts from related research, this Grid-connected system when will be generating more power than what consumers need during daylight hours, the system allows them to send their extra power to the grid and provide credit that they can use when they need it. This system may require a large investment, but it will be cheaper than paying the costs of electricity imported directly from the grid.

1.1 Background and Motivation

An overview on Rwanda's energy sector proves a gap between energy generation capacity and energy demand to meet the needs the country. This gap is one important fact that negatively affects the lifestyle of most of Rwandan. The Government of Rwanda is itself looking for the opportunities to invest in renewables energies to overcome this problem of not having enough electricity. In addition, it will reduce overreliance on fossil fuel which emit the greenhouse gases. The important elements that motivate this study can be summarized as energy demand growth, political and economic issues and environmental worries.

Currently, technologies are being developed to find a long-lasting solution to increase energy capacity while considering climate change issues. The total installed electricity generation capacity is currently 216 MW and the current on-grid access to electricity is estimated at 31% of households (MININFRA*, 2016). Reaching a high level of quality of life causes a high demand of energy that resulted from technological and industrial development. Additionally, the population growth leads to increasing the demand for energy. This growing of energy demand requires building new power plants. In return, building new power plants leads to rising in electricity cost for the government. Similarly, Increasing energy demand leads to high consumption of fossil fuels, which result in an increase in emission of carbon dioxide (Epa & Change Division, 1990).

From the economical point of view, Rwanda's electricity depends on hydro, fossil fuel and imported electricity from neighbor countries and regional shared company (African Development Bank Group, 2013)**.** Rwanda has known an energy crisis during the last two decades due to the lack of investment in energy. It has led the country to be more reliant to import until now, as a matter of urgency, to be mostly dependent to thermal generation at the time oil prices have drastically increased.

The fossil fuel contributed a large percentage energy price in the country (Uwisengeyimana, et al., 2016). Thus, there is a need to reduce fuel-based electricity generation by exploiting and increasing renewable-based methods of generation.

1.2. Problem Statement

For the Government of Rwanda, the principle approach targets to the electricity sectors are to guarantee sufficient, reliable, maintainable and more affordable power supply. There are a number of challenges Rwanda is facing. One of the challenges Rwanda faces today is insufficient energy to meet the energy needs of the country(African Development Bank Group, 2013; MININFRA, 2016), while the previous studies have shown that the country has abundant solar energy potential to support its energy demand. It is therefore important to harness that source in order to find a solution to energy shortage and environmental degradation the country is facing. Thus solar energy is now considered to be one of the most effective and economic alternative resource (Scheer, 2002) for ensuring access to affordable and modern sources of energy which is essential to achieving the EDPRS II objectives (MININFRA, 2016).

Furthermore, the electricity costs are among the highest in the world, and higher than neighboring countries in the region, with grid-connected consumers paying roughly Rwf182($0.22)/kWh) compared to $0.12 in the United States (Livingstone, 2015). This is unaffordable considering the living conditions of Rwandan people and gross domestic product per capita which is still very low at 700 US Dollars (World Bank, 2017). In addition to high costs, the power supply is unreliable. Rwanda sees the high cost and the insufficient and the unreliable supply as the number one barrier to stronger benefits for the business and modern development.

Most of the electricity in Rwanda comes from hydro and fossil fuel (thermal power plants) that account for about 53 % and 43% respectively (Renewable Energy Cooperation Programme, 2017). Only 31% of the population has an access to the national grid. Households that do not have electricity rely on kerosene lanterns and candles to meet their lighting needs, but these sources of light are dangerous for health, low quality and expensive. Currently, Rwanda is one of the fastest growing economies in the continent and this has resulted in an increase of the demand of energy and this has, in turn, lead to increase in fossil fuel consumption and emission of carbon dioxide. Therefore, the need for alternative renewable energy technology is important to meet the growth in the energy demand and avoid building new power plants with a high cost as well as to reduce the sensitivity to economic, environment and energy crisis.

1.3. Objectives of the Study

1.3.1. The main objectives

The central objective of this thesis is to design a grid-connected solar photovoltaic system for Masaka village using roofs of buildings based on available solar radiation and electricity needs of consumers. This objective is also to analyze the technical and financial performance using simulation software package. The proposed system is going to cover the electricity needs of the selected household, and hence contributing to the sustainable and economic development of the country.

1.3.2. Specific Objectives

The study has the following specific objectives and must be accomplished to achieve the output:

i. To identify a region for the case study based on electrical energy demand and available solar radiation in Rwanda,
ii. To investigate the domestic load data from the selected place,
iii. To design a typical grid-connected solar PV electricity generation system for the case study.
iv. To identify electricity solar system supply equipment’s specification that able to power up a selected household electrical appliances.
v. To perform an economic analysis of the solar PV electricity generation system of the case study.

1.4. Limitations

The data related to the electricity consumption of the family has been collected through a questionnaire and a direct interview, and not measured in order to do this particular thesis; so maybe the data doesn’t match perfectly with the building consumption. However, it is only an approximation based on the behavior of other similar families and it was supposed to be enough for this issue.

The meteorological data from another source other than the one RETScreen expert provide was total different. In this case, the solar radiation data is from NASA and not from any meteorological station located in the surroundings. Finally, the simulations carried out through RETScreen are quite different from the ones that we could achieved due to limitations presented, and certain approximations within in.

Chapter 2. LITERATURE REVIEW

2.1.Introduction

Nations throughout the world are dealing with environmental change and energy security concerns. Declining costs and enhanced proficiency and dependability are making the sustainable power source segment alluring. This is leading to increased investment in renewable energy resources. In terms of installed capacity, Solar photovoltaic is the third most essential sustainable power source among sustainable power source assets, after hydro and wind power (International Finance Corporation, 2014). According to the REN21's Renewables Global Status Report 2013, total renewable power capacity worldwide exceeded 1,470GW in 2012, up about 8.5% from 2011. Hydropower rose to an estimated 990 GW, while other renewables grew 21.5% to exceed 480 GW. Globally, wind power accounted for about 39% of renewable power capacity added in 2012, followed by hydropower and solar PV, each accounting for approximately 26%. Solar PV capacity reached the 100 GW milestone to pass bio-power and become the third largest renewable technology in terms of capacity (but not generation), after hydro and wind. In 2007, developed economies invested two-and-a-half times more in renewables (excluding large hydro) than in developing countries; in 2012, the difference was only 15 percent(International Finance Corporation, 2014).

Solar energy sources ensure a clean energy supply and it has been considered to play a significant role of global warming prevention by fighting against climate change (Bouzid & Ghellai, 2016) as their use for electricity generation doesn't require fossil fuel. The amount of power generated by any solar technology at a selected site depends on how much of the sun's energy reaches it(Kumar M. et al., 2014). Despite the major challenge in a solar power plant is to maximize the wavelength of sun rays and minimize the effect of temperature on solar cells(Kumar, M et al., 2014).

Since 1980's, electrification by different solar technologies had been deployed in Rwanda mainly through support from donors and NGOs (Non-Governmental Organizations) and a study conducted by ESMAP (Energy Sector Management Assistance Program)/World Bank project in 1991 provided an assessment of the market at that time(Disch & Bronckaers, 2012).

2.2.Rwanda energy overview

Rwanda is rather well-endowed with domestic energy resources though most of these resources remain untapped. Energy sources for electricity generation include hydropower; geothermal; methane gas; peat; solar and biomass. Geothermal and wind energy resources are presently being explored(Development Bank of Rwanda, 2017).

Rwanda is undergoing rapid change in energy use; it has experienced an energy crisis mostly due to lack of investment in the energy sector. With the growing of the population and development of industrialization and urban areas, energy provided by existing hydro and thermal power plants has been increasingly scarce with high energy costs, and energy instability. Moreover, as biomass (wood fuel) is the most important source of energy in Rwanda, the enduring dependence on it and fossil fuel consumption as well will continue to impact on the process of environmental degradation. Recently, the Government has given priority to the extension of its national electrical grid through the development of hydropower generation projects, and solar PV kits to rural energy through development of alternative energy projects for rural areas where access to the national grid is still difficult(MININFRA, 2016; Development Bank of Rwanda, 2017).

2.2.1. Installation capacity

The total installed electricity generation capacity is currently 216 MW, of which roughly more than 60% comes from hydrological resources and less than 40% from diesel-powered generators and other sources. Rwanda has a very pronounced peak demand load and hence supply is occasionally unable to match demand in these peak hours. The current on-grid access to electricity is estimated at 31% of households(EDCL, 2018b, 2018a).

There is a considerable private sector interest in electricity generation from Rwanda’s indigenous resources such as the recent private sector peat deal to generate 100MW of electricity from south Akanyaru peat reserves(Ministry of Infrastructure, 2015a). Similarly, a unique project to generate 350 MW of electricity from methane held in Lake Kivu is expected to be developed. Through these projects Rwanda will be able to meet ambitious EDPRS targets for economic growth. Electricity demand could be as high as 563 MW by 2018 and a continuous investment from the private sector is necessary to be able to satisfy this demand (Ministry of Infrastructure, 2015a).

In 2013, the projections of demand for electricity was ranging between 250 and 470 MW; requiring the installed generation of 300-564 MW (considering a 20% reserve margin). Rwanda energy group is revising this forecast each year to ensure generation that is in-line with demand. (Ministry of Infrastructure, 2015a) The current target is to have an installed capacity of 563 MW by 2018. Government is prioritizing developing the feasibility of different generation sources to reduce the perceived delivery risks and lay ground for more private sector participation (Ministry of Infrastructure, 2015a).

Projections of electricity demand are along these lines intelligent of government targets as opposed to behavioral variables that ordinarily influence power demand. In view of the objectives set by the EDPRS and the Vision 2020, peak demand was relied upon to develop from 51 MW in 2008 to 204 MW in 2015 and 328 MW in 2020. Extrapolation of the visualized pattern would bring about a pinnacle heap of 500 MW by 2025. These figures were the premise of the broad examination that was done while setting up the Electricity Master Plan in 2009-2010 (Development Bank of Rwanda, 2017). Rwanda's densely distributed population should facilitate network expansion and access to electricity, presently only 31% of Rwanda's households are connected to the grid(EDCL, 2018a). The new cabinet that was formed in October 2010 decided to accelerate the expansion of electricity services. A new target was set to reach an access ratio of 50% by 2017. Extension of the envisaged trends would imply that electricity access would reach 94% by 2025. This target was further pushed up in February 2012 with a government desire to reach 70% access by 2017(Development Bank of Rwanda, 2017).

Rwanda 's location, just a few degrees south of the Equator makes it a prime candidate for the development of solar PV plants(Solar Plaza, 2017). However, this is not yet implemented in potential areas since most of the energy is generated by Hydro and thermal power plants as illustrated by the Figure 2.1(Renewable Energy Cooperation Programme, 2017) presented below.

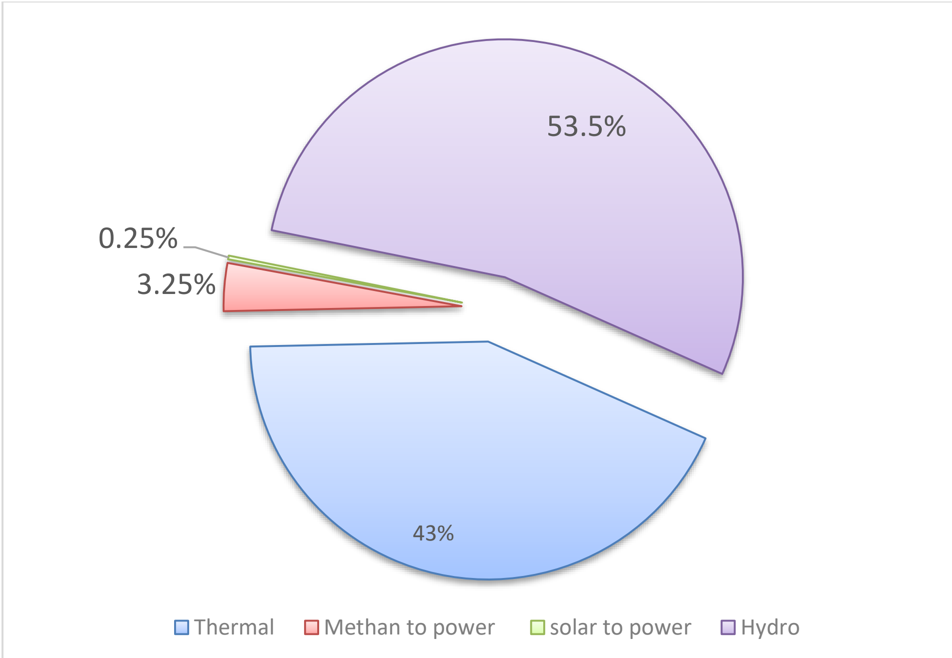

Figure 2. 1 Rwanda's resources in electricity generation 2014

(Renewable Energy Cooperation Programme, 2017)

2.2.2. Rwanda's Solar Energy

Earlier studies have shown that Rwanda has a moderate source of solar energy with an average solar radiation of 4 to 6 kWh/m^2/day and peak sun hours of approximately 5 hours per day. Solar energy becomes an option specifically in Eastern province as it is the highest solar potential compared to the rest of the country (Africa Development Bank Group, 2013).

In July 2013, the government of Rwanda contracted with GigaWatt Global, a Dutch firm, to develop an 8.5MW solar power plant in Rwamagana District, Eastern Province, for a contract of US$23 million. GigaWatt Global would finance, build, own and operate the facility for 25 years, with the power produced sold to Rwanda Energy, the national electricity utility. In February 2014, GigaWatt Global was able to reach financial closure, allowing construction to begin. Interconnection to the national electricity grid was achieved in July 2014, and by September 2014 the power plant was producing at maximum capacity. The power station consists of 28,360 individual photovoltaic panels spread out on a 20 ha field. The final construction price, including the cost to access the national grid came to US$23.7 million(Africa Development Bank Group, 2013). Rwamagana project is the first utility-scale, grid-connected, commercial solar field in East

Africa and it has increased Rwanda's generation capacity by 6% ("Rwanda | Gigawatt Global," 2017).

Currently, Rwanda's Total on-grid installed solar energy is 12.08 MW; Jali, GigaWatt /Rwamagana, Nyamata Solar and Nasho Solar PP solar power plants (see Table 2.1) (Rwanda Energy Group-EDCL, 2018). In addition to that off-grids have been developed where PVs have been installed in different Schools, Health centers, Administrative offices and other projects are underway like the Greenfield 10MW, 10MW grid-connected solar PV Plant in Eastern province (Nyagatare) and (Rwinkwuvu) respectively by Independent power producer (Ministry of Infrastructure, 2015b).

Table 2. 1 Rwanda solar power plants

Power plant	Installed capacity MW
Jali	0.25
GigaWatt /Rwamagana	8.50
Nyamata Solar	0.03
Nasho Solar PP	3.30
Total	**12.08**

(Rwanda Energy Group-EDCL, 2018)

Worldwide, the development of solar energy in the form of grid-connected electricity is considered to be very costly even for countries that have more intense sunlight(Africa Development Bank Group, 2013). However, the use of solar energy for electricity generation in isolated off-grid areas and for water heaters has proven to be economically viable. Rwanda has also chosen a realistic track by focusing on the use of solar PV in two main areas(Africa Development Bank Group, 2013):

i. Electrification of clinics, schools and administrative offices, and
ii. Solar water heating, substituting biomass and electric water heating, with significant environmental and recurrent cost savings.

2.3. The Solar Energy Resource Assessment

The sun generally referred to as “a ball of fire in the sky” is the source of solar and all energy on the earth’s surface. It is composed of a mixture of gases with a predominance of hydrogen gas. As it converts hydrogen to helium in a massive thermonuclear fusion reaction, mass is converted to energy according to Albert Einstein’s formula; $E = mc^2$. As a result of this reaction, the surface of the sun is maintained at the temperature of approximately 5526.850C (5800K). This energy is radiated away uniformly in all directions in close agreement with Planks blackbody radiation formula(Roger A. Messenger, 2010). The energy density per unit area, $\boldsymbol{W}_\lambda$ (W/m2/unit wavelength in meters), as a function of wavelength, λ, is given by:

$$\boldsymbol{w_\lambda = \frac{2\pi hc^2\lambda^{-5}}{e^{\frac{hc}{\lambda kT}} - 1} here} \tag{2.1}$$

Where,

$h = 6.63 \times 10^{-34}$ Ws^2 (Planck’s constant),

$c = 3.00 \times 10^8$ m/s (Speed of light in a vacuum),

$k = 1.38 \times 10^{-23}$ J/K (Boltzmann’s constant), and

T = Temperature of a blackbody in K.

In one hour, the earth receives enough energy from the sun to meet its energy needs for a whole year (Roger A. Messenger, 2010). For a long time, the world depended on the sun for drying and heating until the petroleum discovery in mid-nineteenth century diverted the global energy demand source to overreliance on fossil fuels. The sun radiates solar energy on the earth surface as the earth moves on its own axis and revolves around the sun on an elliptical orbit. This phenomenon makes the suns radiation reaching the earth’s surface to vary as the earth moves around the sun. Consequently, the parts of the earth nearest to the equator receive more solar energy than parts far from the equator. It also justifies the reason why there are longer days and nights depending on one’s location on the earth and time of the year.

The solar energy reaching a solar PV array on the earth surface consists of the main beam which is direct radiation, the diffused beam which is direct radiation affected by atmospheric absorption and the ground reflected beam which is as a result of reflection of the direct beam from the earth surface as shown in Figure 2.2 (John and Willie Leone Familly, 2018)

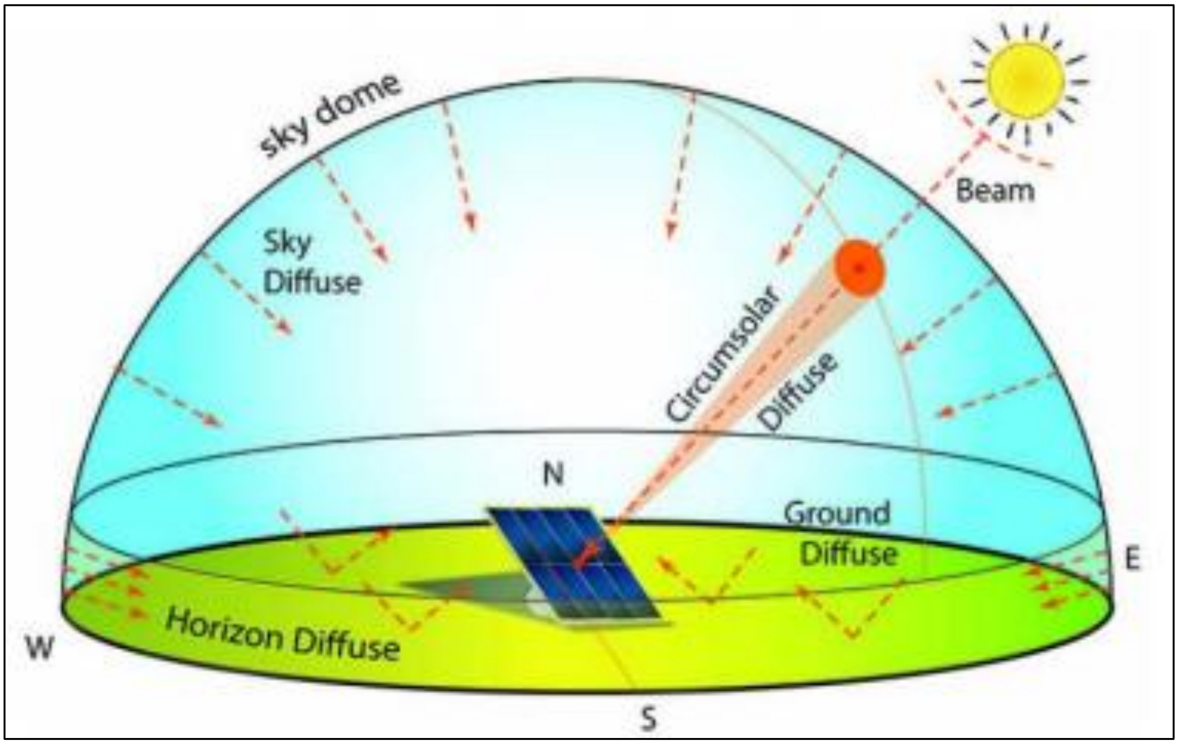

Figure 2. 2 The Solar Insolation on an Array on the Earth Surface

(John and Willie Leone Familly, 2018)

As presented in the Figure 2.2, not all the radiation that is released by the sun will reach the solar PV array surface placed on the earth. This makes the orientation of the solar PV array very important for energy absorption. Positioning the PV panel in a direction and tilt to maximize its exposure to direct sunlight will optimize the collection efficiency. The panel will collect solar radiation most efficiently when the sun's rays are perpendicular to the panel's surface. That's why positioning the PV panel in a direction and tilt to maximize its exposure to direct sunlight will optimize the collection efficiency. Since the earth moves around the sun, the angle of the sun varies throughout the year. Consequently, the optimal tilt angle for a PV panel in the winter will differ from the optimal tilt angle for the summer.

To attain the maximum efficiency, the orientation of the Solar Photovoltaic array has two important parameters; the slope and the azimuth. The slope is the angle of tilt with reference to the ground horizontal surface and the azimuth is the direction towards which the array surface face. When a solar PV array is installed south of the equator, azimuth is due north and when installed north of the equator, azimuth is due south. The azimuth can be due south or due north depending on the latitude of the site or location on the earth's surface(Florida Solar Energy Center, 2003).

The position of the sun on the earth is affected by the latitude and longitude, time of the day and day of the year. The earth receives the maximum radiation where is perpendicular to the sun's rays at noon every day. The angle formed between the plane of the equator and a line drawn from the center of the earth is called the solar declination angle denoted by δ. The declination δ can be found from the approximate equation of Cooper.

$$\boldsymbol{\delta = 23.45^0 \sin\left(360^0 \frac{284+n}{365}\right)} \tag{2.2}$$

Where n is the day of the year and January 1st is day one of the year (n=number of the days). Holding the earth stationary, the time of the day affects the location of the sun in the sky, and this effect is described by an hour angle. The solar hour angle is calculated as;

$$\boldsymbol{\omega = (T_s - 12)\,15^0/hr} \tag{2.3}$$

In this relationship, Ts represents solar time in hours and its value is 12hours at solar noon. It is a time defined by the position of the sun in sky and the length of time between two perfections of the sun is known as a solar day. The time-system in view of this unit is called apparent solar time. By this system, territories on a given meridian dependably have a similar time-readings. A comparison of a sundial with a mechanical clock demonstrates that the solar day has a variable length. Therefore, so-called mean solar time is commonly used.

The hour angle Equation is calculated from the fact that the sun moves across the sky at a speed of 15 degrees per hour. Most solar PV system designers assume that all time-dependent data; such as solar radiation and electric load, are specified in civil time, which is also referred to as the local standard time of the location. It can be defined as mean solar time plus 12 hours, the civil day begins at midnight, while the mean solar day begins at noon. Civil time is usually not used, since it depends on the observer's longitude instead, standard time, which is the same throughout a given time zone, is generally accepted.

The correlation between solar time and standard time is presented by:

$$T_s = T_c + \frac{\lambda}{15^0/hr} - Z_C + E \tag{2.4}$$

Where Tc presents the local standard time corresponding to the midpoint of the time step in hour, λ is the longitude in degrees, Zc is the time zone in hours east of Greenwich Mean Time (GMT), E stands for the eccentric anomaly of the sun due to earth obliquity, currently the earth's tilt is 23.44^0. The solar hour angle and solar time equations demonstrate that the sun covers 15^0 every one hour, so when a solar PV array is tilted 15^0 after every hour, the array will remain almost perpendicular to the sun and a near maximum power output can be achieved.

Earth's daily rotation is shifted by 23.5 degrees with regard to its yearly revolution around the sun. This axial tilt is the reason why Earth experiences different seasons throughout the year (see Figure 2.3 (Ricardo Gradillas and Scott Moushon, 1998)), and also why summer and winter occur opposite each other on either side of the equator and with greater intensity farther away from the equator.

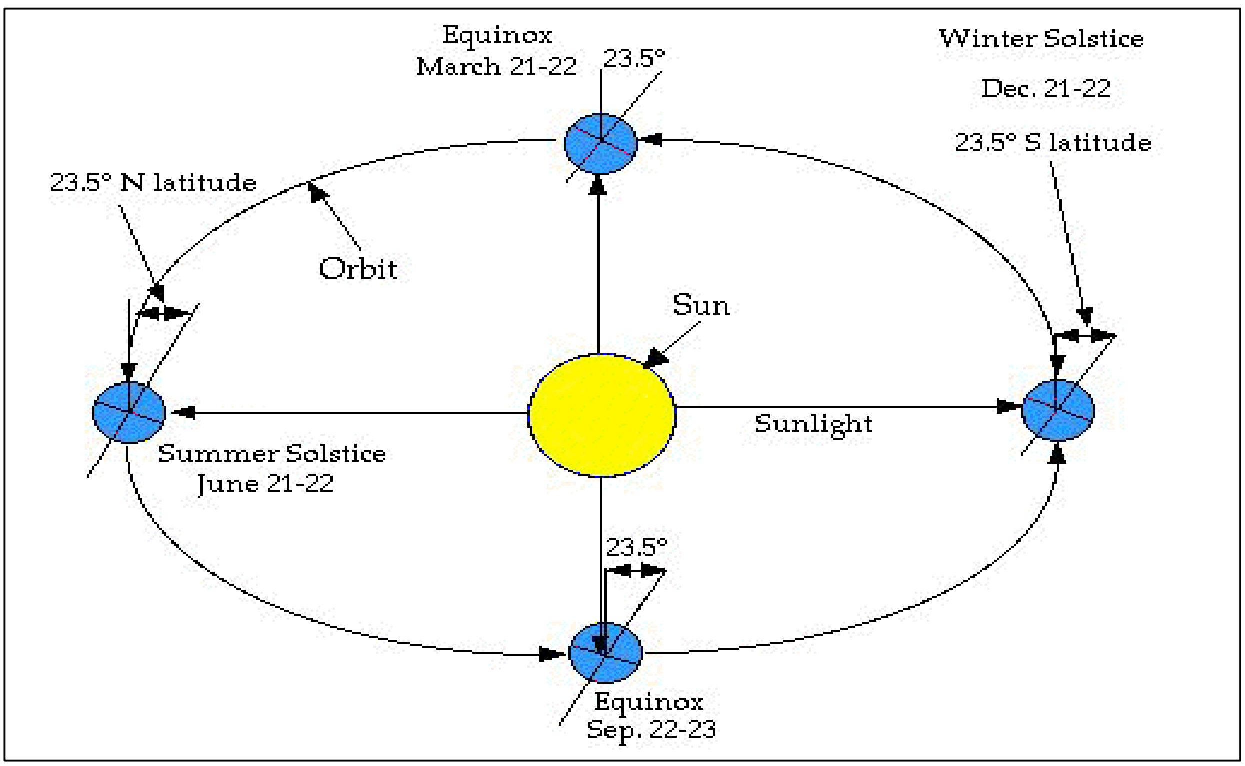

Figure 2. 3 Earth's seasons and their change

(Ricardo Gradillas and Scott Moushon, 1998)

The earth moves around the sun in a set path called the orbit. the movement of the earth around the sun is called revolution.it takes 365days and 6 hours to complete one revolution. This revolution causes what we call seasons. Therefore, different places on the Earth get different amount of heat.

2.4. Solar photovoltaic cell

A solar cell is a device that converts the energy of light directly into electricity characterized by an output voltage and current. The solar energy conversion into electricity takes place in a semiconductor device that is called a solar cell. In order to generate usable power for practical devices, which require a particular voltage or current for their operation, a number of solar cells are connected together to form a solar panel, also called a PV module. For a large-scale generation of solar electricity, the solar panels are connected together into a solar array. The solar panels are part of a complete PV solar system, which, depending on the application, may comprise batteries for electricity storage, DC/AC inverters that connect a PV system to the electrical grid and mounting elements(Hersch, Zweibel, & Energy Research Institute, 1982).

2.4.1. Classification of solar photovoltaic cell

According to Al.Miller &B. Lumby, 2011, PV cells are manufactured from semiconductor materials and most commonly made of silicon (Other materials (e.g.: CIS and CdTe) are under active investigation and may supersede silicon in the long term). As detailed below, it comes in two main types, crystalline, and amorphous thin-film type. Crystalline-type comprises two types: Monocrystalline and polycrystalline where Thin-film PV technologies include three main groups: amorphous (a-Si) and micromorph silicon (a-Si/μc-Si); Cadmium Telluride (CdTe); and Copper Indium-Selenide (CIS) and Copper-Indium-Gallium-Diselenide (CIGS)(Miller & Lumby, 2012). Figure 2.4 (Miller & Lumby, 2012) exposed below summaries of the technology classes for the first and second generation.

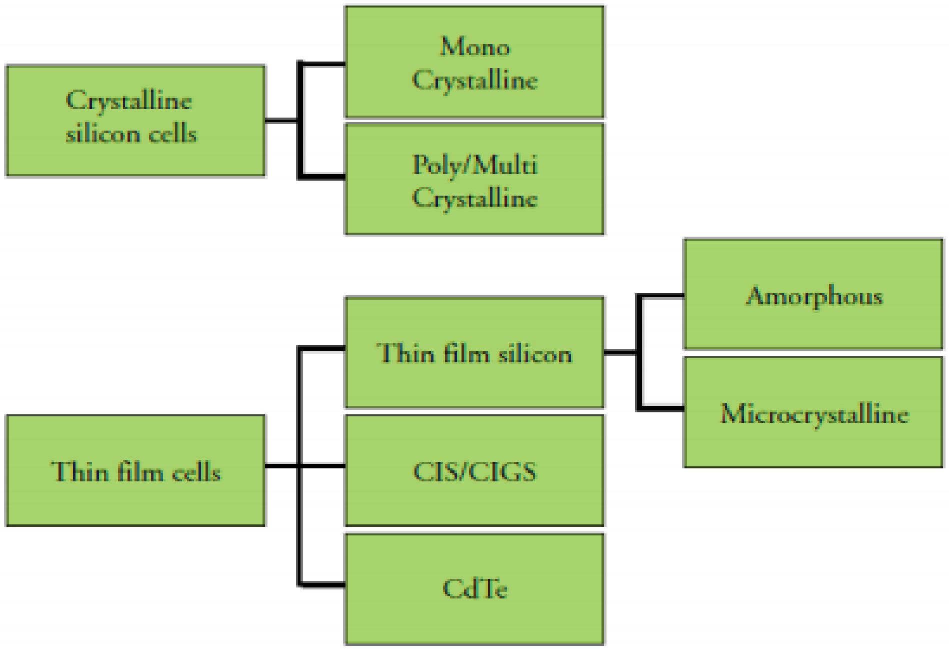

Figure 2. 4 Photovoltaic Technology classes

(Miller & Lumby, 2012)

The Crystalline silicon cells are manufactured from silicon ingots and can be of the monocrystalline or polycrystalline form, whereas the amorphous silicon cells are produced from a non-crystalline structure material. Amorphous silicon (a-Si or a-Si:H) solar cells belong to the category of silicon thin-film, where one or several layers of photovoltaic material are deposited onto a substrate and their low power output limited their use to small applications only. The other types of solar cells are the dye-sensitized cells that are currently under investigation but have very low efficiencies and degrade very first. Research is underway to improve their efficiencies and reduce the effects of degradation (Roger A. Messenger, 2010). For 15 years or so, the silicon crystalline and amorphous silicon modules have been increasingly used for electricity generation: they seem particularly well-suited for wide applications in building-integrated photovoltaics. One of their main advantages is that they are available in the form of monolithically integrated large-area modules. The efficiency of crystalline silicon modules ranges from 12 % to 19 % while thin-film efficiency ranges from 5 % to 13 % average. The characteristics of different cells are presented in Table 2.2 (Miller & Lumby, 2012).

Astounding advancement has been made as of late in enhancing the change efficiencies of various PV devices. Ultrahigh-productivity (η>30%) solar cells have been fabricated from gallium arsenide and its ternary alloys. Record-level efficiencies have been achieved on a silicon-based solar cell based on single-crystal and polycrystalline silicon. Different thin-film advances, for example, amorphous silicon, CIGS, and CdTe materials and device keep on showing noteworthy advances in their conversion efficiency. Some exciting possibilities are emerging on new PV devices with moderate efficiencies and potential for bringing down cost(Deb, 2000).

One of the rapid improvement in PV cell is perovskite solar cell. They have recently emerged as one of the possible solutions in the photovoltaic industry for availing cheap solution processable solar cells. Their improvement has made them the rising star of the photovoltaics world and of huge interest to the academic community. Since their operational strategies are still moderately new, there is a great opportunity for further research into the basic physics and chemistry around perovskites. Furthermore, as has been shown over the past two years -the engineering improvements of perovskite formulations and fabrication routines have led to significant increases in power conversion efficiency with recent devices reaching over 22%, as of April 2017(Tonui, et al., 2018).

Table 2. 2 Characteristics of various PV technologies

Abbreviation	c-Si	A-Si	CdTe	CIGS or CIS
Cost($/Wp, 2009)	3.1-3.6	2.5-2.8	2.1-2.8	2.7-2.9
Percentage of Global installed capacity	78%	22%		
Thickness of cell	Thick layers (200-300µm)	Thick layers (<1µm)	Thick layers(<1µm)	Thick layers(<1µm)
Current commercial efficiency	12-19%	5-7%	8-11%	8-11%
Temperature coefficient for power	-0.50%/^{0}C	-0.21%/^{0}C	-0.25%/^{0}C	-0.36%/^{0}C

(Miller & Lumby, 2012)

These parameters present the commercial efficiency of some PV technology categories. As may be expected, while higher efficiency technologies are more expensively to manufacture, less efficient modules require a larger area to produce the same nominal power. As a result, the cost advantages gained at the module level may be offset by the cost incurred in providing additional power system infrastructure (cables and mounting frames) and the cost of land for a larger module area. Therefore, using the lowest cost module does not necessarily lead to the lowest cost per watt peak for the complete PV system.

2.4.2. PV Cell Characteristic and I-V Curves

As detailed in earlier studies, the solar cell is made of semiconductor material, usually silicon, and is specially treated to form an electric field with a positive charge on one side and negative charge on another. The solar cell has a PN junction, which is a junction between p-type (many holes, no electrons) and n-type (many electrons, no holes) materials. Right where they meet there is actually a "depletion width" within which there is hardly any of either. Within this region, as photons come in they generate electron-hole pairs, which really just means that an electron has been excited from the valence to conduction band, leaving a hole behind. When photons with enough energy hit solar cell, electrons-holes pairs will be generated. In case the electrical conductor connected to the positive side and negative side, current will stream through this circuit.

To depict the electrical behavior, PV cells can be modeled as a current source. When there is no light display to generate any current, the PV cell acts like a diode. As the intensity of occurrence light increment, current is produced by the PV cell. The distinctive equivalent circuit of a solar cell is given in Figure 2.5(National instruments, 2012) which is called the one diode model and it can be used for an individual cell, a module consisting of several cells, or an array consisting of several modules.

The simplified equivalent circuit for a photovoltaic cell consists of a photocurrent source Iph, a reverse diode D and two loss resistances (shunt resistance Rsh and series resistance Rs). When this circuit is associated with an external load, the voltage connectors of the cell and the current are determined by its interaction with the current and voltage characteristics of that load (National instruments, 2012; Steris Kalogirou, 2009).

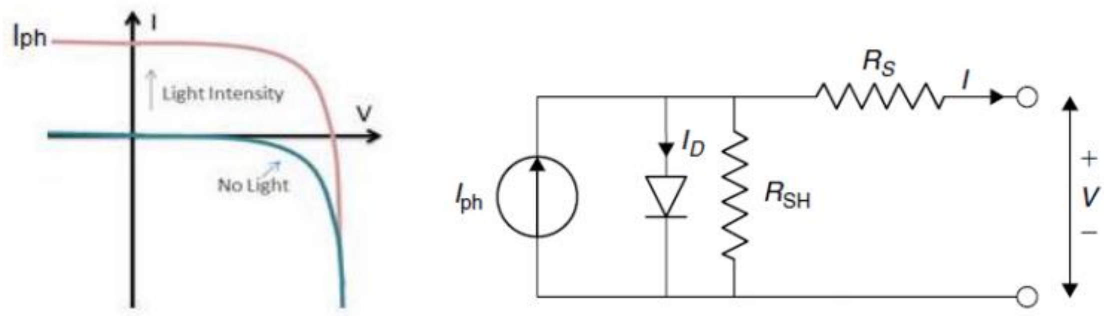

Figure 2. 5 I-V Curve and simplified equivalent circuit model for a photovoltaic cell

Total current I for this circuit, is equal to the current generated by the photoelectric effect minus the diode current, according to the equation(Steris Kalogirou, 2009):

$$\mathbf{I = I_{Ph} - I_D = I_{Ph} - I_0 \left\{ exp \frac{e(V + IR_S)}{kT_C} - 1 \right\} - \frac{V + IR_S}{R_{SH}}} \qquad (2.5)$$

Where,

V = Applied voltage,

e = Elementary charge 1.6X10^{-19} Coulombs,

k =Boltzmann's constant which 1.38X10^{-23}J/k,

$\mathbf{T_C}$ = Absolute temperature in Kelvin, and

$\mathbf{I_0}$ = the dark saturation current or the diode leakage current density in the absence of light.

The shunt resistance should be much bigger than a load resistance just to reduce the power loss through the cell, whereas the series resistance should be much smaller than a load resistance. Accordingly, by ignoring these two resistances, the net current is the difference between the photocurrent, and the diode current, given by(Steris Kalogirou, 2009):

$$\mathbf{I = I_{Ph} - I_D = I_{Ph} - I_0 \left\{ exp \frac{e(V + IR_S)}{kT_C} - 1 \right\}} \qquad (2.6)$$

By using the simplified equivalent circuit model for a photovoltaic cell (see Figure 2.5), the Current-Voltage (I-V) characteristic curve of a PV cell can be produced that describes its energy conversion capability (performance level) under the existing condition of irradiance and temperature. The I-V curve plots current versus voltage from short circuit current Isc through loading to open circuit voltage Voc. The typical I-V curve of an irradiated PV cell is shown in Figure 2.6.(Power Electronics, 2015).

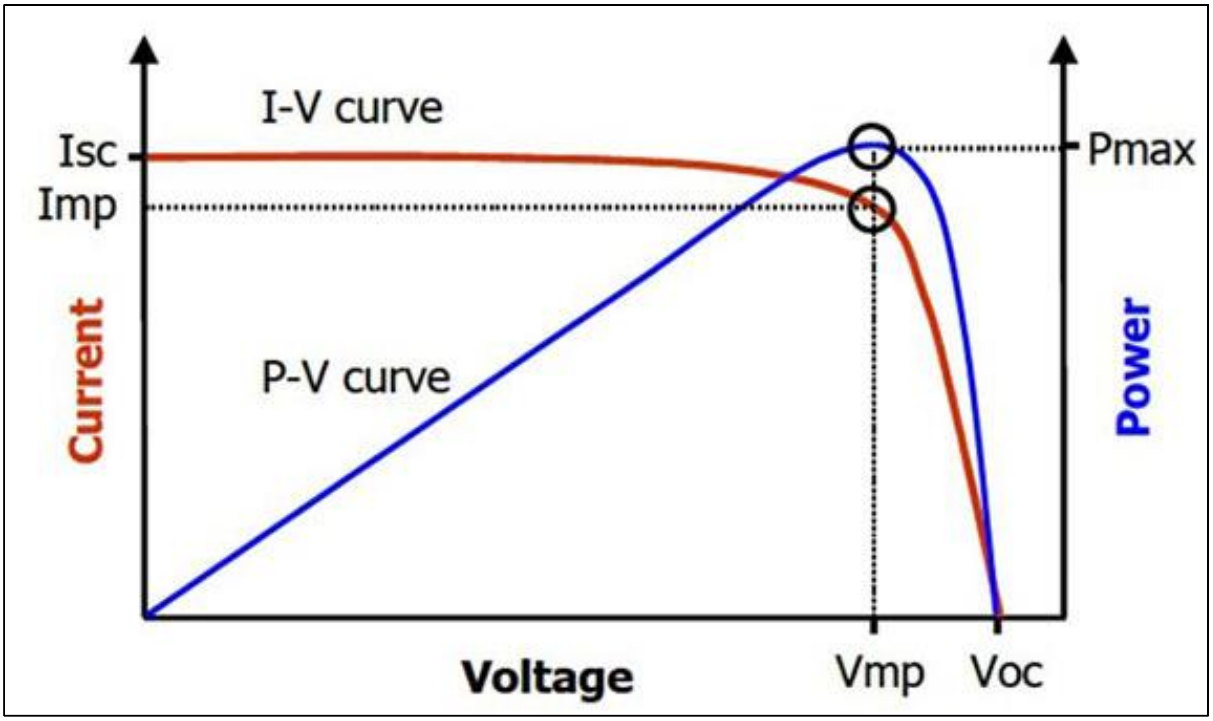

Figure 2. 6 The current-voltage and power-voltage relationships for a PV cell

(Power Electronics, 2015)

As presented on the graph, the I–V curve is characterized by the following points(Gatakaa, 2010; Robert Foster, Majid Ghassemi, 2009):

i. The short-circuit current **(I_{SC})** is the maximum current generated by a cell or module and is measured when an external circuit with no resistance is connected. I_{SC} is due to the generation and collection of light-generated carriers. For an ideal PV cell with the moderate resistive loss, I_{SC} and the light-generated current are identical (I_{SC} is the largest current which may be drawn from the solar cell).

ii. The open-circuit voltage (V_{OC}) is the maximum voltage available from a solar cell, and this is measured when no external circuit is connected to the cell (at zero current).

iii. Maximum power operating current (Imp) is the current for the cell corresponds to the maximum power point on the array's current-voltage (I-V) curve.

iv. Maximum power voltage (Vmp) corresponds to the voltage at the maximum power point on the array's current-voltage (I-V) curve.

v. The maximum power point (MPP) value is the point on the I–V curve at which the solar cell works with maximum power. Maximum power can be easily calculated by the equation (2.7):

$$\mathbf{Pmax = Imp \times Vmp} \tag{2.7}$$

vi. Fill Factor (FF) is essentially a measure of the quality of the solar cell. It is calculated by comparing the maximum power to the theoretical power (PT) that would be output at both the open circuit voltage and short circuit current together.

$$\boldsymbol{FF = \frac{I_{mp} \times V_{mp}}{I_{sc} \times V_{oc}}} \tag{2.8}$$

vii. Efficiency (η) is the ratio of the electrical power output corresponding to the maximum power (Pmax), compared to the solar power input (Pin). To get maximum efficiency solar cell should be operated at its maximum power.

$$\boldsymbol{\eta = \frac{Pmax}{Pin}} \tag{2.9}$$

With, $Pmax = I_{mp} \times V_{mp} = I_{sc} \times V_{oc} \times FF$and Pin is taken as the product of the irradiance of the incident light, measured in W/m2 or in suns (1000 W/m2), with the surface area of the solar cell [m2] (Gatakaa, 2010).

The maximum efficiency (η_{max}) found from a light test is not only an indication of the performance of the device under test, but, like all of the I-V parameters, can also be affected by ambient conditions such as temperature and the intensity and spectrum of the incident light (Franklin St, Fifth Floor, Boston & Se, 2002).

2.4.3. Effects of Irradiance and Temperature on I-V Characteristic curve

The efficient of the solar PV array generally depends on the amount of irradiance incident on the array surface. Once the irradiance incident on the module is reduced, the output current and consequently the power are reduced. The effects of reduced irradiance are shown in Figure

2.8(Seaward Group USA, 2018), where current is greatly affected while the voltage is affected slightly.

On another hand, extremely high temperature also causes heating on the solar cells of the array as the day progresses and affects the output voltage of the module as shown in Figure 2.7. This high temperature also affects the lifespan of the modules by fast weathering. If the effects of temperature are not unmistakably accommodated during the design of solar PV array, a temperature derating factors are applied.

In Singapore Fan Jiang, observed high cell temperatures at noonday when the temperature on the solar PV array rose up to 60^0 C and reduced the array cell output voltage down to 83.94% of the rated 21.1volt open circuit value. Necessary temperature adjustments were made to the design and the project was observed for 8 years and good results were obtained(Fan Jiang, 2007). Figure 2.7(Seaward Group USA, 2018) shows the effects of temperature on a solar cells IV characteristics.

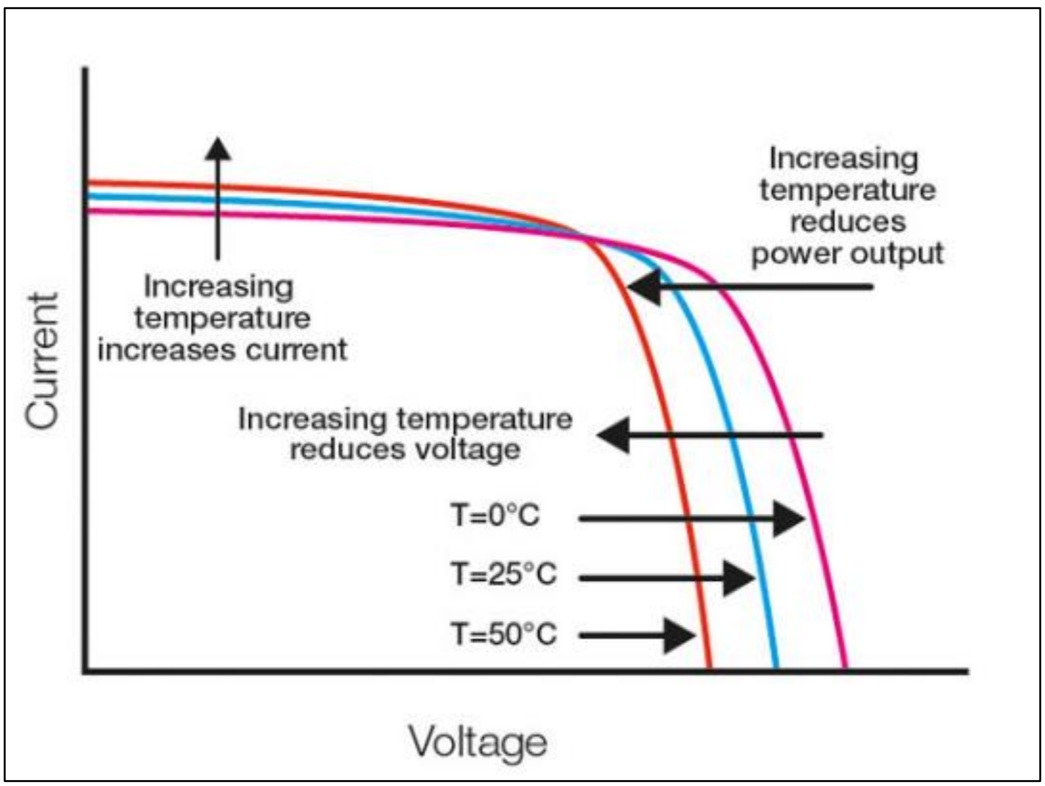

Figure 2. 7 Effect of temperature on solar cell IV characteristics

(Seaward Group USA, 2018)

According to Figure 2.7, as the temperature increases, the power output is reduced for the same solar insolation. Therefore, this trend makes the cell temperature a major factor to be considered when designing a Solar PV system.

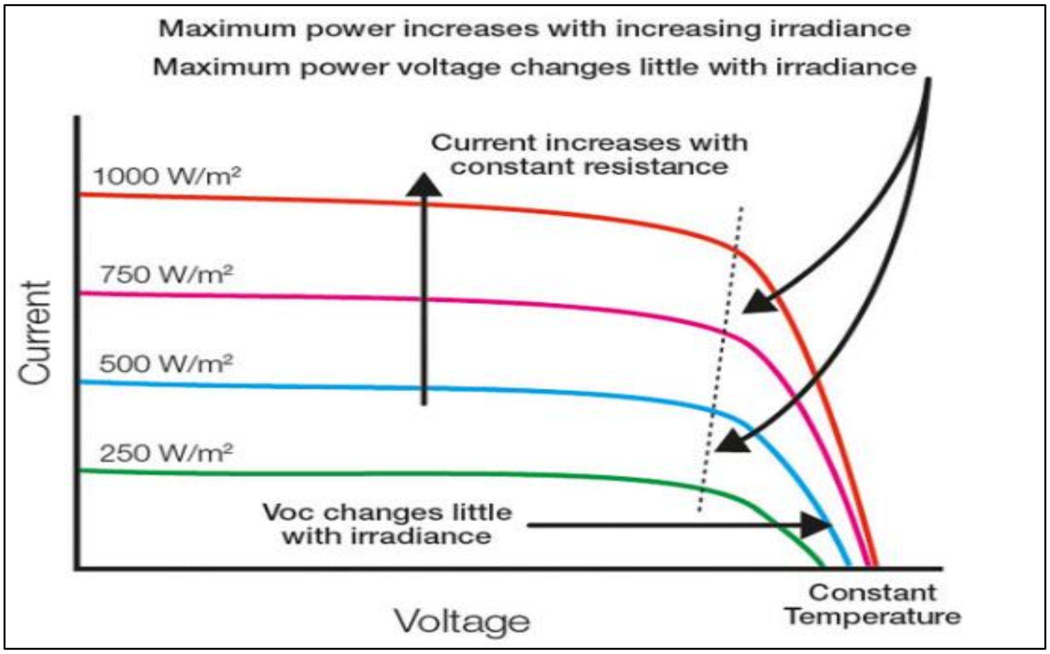

Figure 2. 8 Effect of irradiance on solar cell IV characteristics

(Seaward Group USA, 2018)

2.4.4. Effect of shading on PV arrays

A solar photovoltaic system is constituted of many PV cells that are connected in series and in a parallel way. This system performs by generating electricity well when it receives direct radiation. Module cell shading can be caused by trees, flying objects, and even clouds. In practical situations, when there are shades around this system or arrays, shading will appear on some cells/modules, those with shading in a long series will not produce voltage, while other modules in the same series still produce voltage normally. At the same time, this will make current setting off through this shaded module(Silvestre & Chouder, 2008; Spirito & Albergamo, 1982). However, considering the current flows through those modules, it can't produce the normal output power without photo voltage inside. For this reason, the shaded module becomes a load in the string and dissipates power because of the generated heat. So other normal modules need to work at a higher voltage in order to keep up the total voltage of the whole series and reduce voltage loss of the shaded module. To the modules facing radiation directly, the higher voltage will create less current and more output power loss.

Dividing a string into several parts with some bypass diodes is used as a method to reduce the power loss from partial shading(Alonso-Garcıá, Ruiz, & Chenlo, 2006). The module will be isolated by the bypass diode from other parts, so the voltage and current of this string will lose in proportion to the shading areas. And the output power of other not shaded parts without being protected by the diode will not lose(Liu, et al.,2016; A. K. Sharma, et al.1991).

Short lasting shading does not affect the daily charging current but persistent shading caused by trees and clouds reduces the daily output current of the modules a lot as shown in Figure 2.9(Spataru, et al., 2012).

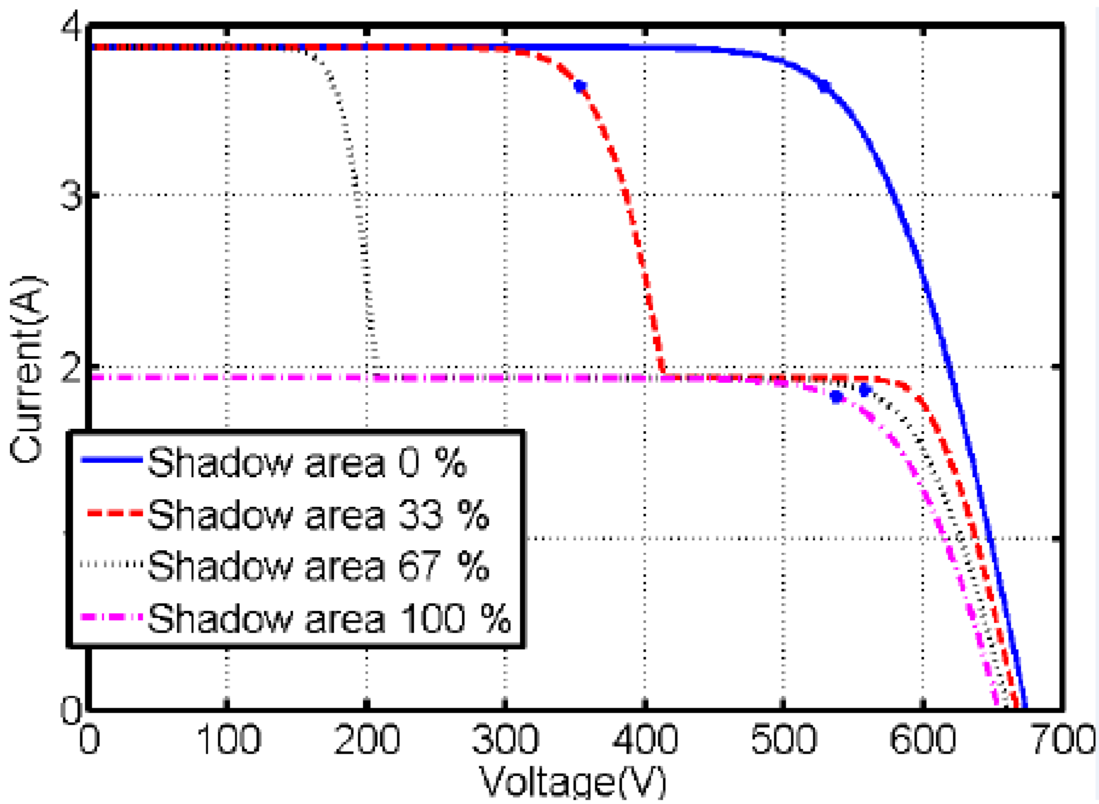

Figure 2. 9 Effect of shading on solar cell IV characteristics

(Spataru et al., 2012)

2.4.5. Solar PV Orientation and Tilt Angle

The tilt angle or slope of PV array will vary depending on the location of its mounting. Previous studies demonstrate that the basic routine and regards to mounting sunlight based modules is to have them at a fixed angle with reference to the ground since it is the least complex and least expensive alternative. Such settled introductions typically receive the scope of the area as the point of tilt with the correct azimuth. An angle of tilt equal to the latitude of the location and the correct azimuth will empower the solar array to extract maximum radiation when irradiance is high between 10 AM and 4.30 PM in many areas. In a design where the point of tilt is made equivalent to the latitude, the systems accomplish better yearly sun based PV energy production compared to other arbitrarily fixed angles schemes(Ahrens, 2007). Because of these reasons, the designer must choose the best method or technique for tilting the array considering the accessible states of the establishment.

Seth Blumsack et al 2010, utilized surface sun based radiation information from the meteorological division at the Pennsylvania State University, USA to design a system having split array of modules whose orientation was fixed toward the East, West and South all at a tilt angle of 250^{o}. The system was grid-connected with no battery storage particularly planned to sell power to the grid during the peak demand. Fixed angle orientation was used, and this study was more advantageous to residential customer-generators as this orientation was more closely matched to the residential customers' load demand. Blumsack concluded that by splitting the orientation of the array panels to East and West azimuth rather than a predominantly Southern azimuth, noteworthy power increases could be acknowledged during the morning and evening demand peaks (Blumsack, Brownson, & Rayl, 2010).

The National Renewable Energy Laboratories (NREL) in the USA conducted a study of solar PV module fixed tilt angles output with correlation with the output from Maximum Power Point Tracking (MPPT) angles output and understood that the fixed angles could give 80% of the MPPT when kept up at specific values. Not only that but also this NREL research has shown that the fixed angles for different latitudes can achieve very good results. Though, for locations very near to the equator, the purpose of titling the array is to allow its natural cleaning by avoiding dust accumulation during rainy seasons. The researchers recommended the angle values for fixed tilt angles schemes as shown in Table 2.3.

Table 2. 3 Recommended Fixed Angles for Solar modules

Latitude Angle	Recommended angle
Latitude < 15 degrees	15 degrees
15 degrees < Latitude < 20 degrees	Latitude
20 degrees < Latitude < 35 degrees	Latitude + 10 degrees
35 degrees < Latitude	Latitude +15 degrees

2.5. Solar Power Applications

Currently, all over the world solar power is being utilized in different ways. Powering appliances are in fashion; from a mobile phone charger to mega power plants solar energy. Solar energy is appropriate for the midsized residential facility or small sized commercial facility(Parida et al., 2011; S. Sharma et al., 2015). Off-Grid Solar Systems, On Grid Solar Systems, and Hybrid Solar Systems, are primarily the types of solar system configurations that are being developed.

2.5.1. Off Grid Solar System

An off-grid solar system is the one where the primary source of power is solar energy only. In this system, the primary source of power is solar energy; the excess power is stored in the battery bank, to be used in nighttime after conversion from DC to AC power with an inverter. This system comprises of Solar Inverter, Battery Bank and Solar Panels(Ali Ahmed et al., 2015).

These systems are generally used in remote areas without grid supply or with unreliable grid supply. The disadvantage of these systems is that the batteries require replacement once in every 3 – 5 years.

2.5.2. On Grid Solar System/Grid-connected

On-grid solar systems are mostly installed in the medium as well as large commercial units and are very popular in the industrial sector. On Grid solar systems are well suited for any facility that has un-interrupted grid power. As this type of solar systems only uses solar energy as a primary source and grid as a reference, there is no storing mechanism inside the system. The surplus energy, if any, is exported to the grid and shortfall, if any, is imported from the grid, which is calculated at the end of each month via Net Metering, Feed-in Tariff or Power Purchase agreement, whichever is applicable (Lashway, C Elsayed et al., 2014; Md. Rajwanur Rashid, 2011) These systems consist of PV panels that are connected to the grid via a tie inverter as shown in Figure 2.10 (Leonics, 2009).

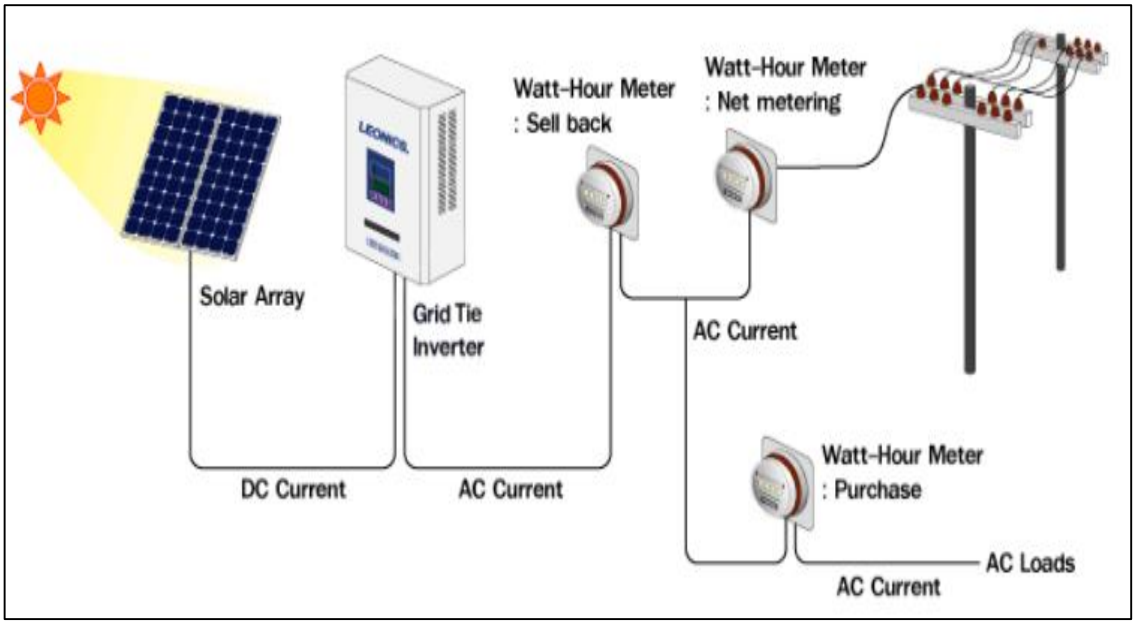

Figure 2. 10 Schematic views of the Grid-connected system

(Leonics, 2009)

2.5.3. Hybrid Solar Systems

As shown in Figure 2.11(Ingole & Rakhonde, 2015), the hybrid solar systems are the mix of off grid and on grid solar systems. They use solar energy as a primary source of energy and meanwhile they store excess energy into the battery bank. When the battery bank is fully charged, the excess power is then fed into the grid for net metering (Ingole & Rakhonde, 2015).

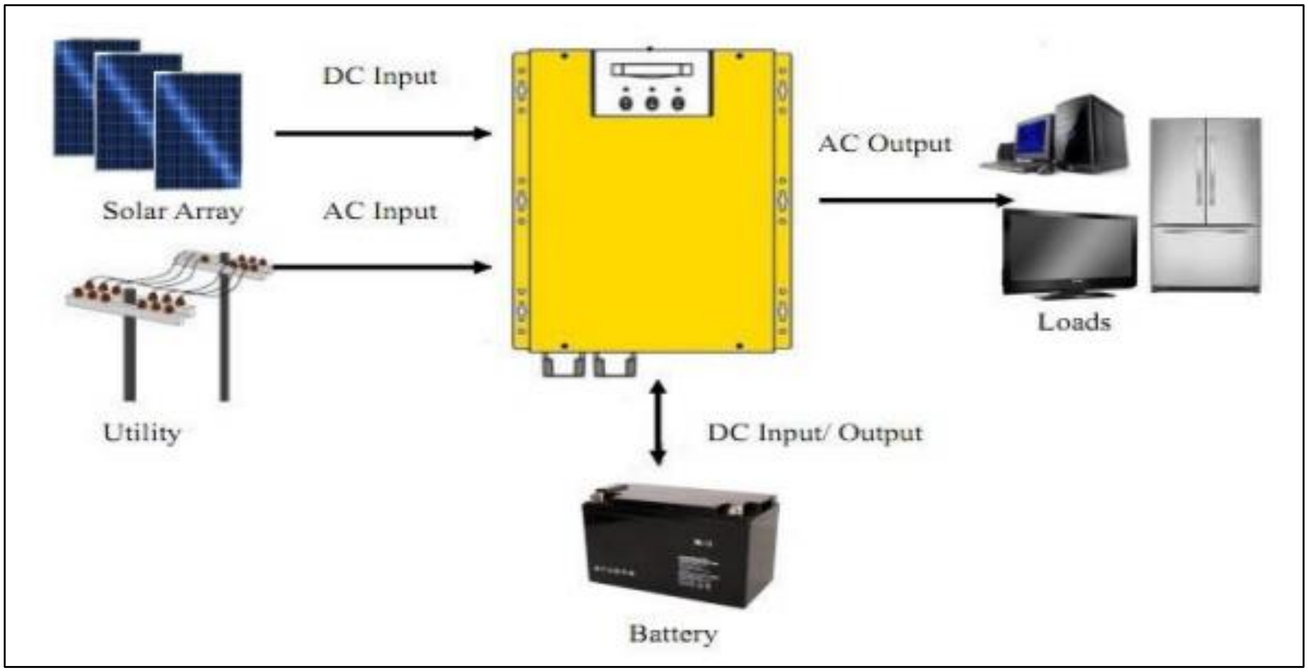

Figure 2. 11 Schematic views of the hybrid solar system

(Ingole & Rakhonde, 2015)

2.5.4. Solar Mini and Micro Grid Systems

Microgrids, continue to be one of the biggest disruptors of the traditional electrical grid. It consists of Renewable energy-based system with a capacity below 10 kW, supplying clean electricity to a group of houses in a remote area. The types of loads that are served by a microgrid are usually residential only, or very small commercial. DC generally generated through solar power is normally preferred where the loads are of low voltage/power, such as lighting, fans, radio, and others household appliances with low consumption(Dr Om P Nangia, 2017).

A microgrid is defined as a renewable energy-based electricity generator with a capacity of more than 10Kw. This system can be used to supply electricity for a localized group of consumers including households, institution, and businesses or industrial set up through a public distribution network(Dr Om P Nangia, 2017).

Both microgrid and minigrid can be powered by different renewable energy sources, like solar PV, biogas or pico-hydro.

2.6. Distributed Generation and Electricity Sell Back

The theory of generating and storing the energy in a variety of microgrids, that are connected to small grid-connected system is known as Distributed Generation System (DER) or Decentralized Energy(Wolsink, 2014). Decentralized energy, as the name designates, is generated or stored by a variety of small, grid-connected devices, referred to as distributed energy resources (DER)(Shah, Mundada, & Pearce, 2015).

Decentralized mostly use renewable sources for electricity generation like solar, wind, biomass, biogas and geothermal. The system can comprise a multiple renewable generation sites, some storage units and distribution units power is located close to the production facility and the region where this power is to be consumed(Shah et al., 2015). Contrary, energy generated from coal power plants, nuclear or oil and gas-driven power plants are known as centralized since are connected to the national grid, very large and require power to be transmitted over large distances, resulting in line losses and electricity theft.

The DERs are directly connected to grid-connected devices and collect excess energy produced, store it in storage units and distribute it to nearby loads. DERs have lower environmental impacts and improved supply of electricity. DER systems are playing an increasing and important role in the electric power distribution system (Toby & Yves, 2010).

From work done previously in solar photovoltaic systems, it is noted that DERs are being used in three ways: Net Metering, Feed-in Tariff (FiT) and Power Purchase Agreements.

2.6.1. Net Metering

Net metering allows producers of the renewable energy to feed the energy into the grid and consume it at any time of the day, regardless of when the energy is generated. This mechanism is important for solar energy producers as they can only produce the energy during the daytime. This system allows the solar producer to use the excess energy provided to the grid at night. If the monthly generated power exceeds the consumption of the consumer, the remaining kWh rolls over to the next month. It allows the produces to use the excess power generated from summer to the winters(Public Utilities Commission of Sri Lanka, 2016).

Net metering only uses one energy meter that is bi-directional which calculates the net energy consumed rather than one meter calculating the energy produced and other calculating the energy consumed. Another advantage of net metering is that it does not require any special metering or even a notification or agreement with the grid(Ontario Ministry of Energy, 2017; Public Utilities Commission of Sri Lanka, 2016).

2.6.2. Feed in Tariff (FiT)

This is a standard purchase contract between the renewable energy producers and the DER(Toby & Yves, 2010). This contract comprises of sell back tariff, penalties, purchase timeline, purchase quantity, and as-sectioned load. FiT aims to offer cost compensation to the renewable energy producers by providing them long-term sell back contracts and price certainty to help them finance their renewable energy system capitals initially(Kahn et al., 2009; Toby & Yves, 2010).

It provides purchase contracts to the residential, commercial, agricultural and private investors. In this mechanism to put a limit to a specific renewable energy source in a specific area, the sell back varies according to the renewable technology used; it might be hydro, wind, roof solar systems or others. Furthermore, renewable energy producers are paid a cost-based return for the energy they supply to the grid. Homeowners, commercial consumers, farmers, and investors can benefit from FiT. It typically offers long-term guaranteed purchase agreement from 15 years to 25 years and the tariff typically declines over the years(Albert Thumann & Eric A. Woodroof, 2013).

2.6.3. Power Purchase Agreements (PPA)

PPA also was known as electricity power agreement, is an agreement between two parties, one which generates electricity as the seller and the other which is looking to purchase electricity as the buyer. The PPA defines all of the commercials for the sale of electricity between the two parties, including when the project will begin commercial operation, scheduled for delivery of electricity, penalties for under delivery, payment terms, and termination. A PPA is a principal agreement that defines revenue and credit quality of a generating project and is thus a key instrument of project finance. There are many forms of PPA in use today, which vary according to the needs of the buyer, seller and the financing counterparties(Albert Thumann & Eric A. Woodroof, 2013).

For instance, a government agency can enter into an arrangement for a private power company to establish a power plant and sell on the power to the government agency, the public agency typically enters into a PPA.

2.7. Summary

This chapter focused on the review of the main features of the solar resource design and sizing methods of solar grid-connected photovoltaic systems. Many obstacles face the energy sector in Rwanda and the futures projections of the major energy needs have been reviewed. In addition to that, many observations have been made concerning the design and sizing methods of solar PV systems in different parts of the world. It has observed that many scientists have done work in the area of solar PV generation using different approaches and achieved very dependable outcomes.

Chapter 3. 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 Methods used to collect load and solar insolation data are presented in details. The methods of data analysis and those used to size the different solar photovoltaic system components are also presented. Sizing methods, flow diagrams and orientation of the modules are also discussed and presented. Finally, the system financial and cost analysis methods are presented and discussed.

3.2. Case study location

The household chosen for the case study is in Masaka village, located in Gasabo district, Kigali province, approximately 17 kilometers by road, south-east of the central business district of Kigali city. It is located about 9 kilometers, by road, south-west of Kabuga, at the eastern edge of the city of Kigali, along KK3 Road (RN3). The coordinates of Masaka are: 01°59'44.0"S, 30°11'30.0"E (Latitude: -1.995556; Longitude:30.191667).

Figure 3. 1 The satellite view Masaka village showing the topography.

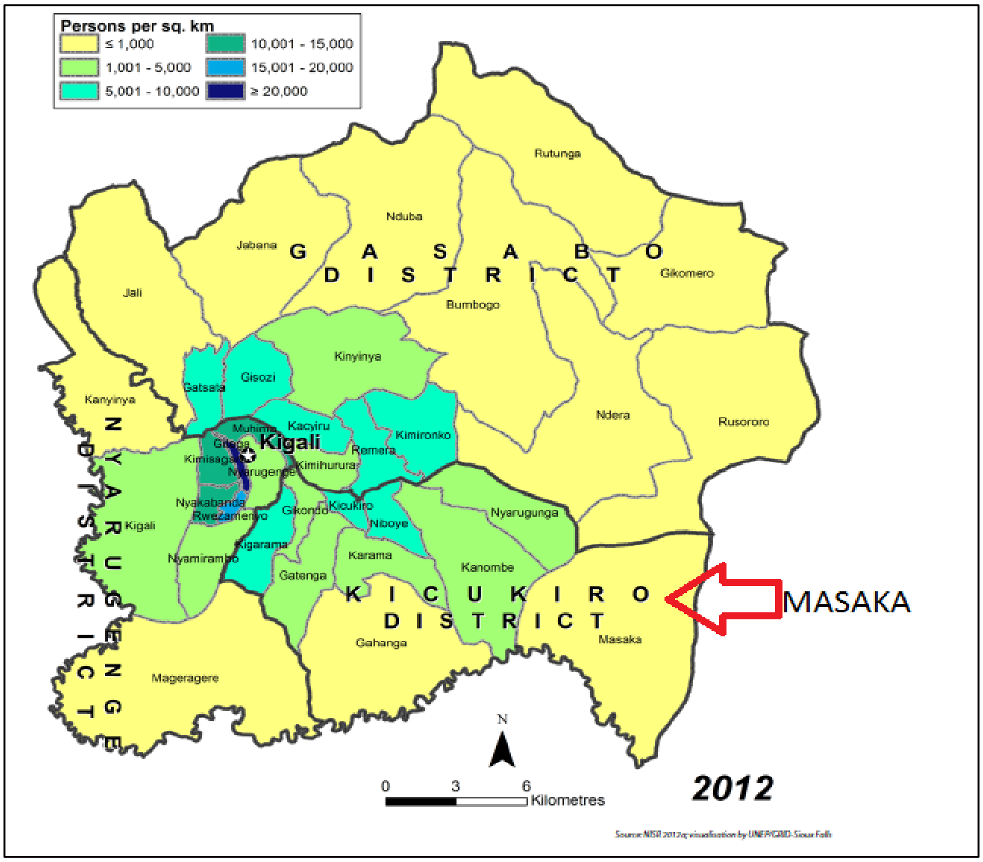

Figure 3. 2 Masaka village position in Kigali map

(City of Kigali, 2013)

Masaka is among the most sparsely populated area in Kigali with an estimated population of approximately 4,558, as of January 2018. This region has no particular temperature seasons; the temperature is relatively constant during the year. During the evening at night, the temperatures drop sharply and July is considered as the month with the high amount of solar radiations and as the driest period of the year with an average of 17 mm of precipitation. Other months around July like June are also dry. The wettest weather is in between March and April with an average of 113 mm of precipitation. Rainfall and other precipitation peaks around the period of April as appeared by the Figure 3.3 (Primary data, 2018) beneath. It is clear that the investigated region is dominated by low wind speeds suitable for small-scale wind power generation.

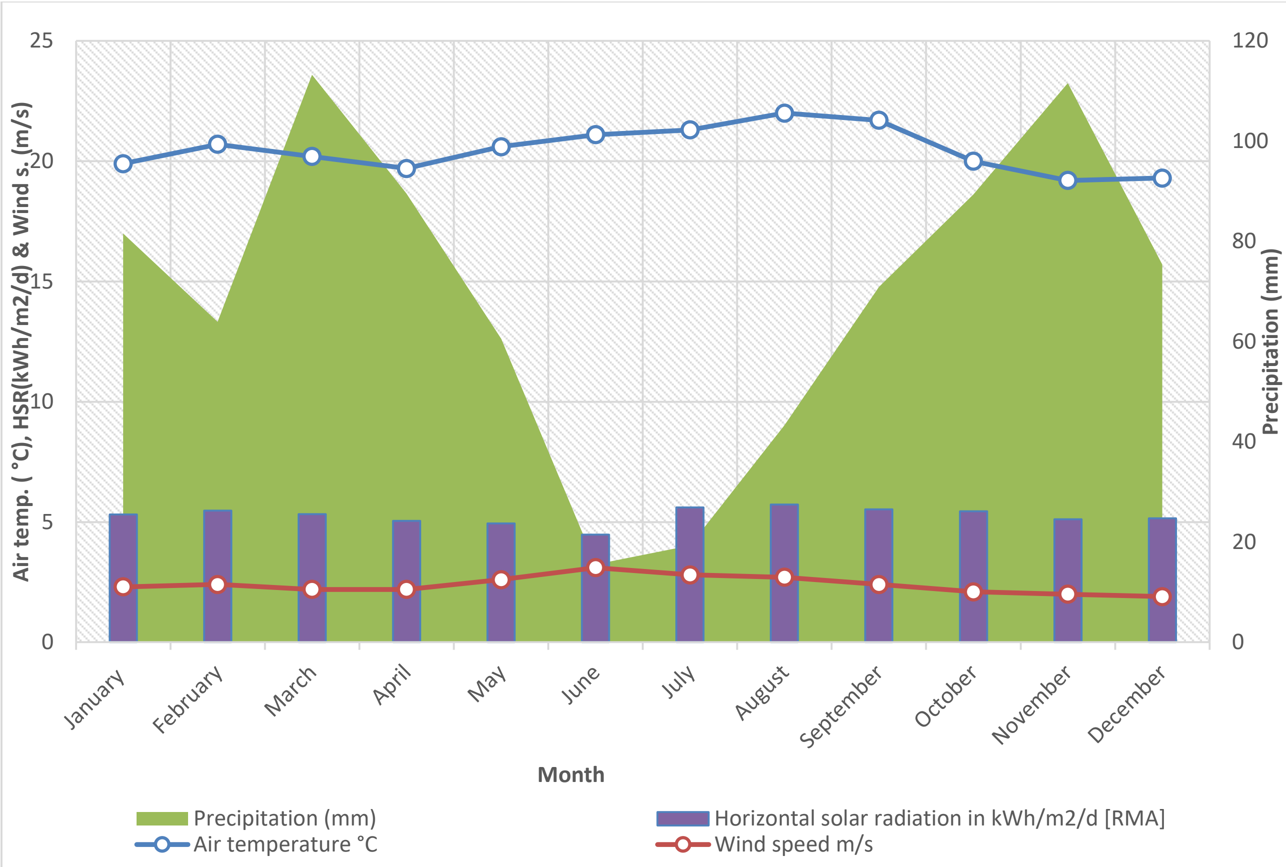

Figure 3. 3 Monthly average values of various climate data for Masaka village.

This Area was selected as the case study because it is currently one of the biggest middle-class surroundings in Kigali city and by extension the country. Buildings at Masaka village have large bare roofs and are occupied by people who are able and capable of embracing renewable energy initiatives for electricity generation. According to the questionnaire data, they can afford a domestic solar PV electricity generation system to avoid the rising price of grid electricity.

It was concluded that the Masaka is a suitable case study, based on financial status (living conditions) of the residents; from the properties they own. For instance, the type of houses, appliances, and vehicles they have. The resident's financial ability was one important key for the study to know whether the residents can afford the proposed scheme.

3.3. Data collection

To carry out this research, some specific data are required, that is solar insolation, site(household) geographical position, and electrical load. The information on different household/dwelling in Masaka village, the roof type, and orientation were picked up by site investigation.

3.3.1. Solar insolation data

Solar insolation data were obtained from two sources: Rwanda Meteorological Agency(RMA) and the National Aeronautics Space and Administration (NASA) website. Data from RMA are from actual ground measurements of solar radiation using a solar radiation measuring device. This data was compared to those of satellite data from the American Space Agency (NASA) (used in the RETScreen Software), and is introduced in Chapter 4.

After an analysis of the solar insolation data obtained (see Figure 4.1), the NASA data was selected for sizing the solar PV system. The Meteorological department collects and stores environmental data that are used to carry out environmental and any other related studies. Such data are like solar insolation and average Ambient temperatures which were necessary for the study. The solar insolation data were in form of raw data as collected by the Meteorological department in watt-hour per square meter (W/m^2), thus they were converted to kWh/m^2 before being used in the design and sizing of the solar PV system.

By referring to other researchers, the historical data used from the RMA, covered a period of two years. For instance, Fan Jiang et al used 2 years' monthly average data from the Singapore National Environmental Agency, the study by Fan Jiang was addressing the availability of solar PV resource in a typical tropical country and its unique weather conditions(Fan Jiang, 2007). While Xiao Jian Ye et al used 8 year's temperature data for a study at Wuhan in the province of Hubei China where the effects of using air conditioning loads during the day were investigated (Ye, et al., 2009). Zakaria Anwar et al used 30 year's solar insolation data for a study in Sudan to investigate the total energy requirements met by a solar PV system. From the periods used by other researchers, it is clear that the data periods were based on specifics like a lifetime of the study, type of study and whether standalone or grid-connected systems where longtime data ranging to 30 years was necessary.

3.3.2. Electrical load data collection

By means of questionnaires and oral interviews, household electrical load data were collected from the residents of case study place, a sample of the questionnaire is presented in Appendix C. Throughout the electrical load data collection, one hundred thirty questionnaires were distributed to the Masaka residents. The filled questionnaires were analyzed for more details and accuracy for the filled data, after which the best was interviewed for physically checking of the appliances. Due to the unavailability of the residents and their willingness to have the interviews, only ninety-seven residents were visited.

Throughout the design of the solar PV system, the data collected from all questionnaires were not used, only data from interviewed households were used to ensure the real energy consumption for those houses.

3.4. Solar Photovoltaic Electricity Generation System

The main components that constitute a solar PV electricity generation system are; the solar PV array, the net metering and the inverter as presented in Figure 3.4 (Courtenay Johnson, 2014; Poole & Nitz, 2002). In designing and sizing, the process started with sizing the solar PV array using the load demand and available insolation. After the array is sized, the component to be determined is the DC to AC inverter whose size normally depends on the peak power of the consumer.

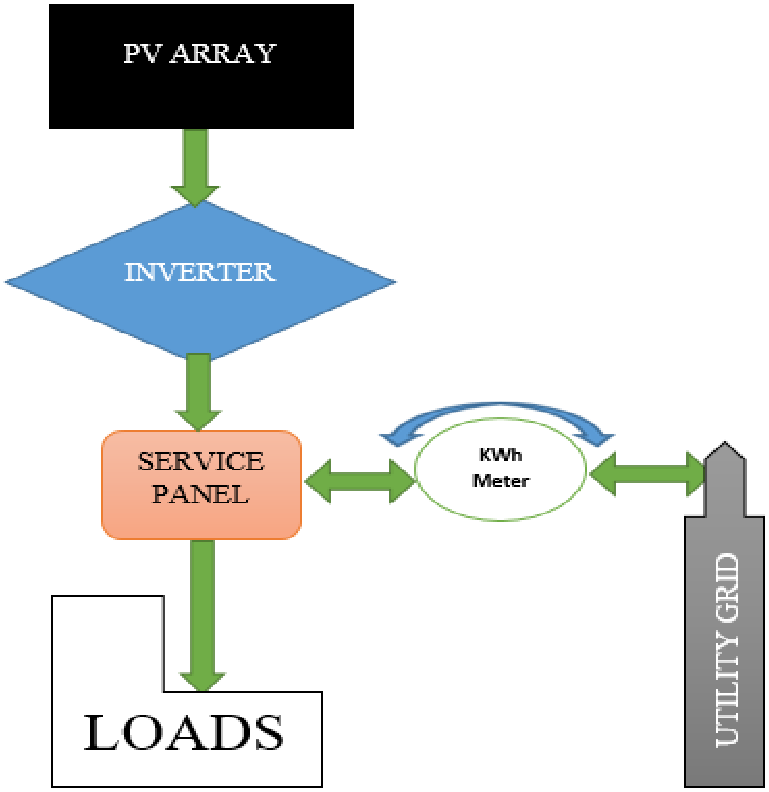

Figure 3. 4 Overview of the proposed design

The last component to be determined is a metering device to be used in the system. An energy meter shall be installed in between the grid and the building distribution board to measure the exported and imported power.

Throughout the design of the system, many factors that affect the design and sizing have been considered. The major factor to be considered during array sizing is the module type, the mode of connection, the angle of tilt, the effects of shading and the effects of temperature and irradiance.

3.5. System Design Software

This part presents the software that was used to design the solar PV system for the case study. By referring to the data collected, different solar PV design software's were investigated to find out the most suitable for this research. And also with regards to some factors like ambient temperature, solar irradiance, shading and other derating factors that are never constant, it implies that the output of the solar PV array will be varying as frequently as the parameters changes. This means that long hand calculation cannot adequately give an accurate design where all conditions are matched.

RETScreen Clean Energy Project Analysis Software was used to analyze the proposed system; a software developed by Natural Resources Canada to undertake feasibility as well as full feasibility studies for most renewable energy projects. The software, which comes with inbuilt solar radiation and other climate data for various locations including Masaka located in Kigali province, as well as system specifications from various manufacturers, has the capability of simulating the technical and financial performance of renewable energy systems over the entire project life.

Apart from climate data, RETScreen requires data about the particular PV module used to calculate energy production. PV technology uses solar cells made of semiconductors to absorb the irradiance from the sun and convert it to electrical energy (direct current (DC) electricity). A group of modules together form an array. The number of modules in the system is chosen to provide the desired energy production. RETScreen expert has a current database of module brands with related input data required to run RETScreen. During the design of the proposed PV, Chine Sunergy Poly-silicon-CSUN 300-72P modules have been used, its details specifications are presented in Table 3.1 (Ebay, 2018).

Table 3. 1 Detailed specifications of selected PV Module

Characteristic	Standards
Maximum Power at STC (Pmax)	300W
Optimum Operating Voltage (Vmp)	35.9V
Optimum Operating Current (Imp)	8.36A
Open Circuit Voltage (Voc)	44.5V
Short Circuit current (Isc)	8.83A
Module Efficiency	15.50%
Operating Module Temperature	-40^{0}C to +85^{0}C
Maximum System Voltage	1000VDC (IEC)
maximum Series Fuse Rating	20A
Power Tolerance	0/+5%
Size	1.94 m^2

3.6. Requirements for inverter selection

An inverter is an electrical equipment that converts DC (direct current) electrical capacity to AC (alternative current) power. All power plants that generate DC power normally require inverters to change over the power created to AC power for use by alternating current rated appliances. Solar PV inverters can be either stand-alone or grid tied. Grid-tied inverters usually monitor both the solar PV system and the grid so as to respond to the consumers' load demand. It also protects the system from grid or utility power blackouts by disconnecting the grid during outages and in some cases incorporate a metering facility to empower adaptable import and export of power from and to the grid(Roger A. Messenger, 2010).

Inverter is the essential equipment for any grid-connected photovoltaic system to convert the direct power from the PV array to alternating power used in the electrical grid. Not only does the inverter convert DC to AC power but it also regulates the PV system. The electronics that perform this task utilize special algorithms known as maximum power point tracking (MPPT) algorithms.

After cautious examination and correlation of present-day inverter datasheets, appropriate basics for inverter was thought to take after:

- ✓ Should have 220/380 VAC output and be comparable with Rwandan 50Hz grid.
- ✓ Efficiency not lower than 97%.
- ✓ Maximum Power Point (MPP) tracker availability is obligatory.
- ✓ Anti-islanding, overvoltage and lightning protection.
- ✓ Compliance with international safety standards.
- ✓ 25-year for Lifespan

As for all grid-tied energy-harvesting systems, the inverter delivers excess power to the grid during periods of high energy from ambient sources is required. During the design of Grid-tied inverter, the designer needs to guarantee that this that this excess power is tightly synchronized to the grid, phase-locked loop (PLL) can be used during the implementation of the projects. Effective PLL grid-synchronization algorithms are created by leveraging the performance and functionality of highly-integrated microcontroller units (MCUs) and related devices. A phase-locked loop (PLL) is an electronic circuit with a voltage or voltage-driven oscillator that constantly adjusts to match the frequency of an input signal.

This system offers customers the chance to earn credit by passing excess generated power to the grid. In this designed system, the grid-tied inverter is responsible for delivering this excess electricity seamlessly, meeting specific requirements for power quality. Among these requirements, the need for tight synchronization with grid power is principal. It offers a stable, sinusoidal AC waveform that matches grid voltage and frequency according to utility standards. Poor synchronization can lead to load imbalances, damage to connected equipment, instability in the grid, and even power outages in the grid itself.

For the proposed case, SUN-3K-G/5K-G single phase grid tie string inverter was chosen based on the desired output and its leading features are presented below and its appearance in Figure 3.5(Ebay, 2018).

i. Max Efficiency of 97.5% and wide input range.
ii. Single MPPT design with precise MPPT algorithm.
iii. Natural cooling, IP65 protection.
iv. Compact and light design for easy Installation.
v. Transformerless GT topology.
vi. RS485, WiFi Interface.
vii. Numerous protection functions.
viii. With Build in Anti-Overflow function.
ix. 9. 5 years’ standard warranty, 25 years’ lifespan design.

Figure 3. 5 The appearance of the selected grid tie inverter

3.7. Financial and cost analysis methods

The Net Present Value (NPV) and simple payback period calculation methods were used to evaluate the economic analysis of this project. They are among the most common financial tools for evaluating renewable energy project's bankability and viability of various generation options. The NPV for the project compares the total cash inflows discounted to present value against all costs for the project. The NPV formula is shown in Equation (3.1). Positive values for the NPV indicate a financially feasible project, with higher likely returns for the financial specialist.

$$\boldsymbol{NPV = \sum \left\{ \frac{Net\ Period\ Cash\ Flow}{(1+R)^{T}} \right\} - Initial\ Investment} \tag{3.1}$$

Where:

- ✓ Initial Investment =Initial Cost + Replacement Cost
- ✓ R= Discount Rate, and
- ✓ T= Lifetime of the proposed project, for the proposed system is thought to be 25 years.

The financial examination of the proposed solar PV system was done to evaluate the cost and proposed advantages of the project. It was completed with the assistance of RETScreen software packages. The software is easy to use and has the capability of simulating the net present value and simple payback period as well as approximating the greenhouse gas saving potential of renewable energy projects over their entire operational life. The NPV and simple payback period will help decide how practical the task will be. Payback period (PBP) Equation is present below:

$$PBP = \frac{\boldsymbol{Initial\ Cost}}{\boldsymbol{Operating\ Cost(Base\ Case) - Operating\ Cost\ (current\ system)}} \quad (3.2)$$

Every single project needs a financial feasibility analysis and economic analysis to approve its viability. With the assistance of the payback period, we can easily evaluate the feasibility of this project. In the event that the payback period is too long, at that point, the project may not be feasible in most of the times.

3.8. Summary

Briefly, this Chapter has defined the methods used to gather all information that was important for the sizing of the different solar PV system components. The chosen methods were an also used previously by different researcher and good results have been achieved. Methods of sizing all solar Photovoltaic system were done and simulation was additionally done with a help of the RETScreen Expert packages. The economic analysis of the designed system has been discussed and the outcomes are presented in Chapter 4. The proposed solar system was presented and collected data was used to do the system simulation. The data was used as the input load and the solar radiation resource data required by the software for simulation and optimization. The other task was to select types of solar PV modules, and inverter among the ones in the RETScreen Expert to be used for simulation.

Chapter 4. RESULTS AND DISCUSSION

4.1. Introduction

In this chapter the analysis of the designed system is made through the sizing software RETScreen and some results are presented and discussed. These results will determine the conclusions we will establish for this thesis. Using the load data collected and solar insolation data, the researcher was able to size the system that would adequately supply electricity to the Masaka households and the surplus will be exported or sold to the grid via net metering system. And when the solar energy is not sufficient to supply the entire domestic load, the required additional power will be imported from the grid.

The distinctive solar PV electricity generation design for Masaka could later be emulated in any other areas in the country. A financial analysis has been done so as to compare the solar PV system to the utility grid supply in terms of unit cost. The net present value has also been determined so as to evaluate the financial viability of the system. Furthermore, an estimated total of the domestic electrical power generation of the case study is done and the amount of enhancement that would result from the solar PV systems implementation in the area is quantified.

4.2. Data Analysis

In this part, the horizontal solar radiation data and load data was analyzed in readiness for the design of a grid-connected PV system for the case study.

4.2.1. Solar Radiation

Sizing a photovoltaic system or any other system that uses solar energy to convert it into electricity or any other form of energy, it is very important to have data relating to solar radiation(Al-Najideen & Alrwashdeh, 2017). The solar resource information data used in this research was collected from Rwanda meteorology agency (RMA) and National Aeronautics Space and Administration(NASA). The selected village is located at 01°59'44.0"S, 30°11'30.0"E (Latitude: -1.995556; Longitude:30.191667)(City of Kigali, 2013). The data was from those two sources was compiled and compared for suitability in the design and the two sources had very similar results as graphically shown in Figure 4.1 (Primary data,2018). In addition, the data on the annual averages of the monthly radiation sum on a horizontal surface are presented.

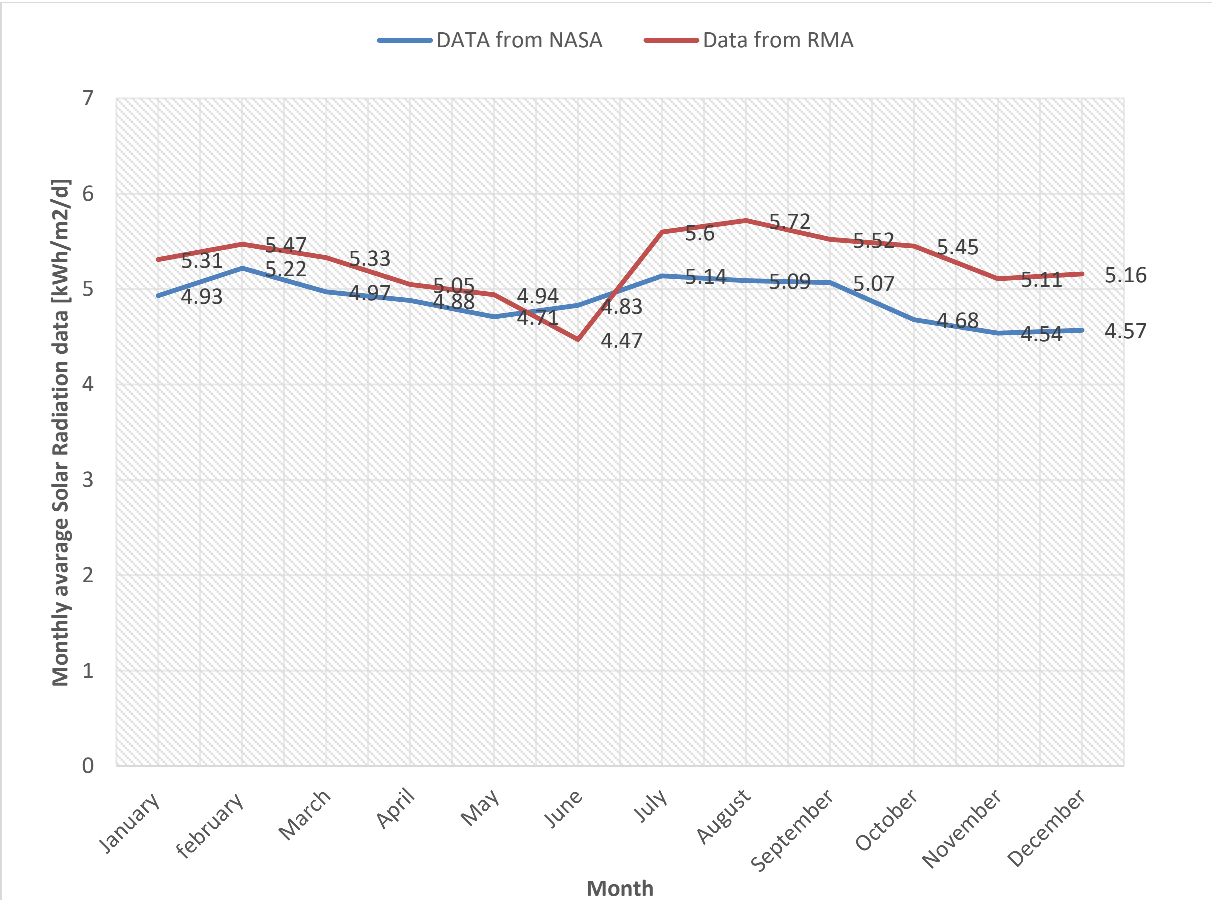

Figure 4. 1 Comparison between the horizontal solar radiation collected from two different sources (RMA & NASA).

The graphs show similarities that validate the two data sources. The data from selected site, the Meteorological department was collected over a period of 2 years, while the data from the NASA satellite station is data accumulated over a period of more than 22years. Even though, the data periods are different but the data pattern resembles a lot. Following this remark, the NASA data was used during the design and sizing of the solar home PV system for the selected households because of its accuracy and resolution by comparing their standard deviation. However, the other set of data from RMA was used for demonstrating the closeness and therefore the justification for using NASA data.

In a majority of studies, it is difficult to assess the accuracy of the collected data without performing independent calculations with various methods. The accuracy of NASA data was quantified by calculating the relative discrepancies (percent errors) between the two set of data collected (data from NASA and data from RMA). Furthermore, the relative discrepancies in each source of data were calculated to compare their consistency in two years' period. The equation (4.1) was used and the results are reported in Table 4.1, Table 4.2 and Table 4.3. In this study, the results are written as an absolute value. However, the relative discrepancy can be expressed as a negative or positive sign to indicate the direction of error from the true value.

$$\boldsymbol{Relative\ Dicrepancy}\ (\%) = \frac{\boldsymbol{NASA\ data - RMA\ data}}{\boldsymbol{NASA\ data}} \times \mathbf{100} \qquad (4.1)$$

Table 4. 1 Monthly Solar Radiation Data for Masaka Village from two presented sources

Year	Horizontal Solar radiation in Kwh/m^2/d [NASA]	Horizontal Solar radiation in Kwh/m^2/d [RMA]	Relative discrepancy %
Jan	4.9	4.16	15.10
Feb	5.19	5.16	0.58
Mar	4.99	5.63	12.83
Apr	4.7	4.72	0.43
May	4.72	4.93	4.45
Jun	4.85	5.58	15.05
Jul	5.23	5.82	11.28
Aug	5.1	5.95	16.67
Sep	5.01	5.84	16.57
Oct	4.72	4.99	5.72
Nov	4.4	4.63	5.23
Dec	4.57	5.06	10.72
Average	**4.86**	**5.2**	**9.55**
Jan	4.93	5.31	7.71
Feb	5.22	5.47	4.79
Mar	4.97	5.33	7.24
Apr	4.88	5.05	3.48
May	4.71	4.94	4.88
Jun	4.83	4.47	7.45
Jul	5.14	5.6	8.95
Aug	5.09	5.72	12.38
Sep	5.07	5.52	8.88
Oct	4.68	5.45	16.45
Nov	4.54	5.11	12.56
Dec	4.57	5.16	12.91
Average	**4.88**	**5.26**	**8.97**

Table 4.2 and Table 4.3 illustrate the process of decision making in selecting the accuracy data between two different years. The results obtained after calculating the relative discrepancy in each source of data support the selection of NASA data to achieve the aim of this research.

The high frequency of relative discrepancies has been identified in an unselected RMA compared to NASA data. Thus NASA data is trustful in this research as their fluctuation in two years is very low. It is clear that the relative discrepancies (1.1%) in the NASA DATA is considerably smaller than the relative discrepancies (8.4%) in the RMA data. It is important to note that a high relative discrepancy implies a high deviation from the mean and this can cause the fluctuation on production of the proposed PV system.

Table 4. 2 Relative discrepancy between the two years NASA data

Month	Horizontal Solar radiation in Kwh/m^2/d [NASA]		Relative Discrepancy %
	Y-2016	Y-2017	
Jan	4.9	4.93	0.61
Feb	5.19	5.22	0.58
Mar	4.99	4.97	0.40
Apr	4.7	4.88	3.83
May	4.72	4.71	0.21
Jun	4.85	4.83	0.41
Jul	5.23	5.14	1.72
Aug	5.1	5.09	0.20
Sep	5.01	5.07	1.20
Oct	4.72	4.68	0.85
Nov	4.4	4.54	3.18
Dec	4.57	4.57	0.00
Average			**1.10**

Table 4. 3 Relative discrepancy between the two years RMA data

Month	Horizontal Solar radiation in Kwh/m^2/d [RMA]		Relative Discrepancy %
	Y-2016	Y-2017	
Jan	4.16	5.31	27.64
Feb	5.16	5.47	6.01
Mar	5.63	5.33	5.33
Apr	4.72	5.05	6.99
May	4.93	4.94	0.20
Jun	5.58	4.47	19.89
Jul	5.82	5.6	3.78
Aug	5.95	5.72	3.87
Sep	5.84	5.52	5.48
Oct	4.99	5.45	9.22
Nov	4.63	5.11	10.37
Dec	5.06	5.16	1.98
Average			**8.40**

Further climatic parameters such as air temperature, relative humidity, earth temperature, wind speed and atmospheric pressure for the case study in different months of the year and their annual average values are presented in Table 4.2.

Different Solar PV react differently to the operating ambient temperature, however in all cases the efficiency of a solar PV decreases as it increases in temperature. As introduced in Chapter 2, in Figure 2.7, extremely high temperature affects the power output of the solar cell by reducing the output voltage of the array and causing the heat on cells. The temperatures and other climate parameters of the selected village very little from month to month and promise better efficiency in the solar photovoltaic system. MASAKA village is warm at the annual average temperature 20.5 °C and as 1.5 °C the variation of mean monthly temperatures. The study also found that the selected village gains an average of 834.11 mm of precipitation per year, this is considered as an advantage as the panels will be naturally cleaned from rain throughout the year.

Table 4. 4 Climatic parameters data for the case study

	Air temperature °C	Relative humidity %	Wind speed m/s	Atmospheric pressure, kPa	Earth temperature, °C	Precipitation (mm)
January	19.9	70.4	2.3	85.6	20.7	81.54
February	20.7	66.5	2.4	85.5	21.9	63.93
March	20.2	76.1	2.2	85.5	21.4	113.23
April	19.7	78.4	2.2	85.5	20.6	89.55
May	20.6	62.8	2.6	85.7	21.8	60.56
June	21.1	49.9	3.1	85.8	23.1	15.51
July	21.3	45.1	2.8	85.8	23.9	19.28
August	22	46.4	2.7	85.8	25.1	43.3
September	21.7	56	2.4	85.7	24.2	70.89
October	20	74.9	2.1	85.6	21.4	89.37
November	19.2	81.4	2	85.6	20.2	111.56
December	19.3	78.1	1.9	85.6	20	75.38
Annual average	**20.5**	**65.5**	**2.4**	**85.6**	**22**	**834.11**

4.2.2. Load Data Results

To do the sizing of the PV system, the energy load profile of the residence was really important to estimate the daily energy consumption of the selected family. The load data for the selected house (middle class family) is composed of some electrical and electronic equipment as shown in Table 4.5. These data were collected using two methods as explained in Chapter 3. Questionnaire and direct interview methods were used to know the real load capacity for a single family, though only the data from direct interview was found to be the most suitable and accurate for detailed appliance information used in this study.

Based on these data the daily power consumption for the selected single house was estimated to be used during the design and sizing of the PV system and are presented in Table 4.5. The 8.36 kWh was obtained as the daily consumption for single middle-class household only.

Table 4. 5 Available active appliances in Masaka village for a Middle class family

S/N	Equipment	Number in use	Rated Power W	Using time in hour/d	Total energy consumption in kWh/d
1	Refrigerator	1	-	24	1.41
2	Iron	1	1200	1	1.20
3	Television	1	150	5	0.75
4	Compact fluorescent lamps for rooms	6	12	6	0.43
5	Compacts fluorescent lamps for outside	2	30	8	0.48
6	Home theater	1	60	6	0.36
7	Laptop Computer	2	100	7	1.40
8	Digital Video Disc (DVD)	1	16	5	0.08
9	Mobile Phone	4	6	6	0.14
10	Blender	1	500	0.15	0.08
11	Electric Cattle for boiling water	1	1800	0.5	0.90
12	Toaster	1	850	0.5	0.43
13	Microwave	1	1000	0.7	0.70
Total					**8.36**

The daily load curve for a single middle- class household in Masaka village was defined based on the daily consumption data and it is appeared in Figure 4.2 beneath. The shape of the graph shows, the maximum power consumption demand, for the picked household is roughly equivalent to 5.93kWp existing at 8 PM and since the refrigerator is connected every day, the minimum average load will always be 1.41kWp.

The annual electricity demand for this household is about 3.1 MWh, during the design this load curve has retained constant over the whole year and the designed system will cover totally the energy consumption for this village. The month where de solar radiation is high, the surplus will be exported or sold to the grid via net metering system and if the generation is low the load, the consumers will import electricity from the grid.

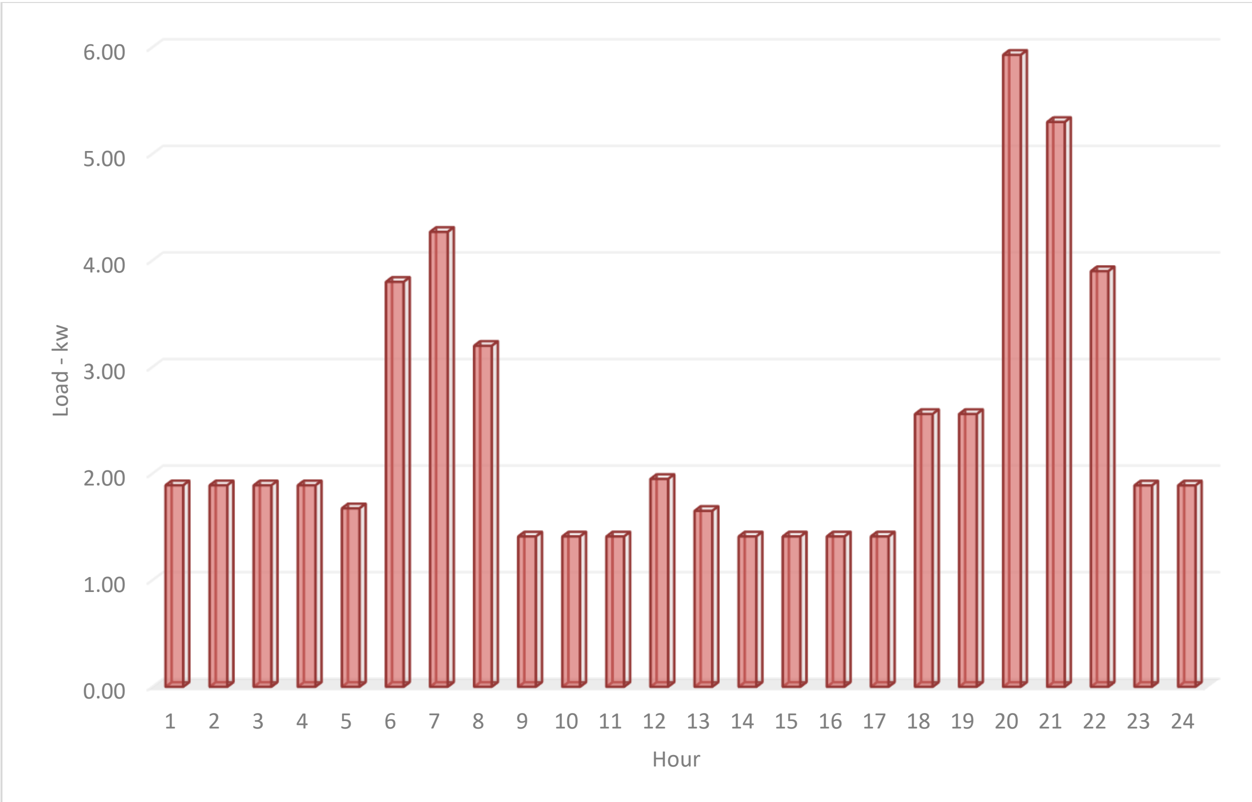

Figure 4. 2 Average daily load profile for a selected house in Masaka village

A load profile provides the electrical load (consumption) versus time and load demand also varies throughout the day because we don’t use all appliances all at once. This curve plays an important role in structuring the energy supply as it offers the information to plan how much electricity will be need to make it accessible at any given time.

4.3. Solar PV System Sizing and Simulation Results

For sizing the PV system for the selected house in Masaka village, RETScreen Clean Energy Project Analysis Software developed by Natural Resources Canada was used. First, in the Benchmark “Location and facility” segment of the software, we have to choose climate zone of a place closest where the study is carried out therefore both Masaka and Kigali climate data were used in the simulation. The software gives the full weather details of the selected village for analysis. It provides data regarding the daily solar radiation(horizontal), heating and cooling days, wind speed, earth temperature as it stands given in Table 4.4 and Figure3.3.

4.3.1. Energy Analysis

This part was done in assistance with RETScreen Expert package. After the completion of all primary data and networking model, the next step was to fill the energy sheet provided in feasibility section. RETScreen provide two levels in energy section, however one can be used depending on your choice. In this simulation Level 2 was used since is more precise as it requests more information with respect to the horizontal and azimuth solar panel inclinations. Appropriate configurations for the PV system were then prepared.

Since Masaka is located in the south hemisphere, the azimuth is selected to be 180 so that the system faces north to the equator. And according to the Table 2.3 presented in Chapter 2, the optimal design slope was found to be a latitude +15^{0} tilt with north facing arrays receiving global horizontal of 4.8 kWh/m^2/day as annual average. The choice of the number of PV technology depends on the data collected about the solar radiation of the site selected site and the daily power consumption (kWh) or types of the electric loads, and the procedure for RETScreen Expert is presented. Figure 4.3 Shows the number and the specification of selected PV panels.

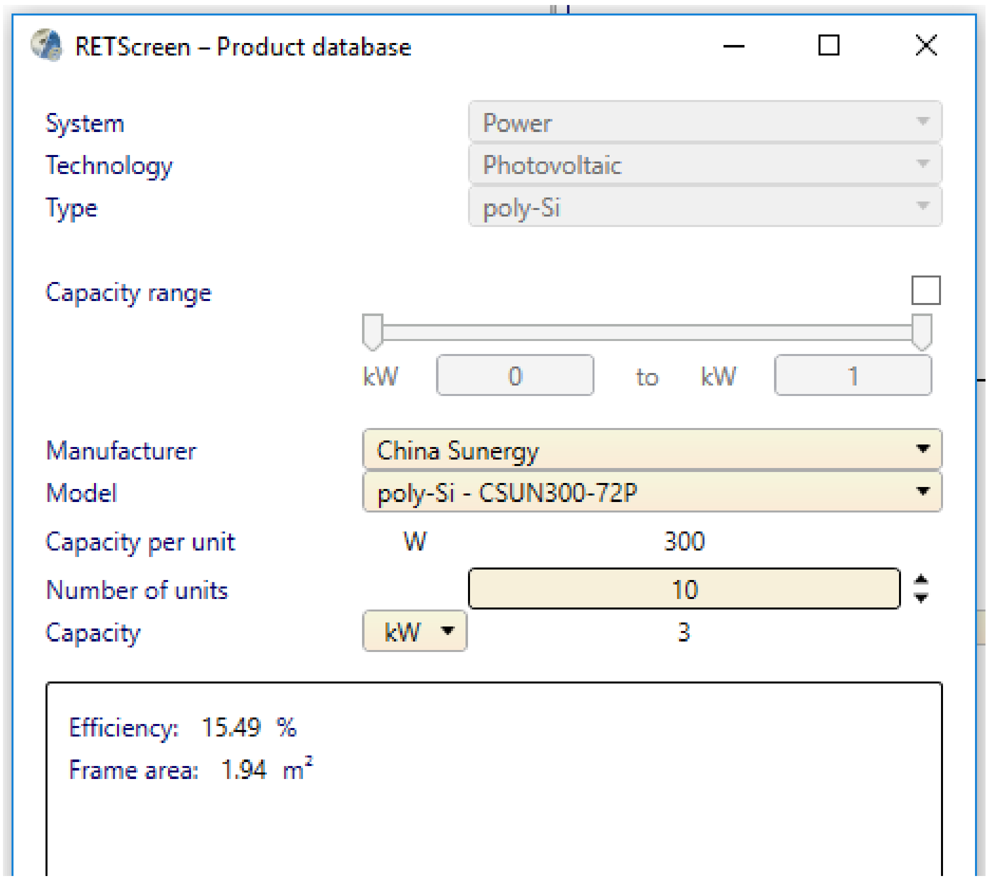

Figure 4. 3 Solar PV panel choice in RETScreen Expert

After selecting the Solar PV type and the number required for our system, the remaining values of the other field as per suitability of the energy model design is calculated by the software as is given in Figure 4.4.

Photovoltaic - Level 2

Resource assessment

Solar tracking mode		Fixed
Slope	°	15
Azimuth	°	180

Show data

Month	Daily solar radiation - horizontal kWh/m²/d	Daily solar radiation - tilted kWh/m²/d	Electricity rate – annual $/kWh	Electricity production kWh
January	4.93	4.47	0.20	376.823
February	5.22	4.88	0.20	369.551
March	4.97	4.84	0.20	408.363
April	4.83	4.90	0.20	400.070
May	4.71	4.96	0.20	415.736
June	4.83	5.20	0.20	419.668
July	5.14	5.51	0.20	457.534
August	5.09	5.26	0.20	437.090
September	5.07	5.02	0.20	405.870
October	4.68	4.45	0.20	376.369
November	4.54	4.18	0.20	343.134
December	4.57	4.13	0.20	350.166
Annual	**4.88**	**4.82**	**0.20**	**4,760.372**

Annual solar radiation - horizontal	MWh/m²	1.78
Annual solar radiation - tilted	MWh/m²	1.76

Photovoltaic

Type		poly-Si
Power capacity	kW	3
Manufacturer		China Sunergy
Model		poly-Si - CSUN300-72P
Number of units		10
Efficiency	%	15.49%
Nominal operating cell temperature	°C	45
Temperature coefficient	% / °C	0.4%
Solar collector area	m²	19.4
Miscellaneous losses	%	1%

Inverter

Efficiency	%	97%
Capacity	kW	4
Miscellaneous losses	%	0%

Summary

Capacity factor	%	18.1%
Initial costs	$/kW	3,300
	$	9,900
O&M costs (savings)	$/kW-year	44
	$	132
Energy saved	kWh	4,760

Figure 4. 4 Energy model details in RETScreen Expert

The amount of electrical energy produced by this PV system depends basically on the solar radiation of the selected village and the efficiency of the selected PV panel. The number of the panels depends on the power required to cover the daily energy consumption which is detailed in Table 4.5 The data about the average gross power load of the selected house (middle-class family) is given by the user through the questionnaire and the interview depending on the specification of appliances they are using. which is then fed to RETScreen expert. The software also asks of how much load ratio of the grid and the PV technology used is to be kept or saved. The charges per kW of energy as per the currency is also fed for a cost analysis by the software.

Power production of Solar PV System can decrease significantly with the accumulation of dust or sand on the surface of the PV cell, often called “soiling.” There have been numerous studies of the soiling effect on PV cells(El-Nashar, 2003; Kimber, 2006; Pavan, Mellit, & De Pieri, 2011). This effect is especially important in the desert conditions where sand storms can deposit large amounts of dust and sand on the PV cell. With reference to the previous studies, only dust was considered in this research and will decrease annual production by 1 percent. This loss of energy production on photovoltaics cell is input into the model as “miscellaneous losses,” representing the percentage decrease in annual production. Furthermore, any miscellaneous losses from the inverter or other power conditioning are taken as zero percent. The selected inverter is reported to operate between 1 to 4 kW, and the percentage of electricity the inverter successfully converts from DC to AC is 97% (Inverter Efficiency).

The peak electricity export occurs in the month of July when production is 457,534 MWh. The decrease in electricity production from September to December is likely due to the change of season which decrease the efficiency of the solar cells.

4.3.2. Financial and Cost Analysis

In the cost analysis sheet/section we have to sort out all details of the cost of different components required for the establishment of the proposed system. In this worksheet, the initial, yearly and intermittent expenses for the case study as well as the incrementally expenses for the proposed PV system must be provided by the designer. The user has the decision between playing out a pre-feasibility or a feasibility study. For a "Pre-feasibly investigation," less point by point and less precise data is normally required while for a "Feasibility examination," more definite and more exact data is normally required. After choosing those parameters from the previous and related research and performing the analysis, the details of the cost sheet analysis is given and presented in Figure 4.5. It is clear that the complete cost depends on the engineering costs, cost of the inverter system depending on their ranges and other labor and management costs.

RETScreen - Cost Analysis | Subscriber: Viewer

Initial costs (credits)	Unit	Quantity	Unit cost	Amount	Relative costs	%	Actual cost
Feasibility study							
Feasibility study	cost	1	$ 180	$ 180			$ -
Subtotal:				$ 180	1.6%		$ -
Development							
Travel Cost	cost			$ -			$ -
Subtotal:				$ -			$ -
Engineering							
Engineering	cost			$ -			$ -
Subtotal:				$ -			$ -
Incremental initial costs							
Show data				$ 9,900			$ -
Subtotal:				$ 9,900	86.2%		$ -
Balance of system & miscellaneous							
Spare parts	%	1.2%	$ 9,900	$ 119			$ -
Transportation	project	1	$ 85	$ 85			$ -
Training & commissioning	p-d	0	$ 0	$ 0			$ -
Inverter	cost	1	$ 1,091.57	$ 1,092			$ -
Contingencies	%	1.0%	$ 11,375	$ 114			$ -
Interest during construction			$ 11,489	$ -			$ -
Subtotal:				$ 1,409	12.3%		$ -
Total initial costs				$ 11,489	100.0%		$ -

Annual costs (credits)	Unit	Quantity	Unit cost	Amount	%	Actual cost
O&M						
Show data				$ 132		$ -
Parts & labour	project	1	$ 140	$ 140		$ -
User-defined	cost			$ -		$ -
Contingencies	%		$ 272	$ -		$ -
Subtotal:				$ 272		$ -
Fuel cost - proposed case						
Electricity	kWh	-4,760	$ 0.20	$ (952)		$ -
Subtotal:				$ (952)		$ -

Figure 4. 5 Cost analysis worksheet from RET Screen Expert

RETScreen - Financial Analysis **Subscriber: Viewer**

Financial parameters

General		
Fuel cost escalation rate	%	6.2%
Inflation rate	%	5.5%
Discount rate	%	7.7%
Project life	yr	25
Finance		
Incentives and grants	$	
Debt ratio	%	0%
Income tax analysis		☐

Annual revenue

GHG reduction revenue		
Gross GHG reduction	tCO_2/yr	2
Gross GHG reduction - 25 yrs	tCO_2	56
GHG reduction revenue	$	0
Other revenue (cost)		☑
Energy	kWh	1,708.6
Rate	$/kWh	0.22
Other revenue (cost)	$	376
Duration	yr	25
Escalation rate	%	6.2%
Clean Energy (CE) production revenue		☐

Costs | Savings | Revenue

Initial costs			
Feasibility study	1.6%	$	180
Incremental initial costs	86.2%	$	9,900
Balance of system & miscellaneous	12.3%	$	1,409
Total initial costs	**100%**	**$**	**11,489**
Annual costs and debt payments			
O&M		$	272
Fuel cost - proposed case		$	-952
Total annual costs		**$**	**-680**
Annual savings and revenue			
Other revenue (cost) - 25 yrs		$	376
Total annual savings and revenue		**$**	**376**

Financial viability

Pre-tax IRR - equity	%	14.6%
Pre-tax IRR - assets	%	14.6%
Simple payback	yr	10.9
Equity payback	yr	8.1
Net Present Value (NPV)	$	11,061
Annual life cycle savings	$/yr	1,010
Benefit-Cost (B-C) ratio		2
Debt service coverage		No debt
GHG reduction cost	$/$tCO_2$	-449

Yearly cash flows

Year	Pre-tax	Cumulative
#	$	$
0	-11,489	-11,489
1	1,123	-10,366
2	1,195	-9,171
3	1,271	-7,900
4	1,352	-6,547
5	1,438	-5,109
6	1,530	-3,579
7	1,628	-1,951
8	1,731	-220
9	1,842	1,622
10	1,959	3,581
11	2,084	5,664
12	2,216	7,880
13	2,357	10,237
14	2,507	12,745
15	2,667	15,411
16	2,836	18,247
17	3,016	21,264
18	3,208	24,472
19	3,412	27,884
20	3,629	31,513
21	3,860	35,373
22	4,105	39,477
23	4,365	43,843
24	4,643	48,485
25	4,937	53,422

Figure 4. 6 Finance worksheet from RETScreen Expert

To estimates the initial cost of the proposed system, various studies and reports were consulted to develop estimates of these costs(International Energy Agency, 2009; Maruoka, 2008; Mitchell, Witt, King, & Ruby, 2002), as the economics of photovoltaics is constantly changing and varies in various parts of the world. The module price is assumed to be $ 3,300/kW, which makes a total cost of PV panels to be $9,999 for a period of 25 years. These estimated values are provided in RETScreen expert depending on the location of your studies. The annual costs consist of operating and maintenance and periodic costs, such as replacing inverters. Operating and maintenance costs are also provided by the software and are relatively small as PV systems are low maintenance, estimated to be $ 272 annually including labor cost. I this study, periodic costs are not counted since PV module themselves are very durable and frequently come with 25yers guarantees. And also the selected inverter has 25 years' lifetime and are estimated to cost approximately $1,091.57.

The annual conventional energy savings due to PV-generated electricity entering the grid is calculated by subtracting the total energy consumption from the net energy production from the designed PV system. The total energy saving is then multiplied by the electricity export rate (the price paid by the utility for electricity from the PV plant that is dispatched to the power grid) to find the savings in $. The minimum electricity export rate is to be equivalent to $ 0.22 per kW. The internal rate of return on investment "IRR" represents the interest earned by the project over its lifetime and is projected to be 14.6 %. In addition to this, the RETScreen expert package has a built-in function to account for increasing energy prices over time, and during this simulation has assumed to be escalating at a 6.2% rate every year. Other input factors are inflation rate and discount rate estimated to be 5.5% and 7.7% respectively(Indexmundi, 2018; PricewaterhouseCoopers Limited, 2017).

According to the cost and Financial analysis, the total initial costs of the proposed project is $11,489 for 25years time period which included the cost of the system and operation and maintenance. The financial viability report indicated equity payback of 8.1 years and a simple payback period of 10.9 years (see Figure 4.6). The graphical annual and cumulative cash flow indicates that the equity payback will start after a mentioned time period which will rapidly increase as presented in Figure 4.7.

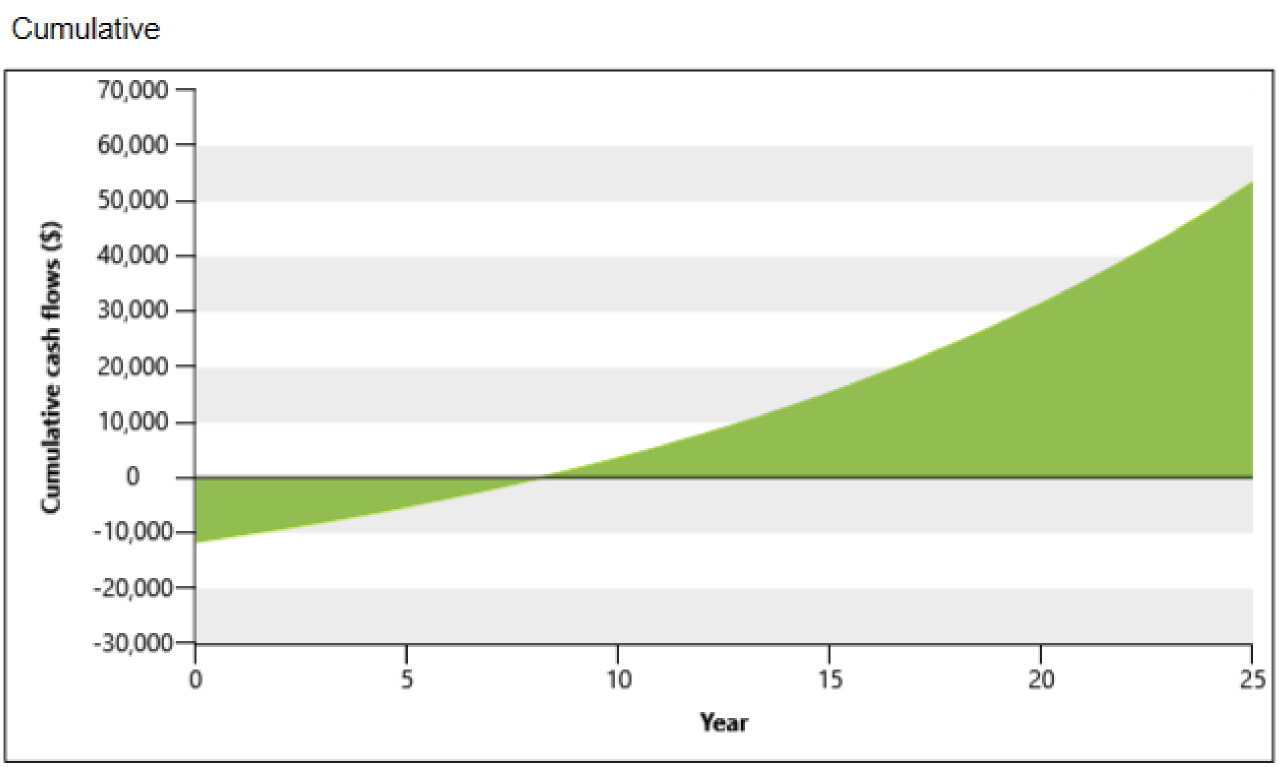

Figure 4. 7 Cumulative cash flow graph over a period of 25 years

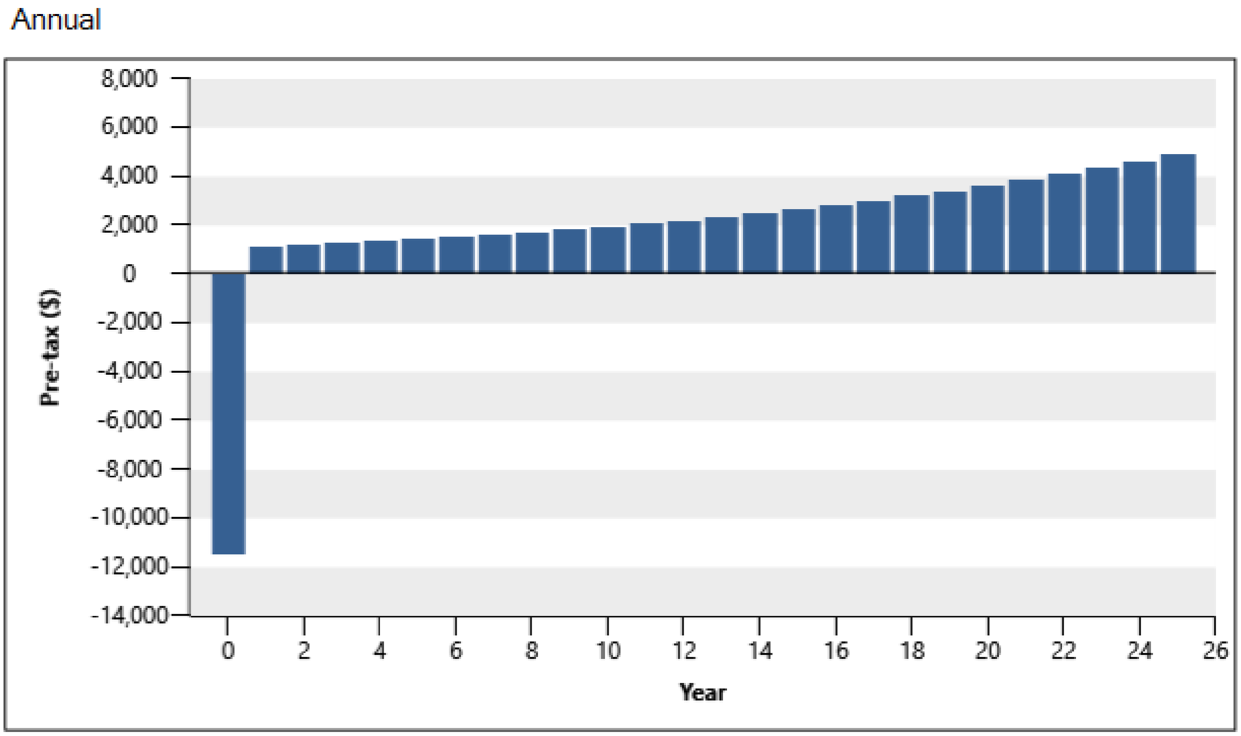

Figure 4. 8 Pre-tax cash flow graph.

The project has 25 years' lifetime, the years to positive cash flow indicates how long it takes to recoup the initial investment only, excluding periodic investments. has a projected 16.9 years to positive cash flow. The pre-tax cash flow consists of the calculation of cash flows before taxes, on a yearly basis, of all expenses (outflows) and incomes (inflows) generated by the clean energy project. Otherwise, It's the amount of money generated by an investment after collection of all revenues and payment of all bills. For year zero, the pre-tax cash outflow is equal to the project equity, that is, the portion of the total investment required to finance the project. The pre-tax cash flow for other years is simply the difference between the pre-tax cash inflow and the pre-tax cash outflow. Figure 4.8 presents the graph of pre-tax cash flow over a period of 25 years.

4.3.3. Emission Analysis

This part is helpful in the prediction of the future benefits of air pollution reduction from using the proposed system in place of the base case technology. The result is given in form of the amount of the carbon dioxide emissions reduced which is shown in the form of tonnes of GHG emission not emitted or other conservation equivalents as is given in the software. The data can vary as per the need. Therefore, this study was able to show that our input data for 25-years lifetime for the system will reduce the amount of GHG emission by 57.5 tonnes (see Figure 4.9) as the designed system replaces the need of some electricity from the existing power grid.

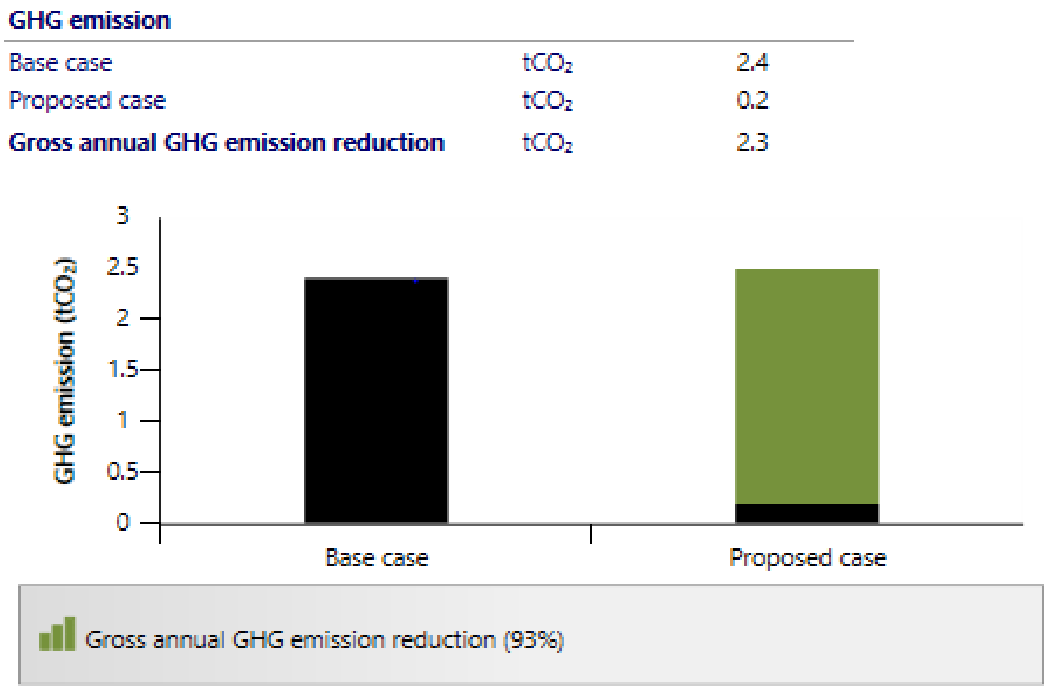

Figure 4. 9 Prediction of GHG Emission using RETScreen Expert

The Green House Gases (GHG) emission effect in base case emission was higher than the proposed case with a total annual output difference of 2.3 tCO2 equivalents to 5.2 barrels of crude oil which will not be consumed by a power plant generating equivalent electricity to the one from the proposed case.

4.4. Summary

According to the outcomes presented in this Chapter, the sizing of the components forming the proposed grid-tied PV system was done well and coordinated with the load demand for the case study. For completing this study, the t array system orientations have been talked about and results presented. The financial analysis results demonstrate that the solar PV system is costly to set up yet the unit cost of the power produced is lower compared to the unit of utility electricity of the base case. In addition to that the financial analysis results have also revealed that the system has a positive NPV which indicates that the future of solar PV is favorable for the selected area. The further studies and the conclusion are discussed in Chapter 5.

Chapter 5. CONCLUSION AND RECOMMENDATION

5.1. Conclusion

The design of a grid-connected solar PV system that can supply electricity to Masaka Village for a middle-class family is the aims of this project. Different studies done elsewhere in the world drilled some special difficulties of the existing systems which have been well taken care of in this design. With the interpretation that the objectives were clearly defined from the beginning, the study conducted has adequately exhausted each specific objective separately thereby fulfilling the main objective of the study. The case study was identified and the study was carried out. After identifying the case study, some parameters were required to achieve the aim of this research. Using the methods introduced in Chapter 3, both solar resource assessment and load data has been carried out for the selected area. This has revealed that Masaka receives about 4.88kWh/m2/day and 5.2 kWh/m2/d according to the data provided by NASA and RMA respectively.

The data collected were analyzed and used to design the typical solar PV electricity generation system for Masaka village. A 3 kW grid-tied PV system suitable to the middle-class households was designed with ten panels of 300Watt capacity each. The system would have need of 19.4 m^2 total roof space for the installation. The PV system must be oriented northwards in order to receive the maximum amount of solar radiation. In selecting the solar PV components, both international and local dealers were contacted and the best in terms of performance and cost were selected. A polycrystalline silicon PV module was selected by considering both the price and Solar collector area required.

By using RETScreen Expert packages, the financial analysis of the designed system was performed over a life period of 25 years, and according to the simulation results, the project is considered as financially viable since its payback period will be about 8.1 years. In addition to that, the study of the RETScreen simulation results divulges that, this project stands the chance of annual saving about 2.3 tonnes of CO2 which would have been emitted by non-renewable power plant generating the same amount of electricity. By looking on the outcomes achieved it is concluded that the selected village has enough solar irradiation for electricity generation to serve individual family (including the remaining classes) and even feed the surplus power into the grid.

5.2. Recommendation

Based on the results achieved and other related previous research, the study recommends that grid-connected solar PV system be implemented as a justification measure to the reduction of the national peak power demand and annual energy demand from the grid. This proposal is made considering the price of solar PV system will lessen as time advances and that power generation using fossil fuel techniques can’t be maintained for so long. Subsequently this PV electricity generation system ought to be supported all through the nation.

Load data was given by the case study residents without using any instruments, however these data are not as accurate as the one through measurements. Therefore, hiring specialized instruments and load data logging, capturing at least one week in every month, would be advised during future studies so as to capture more load data details.

Exploiting diverse kinds of renewable energy source in hybrid systems like consolidating PV and biomass for example, keeping in mind the end goal to use all available renewable energy resources, may offer a possibility for higher reliability. Subsequently, this thesis might be a beginning stage for further work on future research.

Concentrate the effect of high penetration level of PV system on the Rwanda electrification strategy could be great subject for future work. Furthermore, as future innovation becomes smarter, examining the possibility of using smart grid functionality with PV-grid connected system could be also good subject for future work.

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Appendices

Appendix A: Rwanda's daily solar irradiation(Solar Plaza, 2017)

Rwanda's daily solar irradiation ranges from 4 kWh/m² north of the city of Ruhengeri to 5.4 kWh/m² south of the capital, Kigali, in the Southern and Eastern provinces.

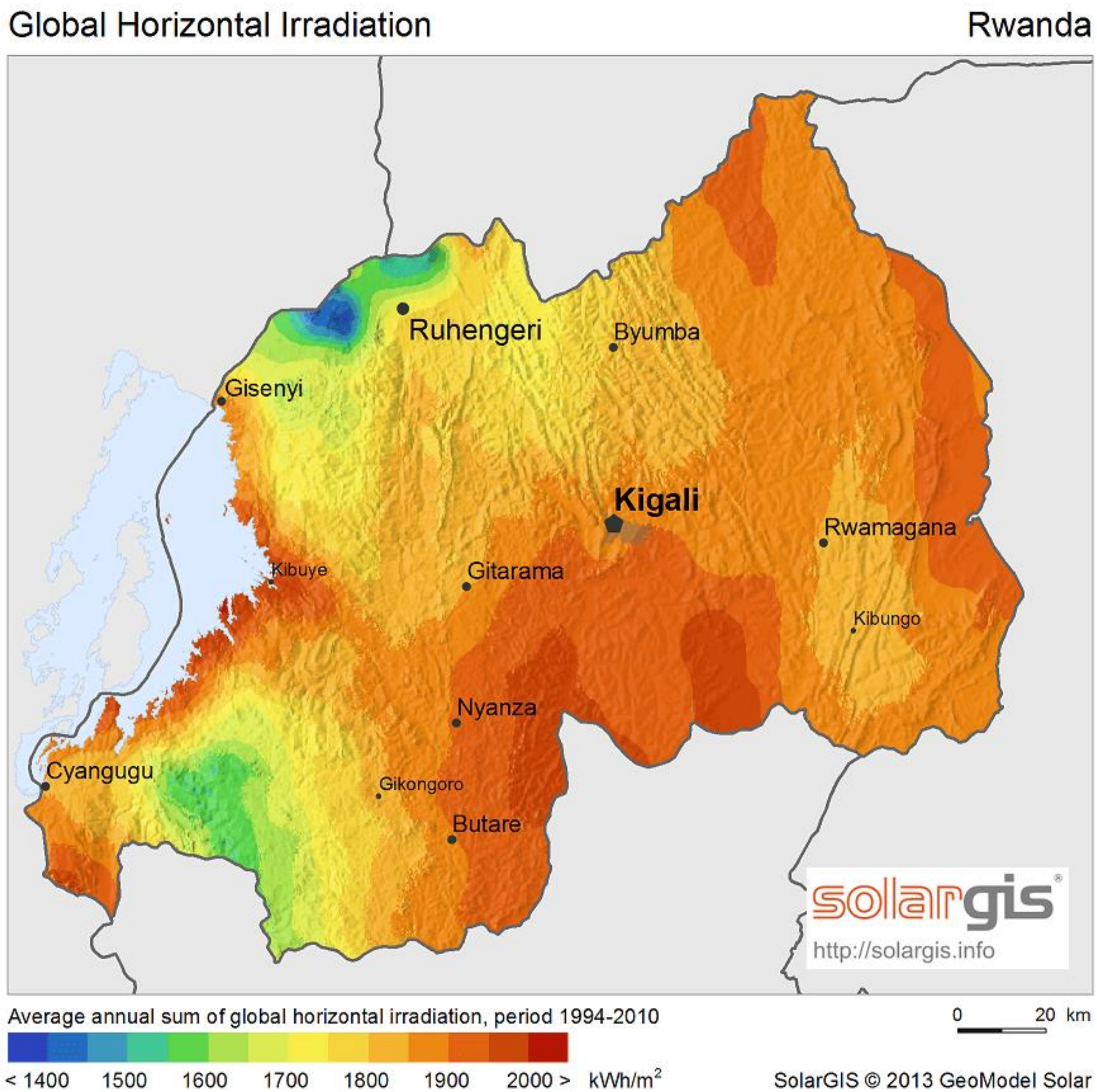

Figure: Rwanda Solar Map

(Solar Plaza, 2017)

Appendix B: Financial viability of proposed system (Input parameters and the results)

Financial parameters

General		
Fuel cost escalation rate	%	6.2%
Inflation rate	%	5.5%
Discount rate	%	7.7%
Project life	yr	25

Annual revenue

Other revenue (cost)		
Energy	kWh	1,709
Rate	$/kWh	0.22
Other revenue (cost)	$	376
Duration	yr	25
Escalation rate	%	6.2%

Costs | Savings | Revenue

Initial costs			
Feasibility study	1.6%	$	180
Incremental initial costs	86.2%	$	9,900
Balance of system & miscellaneous	12.3%	$	1,409
Total initial costs	100%	$	11,489
Annual costs and debt payments			
O&M		$	272
Fuel cost - proposed case		$	-952
Total annual costs		$	-680
Annual savings and revenue			
Other revenue (cost) - 25 yrs		$	376
Total annual savings and revenue		$	376

Appendix C: QUETIONAIRE: FIELD SUVERY ON HOUSEHOLD ELECTRICAL APPLIANCES AND ENERGY CONSUMPTION

Message to the Residents

Dear Respondents,

Greetings to you! I am a Master's Degree understudy at the Pan African University Institute of Water and Energy Sciences (including Climate Change) (PAUWES). In halfway satisfaction for the honor of this degree, I am carrying out a research on Design of Home Electricity Supply System using Solar Energy and its Integration to the National Grid. I am utilizing Nyagatare village as the case study and the enclosed questionnaire aims at collecting data to be used purely for academic purposes. Although your participation is voluntary, we hope you will participate in this important survey of electrical appliances and energy consumption. Personality and every one of the reactions you give me will be kept entirely classified. Your honest participation in responding, to the best of your knowledge would go a long way in making this research a win and would thusly enhance power control would in turn help to improve electricity power generation and leaving benchmarks in the state.

Yours faithful,

Ernest

I. Respondents' details

Date: ………/………/2018.

Respondents location(Name)

Gender:

	Male
	Female

What is your family main activity? In case of working in more than one activity, please refer to the main activity:

	House keeping		Professor, doctor, priest
	Agriculture		Public service
	Cattle		Small commerce
	Building, woodcraft, plumbing, transport		Other (……………..)

Are you a member of your household who is most familiar with your energy consumption?

☐ Yes (you got the person who is most familiar with their energy consumption).

☐ No.

PART II: HOUSEHOLD ELECTRICAL APPLIANCES/LOAD

S/N	Do you have these items/ appliances in your house?	Kindly indicate by ticking the suitable choice that corresponds to your situation		
		Decision	**Description**	**Check the hour of use**
1	Refrigerator	☐ **Yes** ☐ **No**	What size is it? Small / Medium / Larger	☐ Per day ☐ Per Week ☐ Per Month
2	Iron	☐ **Yes** ☐ **No**	What type is it? Dry / Steam	☐ Per day ☐ Per Week ☐ Per Month
3	Electric cooker	☐ **Yes** ☐ **No**	How many plates does it have? Three / Two / One / Other Does it have a grill or oven? Both / Grill alone / Oven alone	☐ Per day ☐ Per Week ☐ Per Month
4	Microwave machine	☐ **Yes** ☐ **No**	What type is it? Small / Medium / Larger	☐ Per day ☐ Per Week ☐ Per Month
5	Electric water heater	☐ **Yes** ☐ **No**	What type is it? Immersion / Portable / Kettle	☐ Per day ☐ Per Week ☐ Per Month
6	Bread toaster	☐ **Yes**	What type is it? Two slice / More than two	☐ Per day ☐ Per Week

		No		Per Month
7	Coffee maker	Yes No	What type is it? Brewing | Worming | Other	Per day Per Week Per Month
8	Hair dryer	Yes No	What type is it? Small | Medium | Larger	Per day Per Week Per Month
9	Clothes washing machine	Yes No	What type is it? Cool dry | Hot dry	Per day Per Week Per Month
10	Desk top computer	Yes No	How many do you have? One | Two | Other	Per day Per Week Per Month
11	Laptop Computer	Yes No	How many do you have? One | Two | Other	Per day Per Week Per Month
12	Mobile Telephone	Yes No	How many do you have? One | Two | Other	Per day Per Week Per Month
13	Television	Yes No	How many inches does it have? 49 | 43 | 32 | 27 | Other	Per day Per Week Per Month
14	Home theater	Yes No	What type is it? 3 in one | 2 in one | Other	Per day Per Week Per Month
15	DVD (digital video disc)	Yes No	How many are they? Three | Two | One | Other	Per day Per Week Per Month
16	Filament lamps	Yes No	How many are they? 6 | 5 | 4 | 3 | Other	Per day Per Week Per Month
17	Fluorescent lamps	Yes No	How many are they? 6 | 5 | 4 | 3 | Other	Per day Per Week Per Month
18	Compact fluorescent lamps	Yes No	How many are they? 6 | 5 | 4 | 3 | Other	Per day Per Week Per Month
	Kindly state any other appliance that you have in your house and is not mentioned please			
19	……………..	Yes No		Per day Per Week Per Month

PART III: CURRENT ELECTRICITY SUPPLY

1. In terms of reliability, are you satisfied with Rwanda electricity power supply?

	Very reliable
	Reliable
	Not reliable

2. How do you rate the cost of electricity in Rwanda?

	Very expensive
	Expensive
	Moderate
	Cheap

3. On which system are you being billed for electrical power?

	Pre-paid system
	Post paid
	Other

If your response is other, please specify…………………………………….

4. Are you satisfied with the electricity power tariff system in Rwanda?

	Satisfied
	Occasionally
	No comment

5. Have you ever been worried about your electricity consumption in the house?

	Always
	Not satisfied
	Never

6. Do you know what constitutes your electricity bill?

	Very accurately
	Roughly
	No idea

7. Have you ever anticipated using energy saving appliances in your house?

	Always
	Occasionally
	Never

8. Would you acknowledge another source of energy generation?

	Strongly agree
	Tend to agree
	Tend to disagree
	Disagree

9. Would you consent to claim your own source of energy generation?

	Strongly agree
	Tend to agree
	Tend to disagree
	Disagree

10. Would you consent to set up your own solar photovoltaic power generation system?

	Strongly agree
	Tend to agree
	Tend to disagree
	Disagree

11. What is your view about sustainable power source (renewable energy)?

	Very reliable
	marginally reliable
	Not reliable
	No idea at all

12. Which among the accompanying sustainable power source assets would you lean toward?

	Biogas
	Wind
	Solar
	Other

13. What number of kilowatt hours (kWh) of power every month did you spend on average over the last 12 months?

14. What was the average monthly cost for electricity over the past 12 months?

15. Kindly fill the table underneath with data from your power charges as precisely as you can.

Period	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
consumption(Units) 2017												
consumption(Units) 2018												

16. Please feel free to add any comment (use a free piece of paper if necessary)

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Thank you for your cooperation. Your response is very important to this research. If you have any questions or comments, please feel free to contact Ernest NSHIMIYIMANA at:

E-mail: *erkey2020@gmail.com*

Phone : +250788976114

Appendix D: Rwanda electricity tariff

ANNOUNCEMENT

The Management of Energy Utility Corporation Limited (EUCL) wishes to inform its esteemed customers that the new electricity tariff as approved by the RURA Board of Directors; in its decision Nº 05/BD/ER-LER/RURA/2016, from the session of 13th/12/2016 is effective starting 1st January 2017as follows;

1. RESIDENTIAL CUSTOMERS:

Consumption (kWh) block/month	FRW/kWh (Without VAT)
[0-15]	89
]15 – 50]	182
>50	189

2. NON- RESIDENTIAL CUSTOMERS

Consumption (kWh) block/month	FRW/kWh
[0 -100]	189
>100	192

3. INDUSTRIAL CUSTOMERS

SMALL INDUSTRIES	FRW/kWh
Water treatments plants, Water pumping stations and Telecom towers	126

MEDIUM INDUSTRIES: (0.4 Kv<V≤15kV)		
Energy Charge	Rwf/kWh	90
Max. Demand Charge (17H00- 23H00) Peak	Rwf/KVA/month	10,469.55
Max. Demand Charge - (08H01'- 16H59') Shoulder	Rwf/KVA/month	5,588.41
Max. Demand Charge- (23H01' – 08H) Off-Peak	Rwf/KVA/month	1,891.54
Customer Service Charge	Frw/Customer/Month	3,125

LARGE INDUSTRIES: (>15 Kv<V ≤ 33 kV)		
Energy Charge		83
Max. Demand Charge (17H00- 23H00) Peak	Rwf/kWh	7,184.44
Max. Demand Charge - (08H01'- 16H59') Shoulder	Rwf/KVA/month	4,004.16
Max. Demand Charge- (23H01' – 08H) Off-Peak	Rwf/KVA/month	1,085.86
Customer Service Charge	Rwf/KVA/month	3,125

Note that this new tariff structure does not include 18% as VAT.

For further information please contact your nearest Branch, Commercial Department at Headquarter or toll free line 3535.

The EUCL management appreciates your usual full collaboration.

Done at Kigali, the 30th December, 2016

The Management

Appendix E: Thesis Budget

Nº	Activities	Description	Cost ($ USD)
1	Ticket (Airplane)& Local Transport	Travel outside of PAUWES for Internship and other research purposes.	1,100
2	Computer Software	Training and Renting Software access that will be used in designing of the System.	400
3	Data collection	Printing Questionnaires	1066
		Daily transportation during data collection	
		Communication (local and international call)	
4	Data arrangement, Project writing and archive	Internet and Computer Supplies	329
		A4 Sheets, markers and pens	40
5	Project report print out (hard copies) & binding	Printing prepared documents (drafts copies)	65
Total			***3,000***