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

OPTIMIZATION OF THE OPERATION OF GRID-CONNECTED SOLAR PV AND BATTERY STORAGE TO MINIMIZE ELECTRICITY COST.

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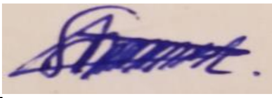
Declaration

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



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APPROVAL

Date of Submission: ______ ______

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

…DR.Francis MULOLANI…. __________ ____

Thesis Advisor Signature

DEDICATION

This thesis work is written in honour of my beloved mum MUREKATETE Esther who with a lot love, prayer and encouragement showed throughout my education.

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The realization of this thesis would not be possible without contributions, encouragement and supports from so many people in various corners of my life. First and foremost, my thanks are due to almighty God for his protection and blessing. I thank my beloved family with their encouragement, moral support and guidance for carrying out this research project.

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God bless you all.

Abstract

The main objectives of this study is to minimize the electricity cost at residential house for the user of grid connected solar PV, in this thesis we use the methods of optimizing the energy generated from the solar PV system which is not used, the idea is to maximize the use of own generated power from the PV system and to minimize the dependability to the grid.

In this study the method of battery optimization by using levelized cost of energy in order to know the best battery according to the battery storage technology, the simulation was done in HOMER software with the purpose of selecting the battery according to the economic point of view, life cycle of the battery and charging and discharging of battery, we found out the best battery with high cycle life and low LCOE is VRFB, Flooded LA and NaS battery technologies.

After the optimization of the battery, and configuration to the grid connected solar PV system, we do the technical analysis of the energy generated from the PV system which is not used, means we have done the analysis of lost energy in the PV system generation by entering the geographical data of the selected location, PV data and the storage of the designed system in PVsyst software.

After entering the required data in PVsyst software we simulate and analyses two scenario of grid connected solar PV configuration model, one with battery and the other without battery storage, the results show that the configuration system without battery storage have an unused energy or lost generated energy in the system which is equal to 17.25% of the total generated energy and the system with battery storage show that the energy generated from the PV system which is not used or lost generated energy in the system is equal to 3.76%.

The analysis of two scenario was done, and we see that the system without battery storage have low installation cost which is $658 less compared to the system with storage, but this system without battery have the high percentage of energy loss of 17.25%, and this make it depend to the grid power in every time there is no sun or in night hours and this is very costly because most of the grid power is generated by using fuel and is very expensive, whereas the system with battery storage have very low energy lost 3.76% which make it very competitive according to the economic point of view, because the user of grid connected solar PV will use the maximum generated power from his own PV system and less dependability to the grid. Hence the optimum system selected in this study which can minimize the electricity cost at residential houses is the use of grid connected solar PV with battery storage.

Keyword: grid connected solar PV, PV system, Levelized cost of energy, electricity cost, Net present cost, solar irradiation

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PV-	Photovoltaic
AC -	Alternating Current
DC-	Direct Current
VAT -	Value-Added Tax
DSM-	Demand Side Management
NASA -	National Aeronautics and Space Administration
GDP -	Gross Domestic Product
REG -	Rwanda Energy Group
EARP -	Electricity Access Roll-Out Program
LTD -	Limited
MW -	Mega-watts
SB-	Soft Bank
HOMER -	Hybrid Optimization Model for Electric Renewable
DOD -	Depth of Discharge
MININFRA-	Ministry Of Infrastructure
NPC-	Net Present Cost
LCOE-	Levelized Cost of Energy
NREL-	National Renewable Energy Laboratory
TRNSYS -	Transient Energy System Simulation Program
LED-	Light Emitting Diode
PR -	Performance Ratio
OPE -	Operating Cost of Electric

CHAPTER ONE

INTRODUCTION

1.1. Background of the study

Today the need of electricity is more than the past century, because of the technology and the development of today which require electricity in every aspect, that's why researchers need different technic and methods for maximizing the existing generation sources of energy in an economical and efficient way but also the government and private investors continue to build new plants to support the existing plants.

This is done by the help of different sources of energy from hydro, thermal and solar which combine a big portion of electricity used here in Rwanda.

The government of Rwanda is encouraging the improvement in using renewable energy and minimizing the use of diesel power plant in Rwanda network, because of the generation cost which is very high for the diesel power plant and the problem of environmental degradation, whereas renewable energy like solar power plant need natural solar to generate power which is free and environmental friendly.

In 2011, around 14% of Rwanda population had the electricity from hydro, since then the government of Rwanda start a program of developing energy and electrification in general where in 2012 the percentage of rural electrification rise from 16% which correspond to 364,000 households to more than 700,000 households which is 31% of the total households in Rwanda, and the target in 2019 was to connect 14,305 households [1]. Only this show how the government of Rwanda put in the effort to do whatever it take to rise the number of electrification in Rwanda, this is the data and information from the reports of electricity access roll-out program (EARP)

Figure1.1 show the generation capacity in Rwanda of 235.6 MW from different sources but with big part occupied by hydro power plants, in this generation capacity there is 50.6% of hydro sources, 43.4% of thermal, 11% of power imported from outside the country and 5% from solar sources.

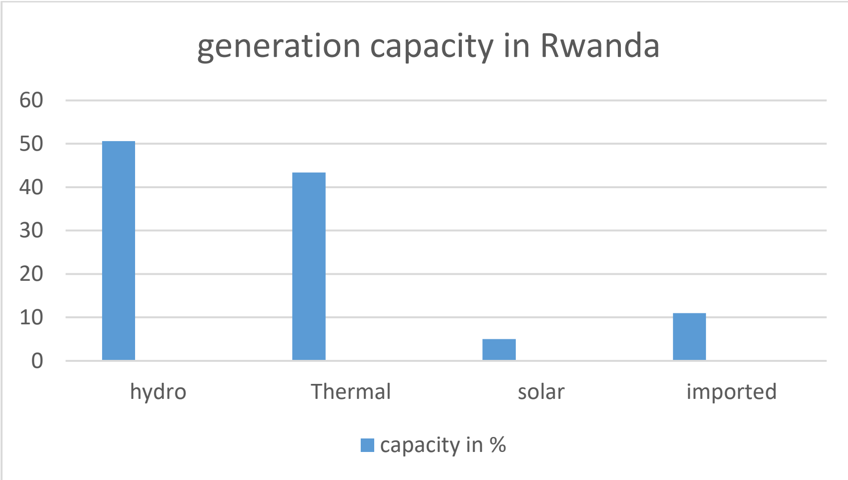

Figure 1.1: generation capacity in Rwanda

With the above chart which show the reason why our electricity cost is high, because the percentage of thermal generation is still high which include the diesel power plant which use fuel in the production of electricity and in the other side solar power generation is still low and is the cheapest sources of electricity in the world.

With the target of government of Rwanda is to maximize the use of energy generation from solar and minimize the use of energy from diesel power plant, where diesel power plants takes 26.76% of the total electricity generation in Rwanda, this occupied by five plants which located in Jabana 1& 2 and SoEnergy LTD of (Birembo, Kigali special Economic zone and Mukungwa) [2].

With the environmental degradation and the rise in fuel in general all over the world, this cause the governments of Rwanda growing attention and focused on renewable sources of energy mainly solar energy which is the cheapest sources of energy and environmental friendly.

1.2. Problem Statement

In Grid connected solar PV where there is no storage, there is the electricity lost which was already generated and not used because the load is already served during a day and the rest is lost because there is no storage, although there will be the need of this electricity in the time of peak hours and night hours or when there is insufficient sun to power the load.

This lost energy which generated from the PV system and not used if exploited well can help to meet the house demand in night hours, and when there isn't enough sun to feed the house load.

As seen the main problem in grid connected solar PV is the energy generated which is not used and cause the consumers who already have the grid connected solar PV to depend to the grid in night hours, and when there is insufficient sun which cause them to use the power from the grid, although this power is generated by the use of fuel which is costly and make the electricity tariff to raise because of the high demand of consumers and dependability of using diesel power plant in the generation, the dependability of diesel power plant will keep increase as the demand increase but the use of grid connected solar PV will help to decrease the high demand to the grid power because of using own generated power and selling the surplus to the grid to support the other consumers.

1.3. Research Objectives

The aim of this project is to look for the methods to minimize the electricity cost by optimizing the generated energy from the PV system which is not used.

This aim would be achieved through the following specific objectives:

i. To evaluate the generated energy from the PV system which is not used by using the PVsyst software, this is done by calculating the PV system generation capacity minus load demand of the houses and the rest is taken as the lost energy or unused generated energy from the PV system.

ii. Sizing of the battery according to the house load and according to the unused energy generated from the PV system by using HOMER optimizer to get the optimum battery storage.

iii. Connect the optimized battery to the grid connected solar PV system in order to store maximum energy for future use, mainly in time of night hour and when there is insufficient sun.

1.4. Significant of the Study

This study is aimed to reduce the monthly electricity bill for household, this will have an impacts for customers, national grid and even in our environment.

- **For consumer**s: The electricity tariff is very high here in Rwanda at $0.22/kwh compared to the neighbor countries of east Africa at $ 0.10-0.12/kwh [3], the government of Rwanda is trying all possible way to reduce the electricity tariff by increasing the solar energy generation capacity which is still low but is very economical and environmental friendly, hence the implementation of grid connected solar PV at residential house can help to minimize the electricity tariff in Rwanda by minimizing the use of grid power, mainly the power generated from the diesel power plant and maximizing the use of own generated power from the PV system but also generate money by selling the surplus to the grid.

- **For national utility grid:** The solar potential in Rwanda is very high in all parts of the county with an average global solar radiation of 5.15KWh/m^2/day and the clearness index of 0.515 [4] , this is show that Rwanda is a good place for solar energy generation plants. The generation capacity of solar energy here in Rwanda is very low with 5% of total generation mix of the country [5], although the implementation of grid connected solar PV in the residential houses in Rwanda will help in the stability of grid power, means will stabilize the problems of load shedding in time of peak demand, because many consumers will be using their own electricity generated from the PV system and they will be selling the surplus power to the grid.
- **For environment**: The generation capacity of diesel power plants in Rwanda is 26% compared to 5% of solar energy generation [5], this show that we have a problem of air pollution and environmental degradation in general here in Rwanda due to the fuel used in those diesel power plants, although the implementation of grid connected solar PV here in Rwanda at residential houses, will supports the target of Rwanda government to reduce the use of diesel power plants and promoting the use of renewable energy especially solar energy because is the sources of energy which is more economical and environmental friendly.

1.5. Thesis organization

The project is organized as follows: chapter one is an introduction in grid connected solar PV, chapter two is the review of grid connected solar PV which go in deep about electricity situation in Rwanda and the literature about the minimization of electricity cost in general, the methods used to minimize the electricity cost is covered in chapter three, Results and analysis is in chapter four and the last chapter five cover conclusion and recommendations.

CHAPTER TWO

REVIEW OF ELECTRICITY COST MINIMIZATION

In this chapter, review of grid connected solar PV contains the following sub chapters: introduction, electricity situation in Rwanda, electricity price in Rwanda, diesel power plant in Rwanda, solar photovoltaic system, battery storage, related literature on electricity cost minimization, research gap, problem formulation and chapter conclusion

2.1. Introduction

Due to the increase in electricity demand in Rwanda and all over the world, the government of Rwanda take a decision to increase the generation plant of electricity either renewable or no renewable in order to meet the demand.

This program of using all possible way to increase the generation capacity, and many of those way used to increase the generation capacity is at high cost due to the technology used in the generation of electricity, like diesel power plant which use fuel which is very expensive and cause the increases in the electricity cost in general.

The implementation of grid connected solar PV system to the residential house in Rwanda can be a good solution for this problem of electrification and electricity cost in general because it's the cheapest source of energy since it use the natural solar in the generation of electricity.

The solar radiation potential here in Rwanda is between 4.5 kwh/m^2/day and 5.5kwh/m^2/day [6], the capacity of solar energy installed to the grid here in Rwanda is 12.230 MW, coming from five (5) solar power plants with Rwamagana solar plant generating 8.5MW which is the biggest, Nasho solar power plant with 3.3MW, Jali solar power plant with 0.25MW, Ndera solar power plant with 0.15MW and Nyamata solar power plant with 0.03MW [7].

The total generation capacity in Rwanda is 235.6 MW [5], the solar energy on grid connected contribute 5% of this generation, which is very low compared to the diesel power plant which is 26% of the total electricity in Rwanda, although this diesel power plant is the one which is very expensive source of energy since it use fuel in the generation of electricity, and the rise in fuel price cause the increase in the electricity price since the diesel power plant which the fuel occupy big part in the generation of electricity in Rwanda. F**igure.2.1** is the generation mix which show the percentage of generation of each sources of energy.

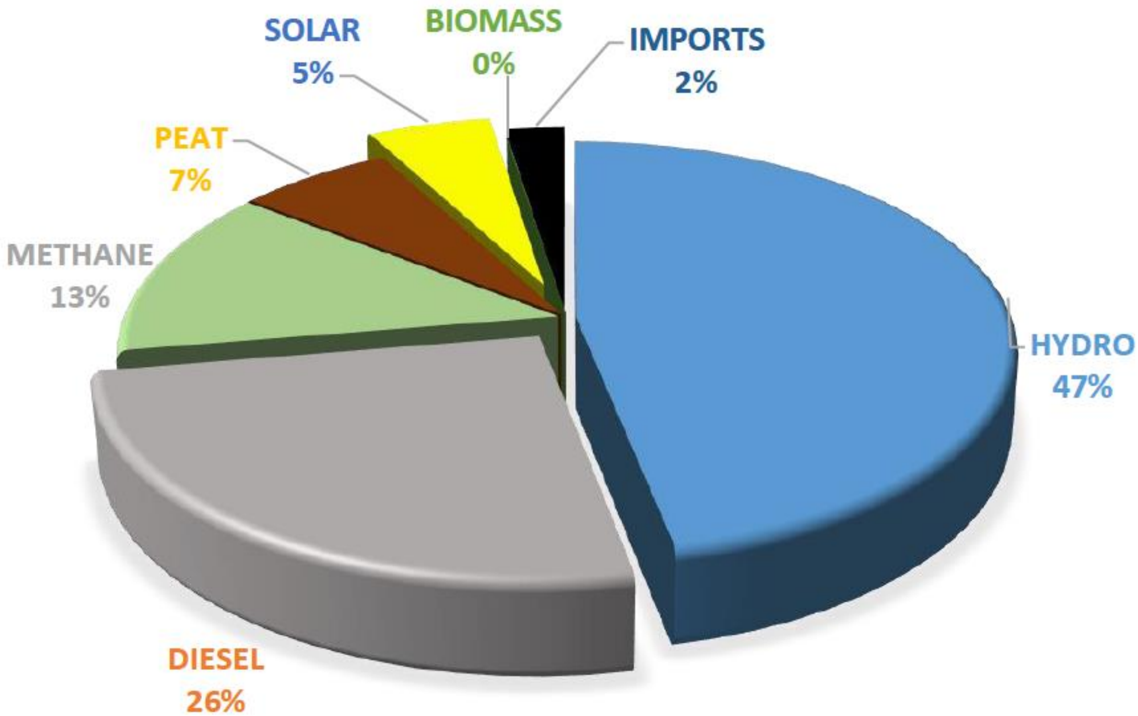

Figure.2.1: generation mix in Rwanda [5]

2.2. Electricity situation in Rwanda

Rwanda is a land-locked country with 26,338 km^2 of area, with a total generation capacity of electricity of 235.6MW from different power plants [8], hydro power plants is the main generation sources of electricity here in Rwanda with 47% of total generation and the diesel power plant with 26% of total generation and solar energy with 5% of the total generation capacity which is equal to 12.230 MW, this 12.230 MW from solar generation is a combination of four solar power plant, 5% of solar generation is very low compared to 26% of the diesel power plants generation which is one of the factors which cause the increase in electricity tariff in Rwanda, because of the increase in price for the fuel used in those diesel power plants [9].

Here in Rwanda we have five solar power plant which connected to the grid but there is no household which use grid connected solar PV, where the individual consumer can use his own generation power from PV system and sell the surplus to the grid or to his neighbors in a system called peer to peer method.

From the report of Rwanda energy situation show that in 2004 [3], the government of Rwanda take a difficult decision in a program they call ‘better expensive energy than none’ in this program Rwanda rented the diesel generators from private companies at high cost and this in addition to the cost of fuel used in those generators, which lead to the increase in electricity price, the price of electricity rise over 100% compared to the price of electricity in the region of east African, where the price of electricity were USD $ 0.22/kwh here in Rwanda, whereas in other countries of the east African region were around US $ 0.10-0.12/kwh [3].

Due to the economic and environmental friendly of renewable energy especially solar energy, the government of Rwanda is encouraging the investors and individual consumers to use the solar energy where the target of Rwanda is to raise the renewable energy sources to 60% in 2030 [10].

2.3. Electricity prices in Rwanda

The price of electricity we use in this research is the real price from Rwanda energy group tariff, we use this price in our calculation to see exactly how much electricity cost for the consumer who use the electricity from grid without using solar energy.

We calculate the monthly consumption according to the proposed house load and proposed monthly kilowatt consumption. T**able.2.1**. Is the electricity tariff according to the range of monthly consumption, at residential houses?

Table.2.1: Electricity tariff in Rwanda *[11]*

Category	**Consumption(kWh) block/month**	**FRW/kWh (VAT exclusive)**
Residential	[0-15]	89
	[>15 – 50]	212
	>50	249
Non **Residential**	[0-100]	227

2.4. Diesel power plant in Rwanda

In the generation capacity of Rwanda electricity , diesel power plant contribute 26% of the total generation, the government of Rwanda is making all the efforts in the energy production development with the aim of reducing the rate of use of electricity generated from diesel power plant in the energy mix in Rwanda. Because it is the most expensive source of power among the other we have here in Rwanda. F**igure.2.2** is the list of diesel power plant we have here in Rwanda and their generation capacity.

Table.2.2: diesel power plant in Rwanda [12]

plant	technology	Capacity (MW)
Jabana 1	Diesel	7.8
Jabana 2	Diesel	20
Mukungwa thermal	Diesel	10
KSEZ Thermal	Diesel	10
Birembo Thermal	Diesel	10

2.5. Solar photovoltaic system

2.5.1. Introduction

Rwanda government have a program to increase the use of solar energy here in Rwanda in order to reduce the production cost caused by other types of generation sources like diesel power plants. Where in 2018 Rwanda signed a memorandum with two companies Mara Corporation Ltd and SB Energy Corporation from Mauritius to develop a solar power of 30 MW capacity with a storage [9], this will make a big contribution to the generation capacity of solar and electricity in general.

With the geographical data show that Rwanda have sufficient solar radiation with a global solar radiation on horizontal surface is between 4.8 kwh/m^2/day and 5.5 kwh/m^2/day which is a good factors for implementation of solar energy plants in Rwanda for the investors and the government [13].

The total grid connected solar power plant generation is 12.230 MW, from five power plant which is Rwamagana Solar Power plant (GigaWatt) is located near Agahozo Youth Village in Rwamagana District was commissioned in 2015, Nasho Solar power plant which commissioned in 2017 with the main purpose was for irrigation and the surplus to light up the surrounding homes, there is also Mount Jali Solar plant which commissioned 2007 and is located at the top of mount Jali in Kigali, the other one is Ndera Solar power plant located in Ndera in gasabo district and nyamata solar power plant located in Bugesera district [7] , this is the five solar plant which connected to the grid. **Table.2.3**. is the list of solar power plant which is connected to the national grid and their capacity of generation.

Table.2.3. grid-connected solar power plant in Rwanda [7]

plant	**Technology**	**Capacity (MW)**
GigaWatt/Rwamagana	solar	8.5
Nasho Solar Power Plant	solar	3.3
Mount Jali Solar plant	solar	0.25
Ndera Solar power plant	solar	0.15
Nyamata Solar power plant	solar	0.03

2.5.2. Operation of grid connected solar PV

A grid-connected photovoltaic system, or grid-connected PV system is an electricity generation from solar PV power system that is connected to the utility grid. A grid-connected PV system consists of solar panels, inverters, a power conditioning unit and grid connection equipment. They range from small residential and commercial rooftop systems to large utility-scale solar power stations. Unlike stand-alone power systems, a grid-connected system rarely includes an integrated battery solution. When conditions are right, the grid-connected PV system supplies the excess power to the grid, after supplying the house load and charge the battery if available [14]. **Figure.2.2**.is the grid connected solar PV configuration, the PV array feed the inverter with DC power and the invert converter the DC to AC and serve the house load and the surplus is sent to grid.

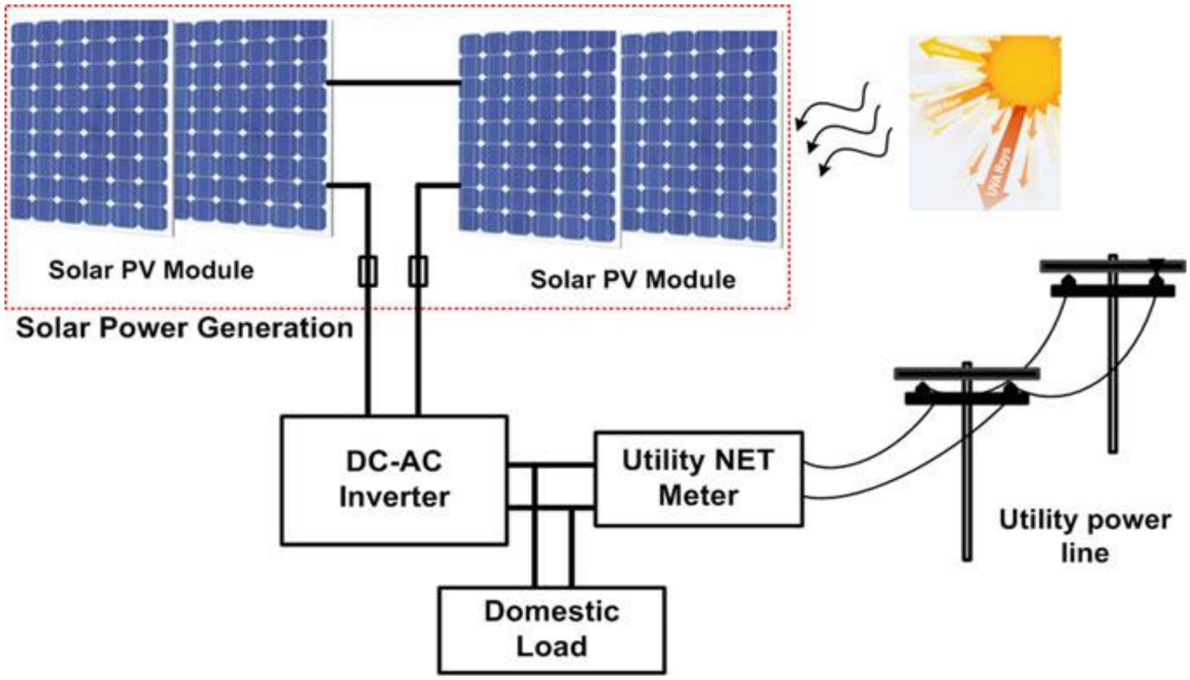

Figure 2.2. Grid connected PV system [15]

2.5.3. Factors that influence the operation of a solar module

The performance of solar module can be affected by different factors namely,

i. **The manufacturing material of the cell**: the materials used in manufacturing of solar cell have a big effects on the performances of solar cells, mainly in the rate of efficiency of light conversion, where the mono crystalline silicon have an efficiency which is between 12% and 18% of conversion of light, for polycrystalline silicon the maximum conversion efficiency does not exceed 12% and for amorphous silicon the conversion efficiency is between 5% and 7%. [16]

ii. **The effect of shading**: the problem of shading is one issue which affects the performance of the solar panel, where a part of module or solar cell module surface is shaded, it affects the output electricity generation, this may cause to partially or not produce electricity at all, and this can be controlled by the help of bypass diodes installation in the system [17].

iii. **The intensity of radiation**: as the intensity of light increase to the module lead to the increase in output power [18]

iv. **The heat effects**: the heat on the module affect the output voltage, because the temperature on the solar cell is inversely proportional to the output voltage, means with the increase in temperature lead to the decrease in the output voltage [19]

2.5.4. Solar energy potential in Rwamagana

Rwamagana district is the place with the solar radiation potential which is high, with the average horizontal radiation of 4.9KWh/m^2/day, this data is the one which help us to know the output power of the solar PV generation.

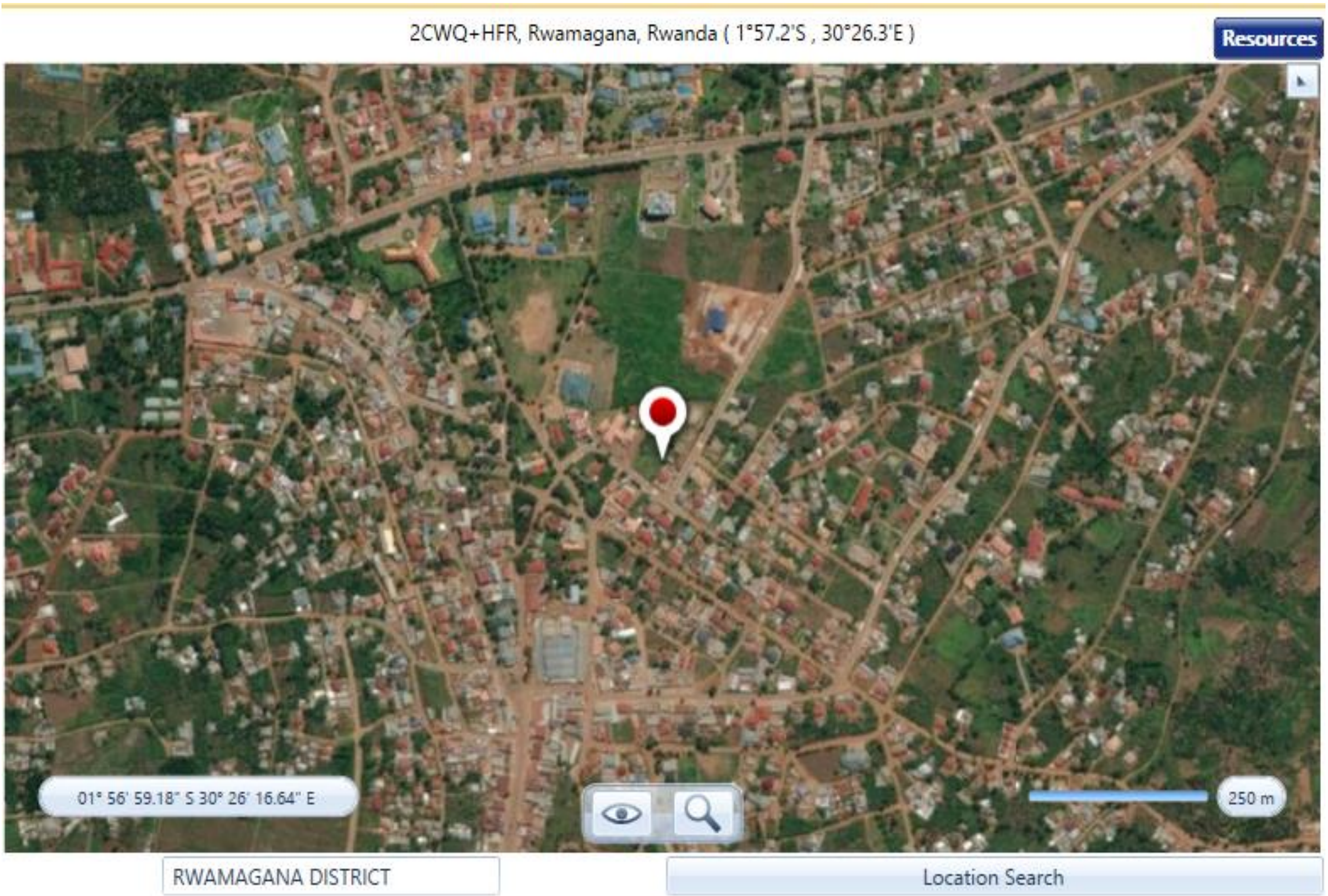

Figure.2.3: geographical map of selected location of Rwamagana district

To know the capacity of solar PV you will use in HOMER software it is better to know the solar radiation data, The information data of solar resource was downloaded from NASA (National Aeronautics and Space Administration) by using the HOMER software, T**able.2.4**. Show the Monthly average daily solar radiation on a horizontal surface of Rwamagana district.

Table.2.4: daily solar radiation and clearness index of Rwamagana district

Month	Clearness Index	Daily Radiation (kWh/m²/day)
January	0.473	4.855
February	0.467	4.914
March	0.459	4.828
April	0.456	4.605
May	0.470	4.452
June	0.552	5.015
July	0.581	5.366
August	0.539	5.271
September	0.507	5.220
October	0.479	5.004
November	0.454	4.664
December	0.471	4.776

These data is annual solar radiation with an average of 4.91 kwh/m^2/day and the clearness index of 0.491 kwh/m^2/day

Clearness index is the ratio of the average monthly of the total daily radiation on a horizontal surface. The global horizontal radiation **figure.2.4** In Rwamagana district show that the months with high radiation and clearness index is from June to August and the lowest is from April to May.

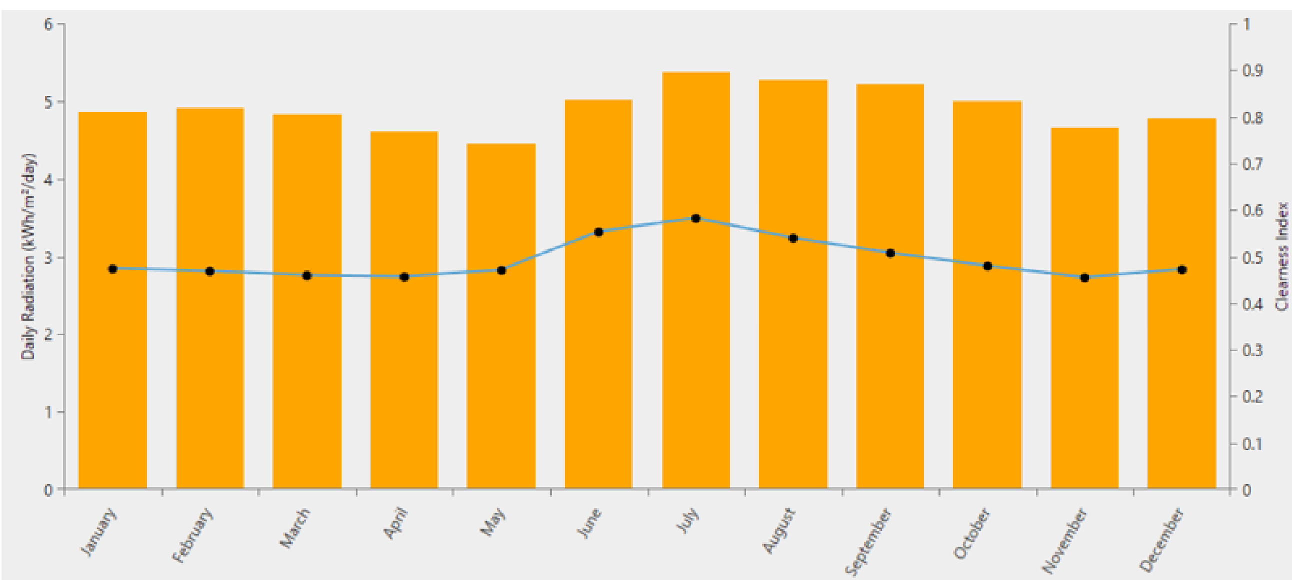

Figure.2.4: Daily radiation and clearness index in Rwamagana district in kwh/m2/day

2.6. Battery Storage

The storage in the grid connected solar PV system help in storing the energy produced from the PV system for future use, hence reducing the dependability of the customer to the utility grid, this help the consumer to save the money would be used to buy the electricity from the grid when the consumer haven't the storage battery in the system.

The commonly used types of batteries is the Lithium batteries which differ from their efficient and the depth of discharge [20], for lead acid batteries have the depth of discharge of 50% and the efficient which is between 80-85% and this type of batteries is recommended for the user who have the main criteria of cost and the requirement for power is less , whereas the lithium batteries have the efficient which is between 90-95% and the depth of discharge is between 80-90% which is better for the consumer who have the main requirement is the depth of discharge and regular usage of electricity.

The depth of discharge is define as the actual amount of the energy that can be withdrawn from the battery.

The selection of the batteries storage is very important, you have to look at the efficiency, daily load usage and battery lifespan.

The factor affecting the battery sizing is: rated battery capacity and battery life, maximum depth of discharge, daily energy demand, days of autonomy and temperature.

Below is the mathematical expression of the battery capacity.

$$C_B = \frac{ElSD}{VB(DOD)maxTcfnB}$$

C_B: capacity of battery [Ah]

E_L: the electrical load [Wh]

S_D: battery autonomy [days]

V_B: storage battery voltage [v]

$(DOD)_{max}$: maximum depth of discharge of battery

T_{cf} : temperature correction factor

ηB : efficient of battery [%]

2.6.1. Types of battery and technology

Table.2.5 is the type of batteries and the technology used in those battery, this is one of the characteristics which help in the selection of the battery when you are going to buy to the markets.

Table.2.5: technology considered in different types of batteries [21]

Type	Technology
Flow	Vanadium Redox (VRFB)
	Zinc Bromine (ZnBr)
High Temperature	Sodium Nickel Chloride (NaNiCl)
	Sodium–Sulphur (NaS)
Lead-Acid	Flooded Lead Acid (Flooded LA)
	Valve Regulated Lead Acid (VRLA)
Li-Ion	Lithium Iron Phosphate (LFP)
	Lithium Titanate (LTO)
	Nickel Cobalt Aluminium (NCA)
	Nickel-Manganese-Cobalt / Lithium Manganese Oxide (NMC/LMO)

2.6.2. Parameter of different battery according to the manufacturing technology

Table.2.6. is the technology parameter which show the cycle life of the battery, the cycle life of batteries is the number of charge and discharge cycles that a battery can complete before losing it performance. The cycle life of Li-ion batteries is affected significantly by the depth of discharge. The depth of discharge is the amount of battery's storage capacity that is utilized.

The battery round-trip efficiency is the round trip DC-to-storage-to-DC energy efficiency of the storage bank, or the fraction of energy put into the storage that can be retrieved.

Self-discharge is a phenomenon in batteries in which internal chemical reactions reduce the stored charge of the battery without any connection between the electrodes or any external circuit. Self-discharge decreases the shelf life of batteries and causes them to have less than a full charge when actually put to use. With the **table.2.6** VRFB is the one with the highest cycle life of 13000, and the one with the highest self-discharge is znBr flow battery which is 15%.

Table.2.6.technology parameter of different battery [22]

types	technology	Round-trip Efficiency (%)	Cycle life(equivalent Full-cycles)	Depth of discharge (%)	Self-discharge(% per day)
flow	VRFB	**70**	**13000**	**100%**	**0.15**
	znBr	**70**	**10000**	**100%**	**15**
High temperature	NaNiC1	**84**	**3000**	**100%**	**5**
	NaS	**80**	**5000**	**100%**	**0.05**
Lead acid	**Flooded LA**	**82**	**1500**	**50%**	**0.25**
	VRLA	**80**	**1500**	**50%**	**0.25**
li-Ion	**LFP**	**92**	**2500**	**90%**	**0.1**
	LTO	**96**	**10000**	**95%**	**0.05**
	NCA	**95**	**1000**	**90%**	**0.2**
	NMC/LMO	**95**	**2000**	**90%**	**0.1**

2.7. Related literature on electricity cost minimization

In July 2020, Laurentiu-Mihai Ionescu, Nicu Bizon , Alin-Gheorghita Mazare and Nadia Belu in their research named “Reducing the Cost of Electricity by Optimizing Real-Time Consumer Planning Using a New Genetic Algorithm-Based Strategy”, [23] in this study their aim was to ensure the use of energy produced from renewable energy sources in order to reduce the electricity costs with the methods of planning of how to use the conventional sources of energy and renewable energy, the proposed planning method they use to achieve the aim of reducing the electricity cost was based on the genetic algorithm approach, which solves a cost minimization problem by considering several input parameters. These input parameters are: the consumption for each unit, the time interval in which the unit operates, the maximum value of the electricity produced from renewable sources, and the distribution of energy production per unit of time. In their research they show that One consumer can use the equipment without any planning, in which case he will consume energy from utility companies or energy produced from renewable sources, if it is available at the time he operates the equipment but the other consumer who plans his operating interval can use more energy from renewable sources because the planning is done in the time interval in which the energy produced from renewable sources is available, in their research they show that the consumer with planning methods will save more energy bill than the ones who operate without planning, means that the total cost of energy to the consumer without any planning will be higher than the cost of energy to the consumer with planning, because the energy produced from renewable sources is cheaper than that provided from conventional sources. But the problem or gap of this study is the way the consumer use his own electricity and equipment according to the time the renewable source is available, means here the consumer target the time the renewable source is available and start to operate his own activities, there is a lack of freedom in the use of his equipment, means he don't do things as he want, he do things depend to the availability of renewable sources, even this system help in reducing the electricity cost but the owner of the system will still use the grid power in time of peak hour and in the night hours which will cause the high demand to the grid and hence the utility operators need to switch ON other power plants which use diesel and is very costly.

In 2012 N. F. Hamidi, M. P. Abdullah, M. Y. Hassan, F. Hussin in their research named "Load Shifting and Retrofitting Strategy for Reducing Electricity Bill in Malaysia" [24] the aim of this researchers was to reduce the monthly electricity bill by using the methods of load shifting and retrofitting strategy, where the consumer can reduce their electricity consumption by replacing their current electrical equipment with energy saving ones, this strategy is known as retrofitting, which requires financial investment. Another strategy that is costless and can be effective is load shifting. It can minimize the maximum demand charge by simply shifting the consumption into another period.

In this research they evaluates the two strategies in terms of their ability in reducing the electricity bill of commercial consumer under Malaysia electricity tariff structure. This study explores the possibility of implementing Demand Side Management strategies to reduce the electricity bill, where retrofitting strategy require additional investment in the equipment in order to replace the old ones with the energy saving equipment's, whereas load shifting is defined as the process of shifting loads from peak periods to off-peak periods. The reason for this is to take advantage of the difference in electricity price between peak-hours and off-peak hours. Load shifting is considered as an easy method in achieving load reduction because it only involves proper time and usage management, where operations that are normally carried out at a certain hour, are put off or postponed to a later point in time. For most business and commercial electricity consumers, load shifting is performed by shifting their operations to night time. Thus, the total electricity consumption will be charged based on off-peak tariff which is much cheaper than the peak tariff. They conclude this research by showing that load shifting strategy offers higher savings on electricity bill than retrofitting strategy since load shifting only require the consumer to shift the load from peak hours to off-peak hours where the electricity bill is low, in this study they prefer to use load shifting than retrofitting strategy even if is cheaper than retrofitting strategy it has two problems, one is the methods of using conventional energy which is normally expensive than the use of renewable source of energy, the second gap of this study is that this method dictate the consumer to shut off his equipment or operations for another time where the electricity cost will be low, which is not good for the user who want to use his own equipment freely.

In 2017 Suresh Choudhary, Srijit Saha, Sheryl Jacob, Sai Ikshith and Mohini Kher in their research named "reduction of electricity bill with stand-alone solar PV system" [25] the main aim of Demand Side Management (DSM) is to encourage the consumer to minimize the energy usage during the peak hours or to shift the time of energy use to off-peak duration. There is one more way to perform the energy demand management at residential stage using renewable energy sources such as solar photovoltaic (PV) power or wind energy. In this paper demand side management (DSM) is carried out using solar PV and energy storage system for managing the electricity charges corresponding consumption of units. Centralized generation has bulk power generation and it requires transmission and distribution network for supplying power to the consumer. Whereas distributed generation helps to enhance a demand side management, as the energy generated from these sources can be stored in the storage devices and can be utilized during peak hours. The aim of the present study is to develop a solar PV system for residential load that will reduce the electricity bill using light and fan load of house during non-sunshine hours. In this study selection of proper battery, DC-DC converter, and panels for residential load such as fans and lights was proposed. In this study they conclude that, during the peak hour, the supply from the grid can be utilized to run the power devices and the battery storage will be used to supply the lighting and the fans during peak load, which will save the high bill during the peak hours, in this research the gap is the time of battery discharge, means there is some times where the battery will discharge and the consumer will need the power from the grid to run his equipment and this is where he will use the normal power as the who are not using the system, and the other gap in this study is the time the battery will be full charged and the consumer is not using his load, here the energy produced by the PV panel will be lost for nothing although this power would be needed in the other time.

In 2012Aditya Mishra, David Irwin, Prashant Shenoy, Jim Kurose SmartCharge and Ting Zhu "Cutting the Electricity Bill in Smart Homes with Energy Storage "in this research they encourage the Market-based electricity pricing provides consumers and opportunity to lower their electric bill by shifting consumption to low price periods. In this paper, they explore how to lower electric bills without requiring consumer involvement using an intelligent charging system, called Smart Charge, and an on-site battery array to store low-cost energy for use during high-cost periods. Smart Charge's algorithm reduces electricity costs by determining when to switch the homes power supply between the grid and the battery array. In this research they propose Smart Charge, an intelligent charging and discharging system that determines when and how much to store low-cost energy for use during high-cost periods based on expectations of future demand. Smart Charge's primary benefit is that it does not require consumers to alter their electricity usage to reduce their electric bill under market-based pricing plans. Instead, Smart Charge reduces costs by determining when to switch a home between using (and storing) grid power and using previously stored power from a battery array. They conclude their study by saying that combining Smart Charge with market-based pricing is capable of reducing electricity costs for consumers over the short- and long-term. Over the short-term, consumers save by storing energy during low-cost periods for use during high-cost periods. Over the long-term, as Smart Charge penetration increases, average prices will fall due to significant reductions in peak demand, in this study they do a good proposal of using smart charge but the problem which is in this study is that they use the power from the grid to charge the battery which is costly and the other problem in this study is that they didn't consider the discharging of battery in time of high demand where they would need to charge again the battery when they are still in time of peak hours which would also cost them the electricity bill at high rate [26].

Ali Al Maqousi, Tatiana Balikhina, AbdElkarim AlBanna in 2015 in their research called "Smart Home Algorithms to Control and Reduce Electricity bill at Residential Buildings" they presents the work to build a software system that could be used to monitor and control home appliances. The proposed system is software that can be used by any residence (user) to make control on the electricity bill value; this control can be done by limiting the electricity consumption to an upper limit while preserving user's comfort. The main objective of the system is to reduce the electricity bill of residential buildings while preserving user's comfort, in this study their aim was to reduce the electricity bill by controlling and monitoring the user consumption by providing some information on which appliance is consuming high electricity and the software help in controlling this high rate of consumption, this paper show the objectives of reducing the electricity bill by the method of monitoring and controlling, but it don't show how the electricity lost can be controlled and the other one it use totally the power from the grid instead of using the renewable energy which is totally cheap[27].

2.8. Research gaps

The authors described in the literatures their aim was to minimize the electricity cost at residential houses but I didn't see the one who write about the feasibility of grid connected solar PV at residential houses here in Rwanda, grid connected solar PV at residential houses is not yet implemented here in Rwanda.

The authors didn't consider the unused generated energy from the PV system caused by the lack of storage system to store the generated power from the PV system, that's why I come up with the method of adding the optimized battery storage to the grid connected solar PV system in order to minimize the electricity bill for the user of grid connected solar PV by storing the maximum energy would be lost because of the lack of storage facilities.

Even if in the other literature they talk about the methods of reducing electricity cost, but The geographical data in Rwanda is different from the other place where the researchers consider as their research study, that's why I need to look for the feasibility of grid connected solar PV at residential houses here in Rwanda.

2.9. Problem formulation

With the grid connected solar PV, here we will be having three sources of electricity the consumer can use , one from the grid , the other from the solar PV and the one which stored in the battery.

But also the energy from the solar PV have three option to be consumed, one is used by the consumers directly, the other one is charging the battery and the rest is selling back to the grid through the surplus power.

Hence below is the formation of the problem, with the input

- Average electricity demand at each hour by residential users (Dt)
- Electricity cost at each hour (Ct)
- Available solar energy for each hour (kWh/m^2) for the solar panels (St)
- solar panel efficiency in converting solar irradiation to power (PVeff)
- battery charge and discharge efficiency, (Beff)

Variables we will use in this system

- Gt: power used from the grid
- PVsize: size of the solar panels in square meters.
- Bsize: size of the battery bank in maximum storage (kWh).
- PCt: flow of power from solar panels to the battery bank.

- Bt: battery power discharge
- Pt: flow of power at each hour from the PV to directly support the load.
- Lt: extra energy that gets lost because of the limitation in the size of the battery bank or low electricity demand.

From the Figure.3.3 The electricity come from three sources solar panels, battery bank and utility grid. Hence the average electricity demand of the system should be equal to the sum of all three source, (battery power, solar panel power and power from the grid)

$D_t = G_t + B_t + P_t$ ……… (1)

For the energy produced by the solar panels is divided into three parts, one to feed the load (P_t), the other to charge the battery (PC_t) and the rest for lost power in case the load is being feed and the battery is at maximum (L_t).

Size of the solar panels and solar energy irradiation and efficiency is equal to the energy produced by the solar panels

St *PVsize = Pt + PCt + Lt …………………… (2)

The energy stored in the battery (E_t) is a function of input energy in the battery minus the output energy in the battery at period of time.

$$E_t = E_{t-1} + B_{eff} * PC_{t-1} - B_{t-1} + E_0 \Longrightarrow E_t = \sum_{i=1}^{t-1} (B_{eff} * PC_i - B_i) + E_0 \dots\dots\dots \ (3)$$

Where B_{eff} and E_0 is the battery efficiency and initial energy stored in the batteries

- **Objective function:** Here we consider the electricity cost for the period time (t) ,real time price of the electricity and the energy absorbed from the grid at each time, will be:

$$C = \sum_{i=1}^{t} (G_t * C_t) \dots\dots\dots \ (4)$$

Let combine **equ. 2 and 1** to reach to our objective of minimizing the electricity bill for a specific period of time

$G_t = D_t - PV_{size} * S_t + L_t + PC_t - B_t \dots\dots\dots$ (5)

Hence we need to minimize this objective function below:

$$C = \sum_{i=1}^{t} ((D_t - PV_{size} * S_t + L_t + PC_t - B_t) * C_t) \dots\dots\dots (6)$$

- **So the constraints in our equation is:**

Grid: grid power Gt, we assume that is always greater than zero ($G_t > 0$), hence the energy from solar panel will feed the load or charge the battery, so the **equ 5 become:**

$$D_t - PV_{size} * S_t + L_t + PC_t - B_t \geq 0 \dots\dots\dots (7)$$

Batteries: the value of energy stored in the battery is always greater than zero, so the constraint becomes:

Let consider **equ 3 we get:**

$$\sum_{i=1}^{t-1} (PC_i - B_i) + E_0 \geq 0 \Rightarrow B_{eff} * \sum_{i=1}^{t-1} PC_i - \sum_{i=1}^{t-1} B_i \geq E_0 \dots\dots\dots (8)$$

Size of the Battery Bank: the size of the battery and the energy stored in the battery, this energy stored in the battery cannot exceed the maximum capacity of the battery bank. Hence this cause the constraints to become for the **equ 3:**

$$E_t \leq E_{max} \Rightarrow B_{eff} \sum_{i=1}^{t-1} PC_i - \sum_{i=1}^{t-1} B_i \leq E_m ax - E_0 \dots\dots\dots (9)$$

Battery Discharge: the battery energy discharge for a discrete period of time can’t be great than the available energy stored.

Considering **Equ.3** to get the following constraint:

$$B_t \leq E_t \Rightarrow B_t \leq B_{eff} \sum_{i=1}^{t-1} PC_i - \sum_{i=1}^{t-1} B_i + E_0 \dots\dots\dots (10)$$

For discharge rate has no constraint we practically consider this one.

Hence with the above equations show that the owner of grid connected solar PV have three option from three sources, and the control and choice of using those three sources of power is all based on economic benefits of consumer.

So with the objective of minimizing the electricity bill of the consumer, the system should be controlled so that, the first priority is to use the energy generated from the solar panel to feed the load, to charge the battery and sell the surplus if is the right time and there is enough generated power.

The second option, is in night hours or when there is insufficient sun, the consumer will feed the load by using the power stored in the battery (the discharge of battery), the rate of discharge will be depend to the capacity of the load and the size of the battery.

The third option is when the there is insufficient power from the panel to feed the load and the stored energy in the battery is full discharged, hence this is the time the consumer will start to use the grid power and the electricity bill start to count depend to the kilowatt-hours of grid power used, but this is used in few period of time since it happen in few period of night hours.

2.10. Chapter conclusion

Economically It has seen that the use of grid connected solar energy without storage battery is not sufficient since there is unused generated power from the PV caused by the lack of storage, but the use of grid connected solar PV with battery is viable solution which can help the consumer to store the energy and hence minimize those losses in the system. This research will look for the methods to optimize the generated energy lost in the PV system, this will help the consumer to minimize the dependability to the grid power and maximize the use of own generated power from the PV system, hence the electricity bill will be minimized and the electricity tariff will be minimize because the dependability to the grid power will be minimized and the dependability to the diesel power plants will be minimized.

CHAPTER THREE

METHODS USED TO MINIMIZE THE ELECTRICITY COST

3.1 Introduction

The methods used for this study in order to achieve our objectives is:

- To collect solar data from different institutions and by using homer and PVsyst software to get the geographical data of the selected location.
- To determine the load of the selected house and determine the house demands.
- To determine the monthly unused generated energy in the PV system by using PVsyst software.
- To determine the monthly bill according to the consumption of the consumer, by considering the tariff range from REG Rwanda.
- To determine the total cost of the PV system installation equipment by using homer software and compare with the ones which is not connected to the grid.
- To look for the costs and characteristics of the components which is the input parameters to put in the HOMER software for system modeling and simulation.
- Calculation of net present cost (NPC) and levelized cost of energy (LCOE) for our system.
- Optimization of PV and battery storage using HOMER pro tool.

3.1.1. Data collection

In this research we collect data which is primary data interviewing 80 local households in Rwamagana district about their use of electricity equipment in their home and monthly consumption and also by visiting the official website of the government institution like REG ltd (Rwanda Energy Group) where I get the data for the generation capacity of different plant in Rwanda and the real tariff of electricity, MININFRA (Ministry of infrastructure) , Rwamagana gigawatts after this I look for the secondary data by reading the papers, articles, reports and literature from the others researchers.

3.2. System control

In this study we use two types of dispatch strategies such as load following and cycle charging which we found in HOMER software simulation. In the load following strategy, only PV arrays for the considered system charge the batteries. The load is served by the power stored in the battery or from the grid.

In the cycle charging strategy, the load is first served by PV power generation and excess power from PV arrays charges the batteries and the surplus is sent to the grid. In this study we select to use the cycle charging strategy as the control our system.

3.3. Load characteristics of the residential house

Below is the load characteristics of the house hold, which show us that the high demand is in the time between 18h00 and 22h00 where all the family member will be available at home and using different equipment like television, radio, connecting their cell phones, using laptop, almost all home light is ON and ironing their clothes, whereas in the time between 22h00 and 08h00 is the time with the lowest load, where it's in night and all member of family is sleep they are not using any equipment except fridge and charging the cell phones so the other time is when there is the home activities of preparing the lunch and doing the cleaning at home in the time between 08h00 and 18h00 where the electricity consumption rise again but not much where the activities is the ironing the clothes, watching television, listening to the radio , fridge is always connected and charging the cellphones. F**igure.3.1** is the daily electricity consumption of residential house, where the big consumption is between 18h00 and 22h00.

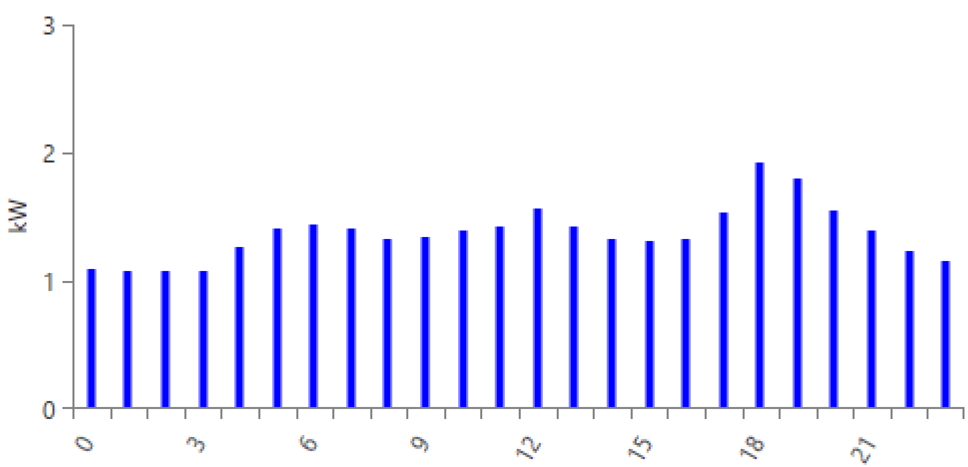

Figure.3.1: load consumption in kilowatts every hour in 24hours per day

3.4. Modeling and simulation software

3.4.1. PVsyst software

PVsyst is the most develop instrument used in the modeling and analysis of photovoltaic solar systems for different applications (grid-connected, standalone, water pumping) [28]. This tool allow the user to use shadow effects as well. A huge database is installed with the tool related to the PV system components that are currently available on the market. It is also possible to perform a detailed economic analysis. PVsyst is a simulation and design software. It is designed to provide easy-to-use ways to develop projects. PVsyst contains a large base of meteorological data for several locations in all countries of the world. You can also manually add measured data to sites that are not in the software. The results are presented in the form of a complete report that includes graphs and tables. This software tool consists of photovoltaic modules, charge controller, inverters and grid interface. [29]

3.4.2. HOMER pro software

The HOMER software developed by the National Renewable Energy Laboratory (NREL) is suitable for carrying out feasibility, techno-economic, optimization and sensitivity analysis of stand-alone and grid-connected renewable energy systems [30]. With the objectives of the study which is to reduce the energy cost by decreasing the use of fuel power plant through minimizing the dependability of consumers to the grid and maximizing the use of solar PV system in grid connected solar PV.

in this study HOMER software used for techno-economic analysis and in the optimization of the system, in order to simulate and do some analysis HOMER software needs the input in order to generate the output or the results, **Figure.3.2.** is the input data in HOMER software and the output results after the simulation, in this research we consider the use of battery storage in grid connected solar PV which will help for the storage of generated power from PV system, so we use HOMER software for simulation and optimization of this system.

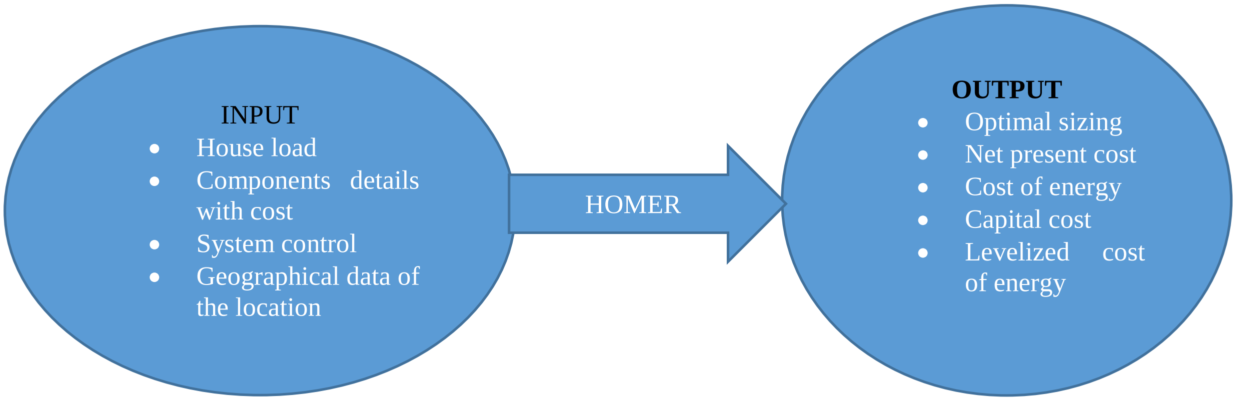

Figure.3.2: Schematic presentation of homer software

3.4.3. Reason for the modeling tools

There are many software tools which used in the study of the renewable energy systems. And they are classified in four categories

RETScreen as a pre-feasibility study software is often used to compare cost and benefits from renewable energy power generation and conventional energy generation projects. The disadvantage of RETScreen is that there is no function for optimization.

HYBRID2 simulation model uses both time series and statistical methods to evaluate the performance of hybrid renewable energy systems. Although this tool has high technical precision in simulation, it cannot optimize the energy system.

TRNSYS is a famous tool for transient simulation of thermal and electrical systems. However the software is not very easy to use, and requires professional technology to use accurately. Meanwhile, it cannot be used for system optimization. It can be seen that RETScreen, HYBRID2, and TRNSYS tools are not suitable for the techno-economic and optimization analysis of renewable power systems.

HOMER pro software uses inputs like meteorological data for selected areas, various technology options, component costs, and load data to simulate different system configurations, and selects the feasible ones according to the total NPC (Net Present cost) and LCOE (Levelized Cost of Energy) as the objective function, Homer is suitable for selecting the optimum system configuration hence is the best for optimization.

3.5. Architecture diagram of the system

The system will be connected so as the PV panel will feed the load and the rest charge the battery and the surplus will be sent to the grid to support the grid.

When there is no availability of the sun, the stored energy in the battery will feed the home load up to the rate the battery will be discharged and start to use the power from the grid.

For our system, the battery sizing and optimization, the full charged battery will be able to feed the home load for the hours the sun is not available and the consumers will depend less to the utility grid.

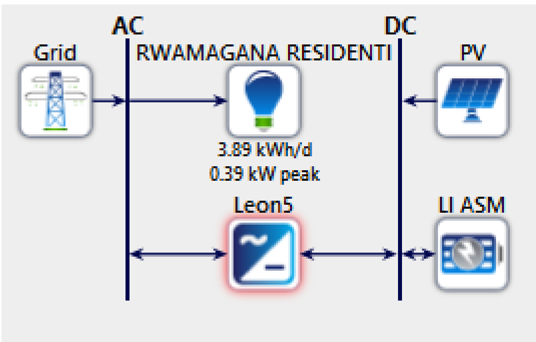

Figure.3.3: architecture diagram of grid-connected solar PV with battery storage.

3.6. House load estimation

With the geographical data of the selected location which show that there is enough solar radiation, we need to estimate the load of the house with full equipment in the house, and calculate the required PV system and battery storage size.

Here we do the interviewing questions for the 80 households in Rwamagana district, where we arrange those households in three different level according to the electrical equipment they have in their house. First level we call it low income family where they have the light and radio only, the second is medium income family where they have light, radio, cellphone and TV and the third is rich family who have all like medium but in addition with fridge, iron, laptop and sometimes cookers.

After our study for 80 household, we do an average of monthly load, **table.3.1** is the house load estimation of an average rich family which equipped with 7 fluorescent lamps, one fridge, one iron, TV, two cellphones and Radio. We see that the peak hour is in the evening hour of the day where all the family member are coming from the work in order to take a rest at home watching TV, charging the cellphones and listening to the radio and not forget that it's the time almost all the light will be ON. For the case of refrigerator we consider that it will run 24 hours per day but with a compressor which will run 8 hours ON, this implies that this refrigerator will consume the power for a duration of 8 hours. Table.3.1. is the estimated equipment of the house with the corresponding power consumption.

Table.3.1: watt-hours consumption of homes equipment

No	Equipment	No of equipment	Power (watts)	Total Power	Hours/day	Watt-hours/day
1	Refrigerator	1	130	130	8	1040
2	Iron	1	1000	1000	1	1000
3	LED TV	1	80	80	5	400
4	Cellphones	3	5	15	3	45
5	Radio	1	5	5	8	40
6	Fluorescent Lamps	7	14	98	8	784
7	laptop	1	100	100	2	200
TOTAL						3509

Above table is the possible equipment of rich families can possessed according to their daily needs, whereas the low and medium income families they have only light bulb, TV, cellphones and the radio for information.

According to the interviewing of 80 households, the results show that the peak demand of those households is between 18h00 and 22h00 where all the equipment will be required for use.

3.7. Modelling and optimization

In this study we have used two software, the HOMER pro which help in the economic optimization of the battery storage by using levelized cost of energy, the other one is the PVsyst which used to calculate the energy generated from the PV system which is not used, in order to look for an optimum operation of the grid connected solar PV, which help the consumer to operate his system with the maximum use of his own generated power and less dependability to the grid.

The optimization model used in this study help for the evaluation of the optimum operation of the grid connected solar PV was done by the help of the HOMER software.

Optimization and comparing different technology used in storage for the case of grid connected solar PV by using levelized cost of energy in an optimization tool called HOMER pro.

We have used levelized cost of energy to compare different size of battery technology by using HOMER pro to optimize and compare the best battery for the system.

After knowing the total load of the selected house, we have done the calculation of the energy generated by the PV which is not used either for the consumer with optimized battery and without the battery by using the PVsyst software.

In this study we look at two scenarios with the same load, where the first scenario is the grid connected solar PV without storage battery and the second scenario is the grid connected solar PV with storage battery. To clarify the economic benefit of the consumer, the comparison of both scenario was performed, and the analysis of kilowatts of electricity injected to grid per months was done, as well as the analysis of electricity generated from the PV system which is not used was analyzed in this research by the help of PVsyst software. The simulated results of the Techno-economic analysis of this study is in chapter four.

CHAPTER FOUR

RESULTS AND ANALYSIS

In this chapter, we discuss the system modelling and the obtained results after the simulations from PVsyst software and homer software, hence we have done the economic and technical analysis of the system.

4.1. Technical analysis

In this part we look at the lost energy in the system, means the energy generated by the PV system which is not used and the dependability of the consumer when the grid connected solar PV is equipped with battery and no battery.

We simulate the model in grid connected with no battery and after we simulate after adding the battery, in order to see the energy generated by the PV system which is not used in those two cases of battery and no battery to grid connected solar PV.

And also we analyses this two scenario of grid connected solar PV configuration with battery and no battery according to the amount of energy injected to the grid, to see exactly the best configuration we can choose which inject much energy to the grid and with minimum energy lost.

4.1.1. Scenario I: Grid connected solar PV without storage battery

After the simulation results in table.4.1. Show that the high amount of energy injected to the grid is in July where it injects the amounts of energy which is equal to 403.4 KWh and the lowest month of energy injected to the grid is in December where the system inject the energy which is equal to 277.3 KWh.

Table.4.1: energy injected to the grid, for the grid connected solar PV without battery.

Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_Grid kWh	PR ratio
January	157.6	74.24	21.22	118.0	112.0	310.4	298.9	0.780
February	138.0	62.69	22.10	111.8	107.0	275.8	265.6	0.731
March	158.4	76.65	21.98	143.9	139.2	345.2	333.0	0.712
April	146.8	69.03	20.66	147.9	143.9	339.9	328.0	0.682
May	154.2	61.43	20.41	168.8	165.1	363.8	351.2	0.640
June	156.1	57.24	19.23	178.0	174.8	383.2	370.3	0.640
July	165.1	65.98	18.57	186.6	182.7	417.2	403.4	0.665
August	159.9	64.21	19.38	168.2	164.3	377.4	364.5	0.667
September	151.9	67.51	19.93	142.8	138.5	333.1	321.3	0.692
October	157.1	76.08	20.99	133.8	128.5	334.7	322.9	0.743
November	144.7	70.25	20.26	113.0	107.6	292.1	281.3	0.766
December	152.4	62.46	21.07	108.7	102.7	288.3	277.3	0.785
Year	1842.3	807.77	20.47	1721.4	1666.2	4061.2	3917.8	0.700

Legends

GlobHor	Global horizontal irradiation	EArray	Effective energy at the output of the array
DiffHor	Horizontal diffuse irradiation	E_Grid	Energy injected into grid
T_Amb	Ambient Temperature	PR	Performance Ratio
GlobInc	Global incident in coll. plane		
GlobEff	Effective Global, corr. for IAM and shadings		

Figure.4.1 is the simulation results in PVsyst software, show that 3189 kWh of energy is injected into the grid annually, and 17.25% of generated power is not used because there is no storage, this 17.25% of 5428 KWh generated correspond to 936.33 KWh annually of unused energy, and this means that is taken as the lost energy after generation.

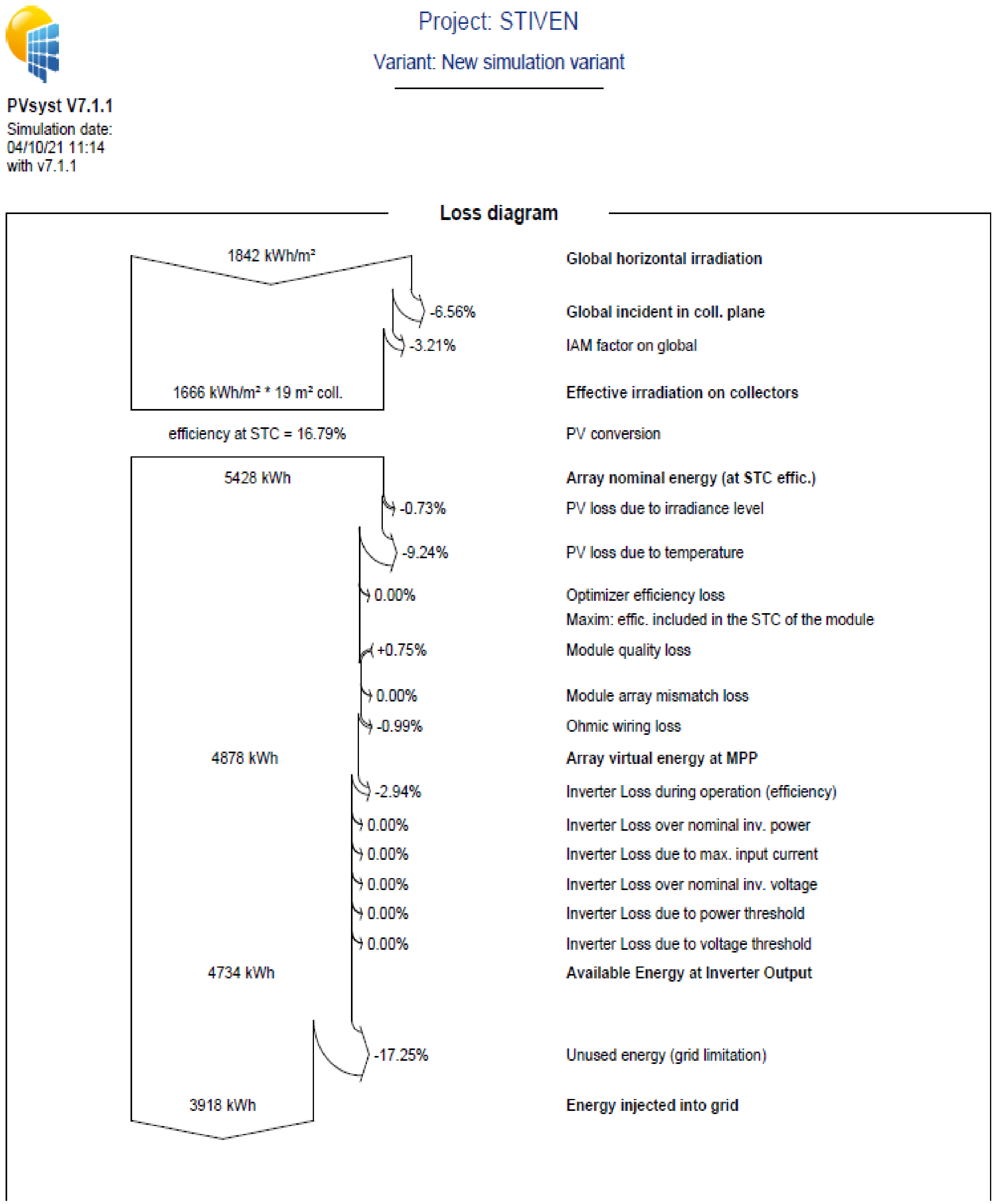

Figure.4.1: unused energy generated from the PV system

4.1.2. Scenario II: Grid connected solar PV with storage battery

Figure.4.2 is the monthly consumption of consumer who use grid connected solar PV with the storage battery, and it show less dependability to the grid and much power used is from the PV system.

Figure.4.2 is the monthly characteristics of the consumer who have grid connected solar PV with storage system, green color is the power consumption from the grid and orange color is the amount of electricity consumption from the PV, Figure.4.2 show that the consumer of this system with storage battery will depends less to the grid and much energy used is from the PV system.

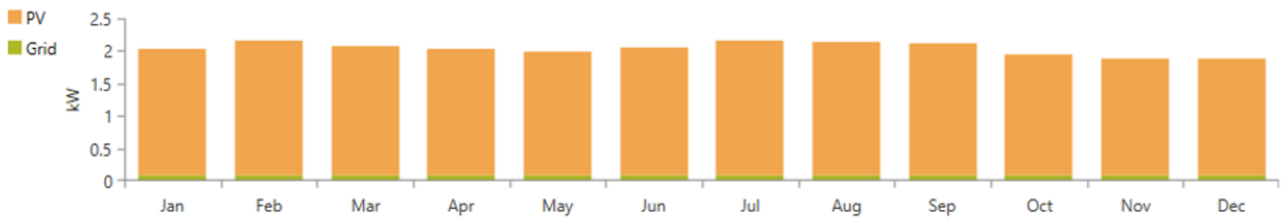

Figure.4.2: monthly consumption for grid connected solar PV with storage.

Table.4.2 show that the highest month the system inject the energy to the grid is in July with 476.7 KWh and the lowest month the system inject the energy to the grid is in December with 292.9 KWh, but because this system have the battery storage has also the power generated from PV system which used to charge the battery for future use.

Table.4.2: energy injected to the grid for grid connected solar PV with storage system.

Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_Grid kWh	EBatDis kWh	PR ratio
January	157.6	74.24	21.22	118.0	112.0	333.1	319.1	21.54	0.832
February	138.0	62.69	22.10	111.8	107.0	313.2	297.5	33.65	0.819
March	158.4	76.65	21.98	143.9	139.2	405.6	375.8	45.32	0.804
April	146.8	69.03	20.66	147.9	143.9	419.0	381.5	56.52	0.794
May	154.2	61.43	20.41	168.8	165.1	475.3	413.0	65.21	0.753
June	156.1	57.24	19.23	178.0	174.8	506.0	435.4	68.82	0.753
July	165.1	65.98	18.57	186.6	182.7	533.1	476.7	77.48	0.786
August	159.9	64.21	19.38	168.2	164.3	477.9	424.4	63.44	0.777
September	151.9	67.51	19.93	142.8	138.5	405.7	370.8	52.25	0.799
October	157.1	76.08	20.99	133.8	128.5	380.2	360.1	39.28	0.828
November	144.7	70.25	20.26	113.0	107.6	321.5	305.6	25.73	0.832
December	152.4	62.46	21.07	108.7	102.7	307.2	292.9	16.71	0.829
Year	1842.3	807.77	20.47	1721.4	1666.2	4877.8	4453.0	565.97	0.796

Legends

GlobHor	Global horizontal irradiation
DiffHor	Horizontal diffuse irradiation
T_Amb	Ambient Temperature
GlobInc	Global incident in coll. plane
GlobEff	Effective Global, corr. for IAM and shadings
EArray	Effective energy at the output of the array
E_Grid	Energy injected into grid
EBatDis	Battery Discharging Energy
PR	Performance Ratio

from the simulation in Figure.4.3 show that the total energy injected to the grid is 4453 KWh annually and the corresponding energy stored in the battery is equal to 13.2% of the 5428 KWh of the generated energy which is equal to 716.496 KWh and this is taken as the profit or gaining energy from the system, where unused power is equal to 3.76% of the total generated power which is equal to 204.09

KWh of energy which is not used after the load is served and the battery is full charged and the surplus is sent to the grid, and the rest is taken as unused energy or simply the lost energy.

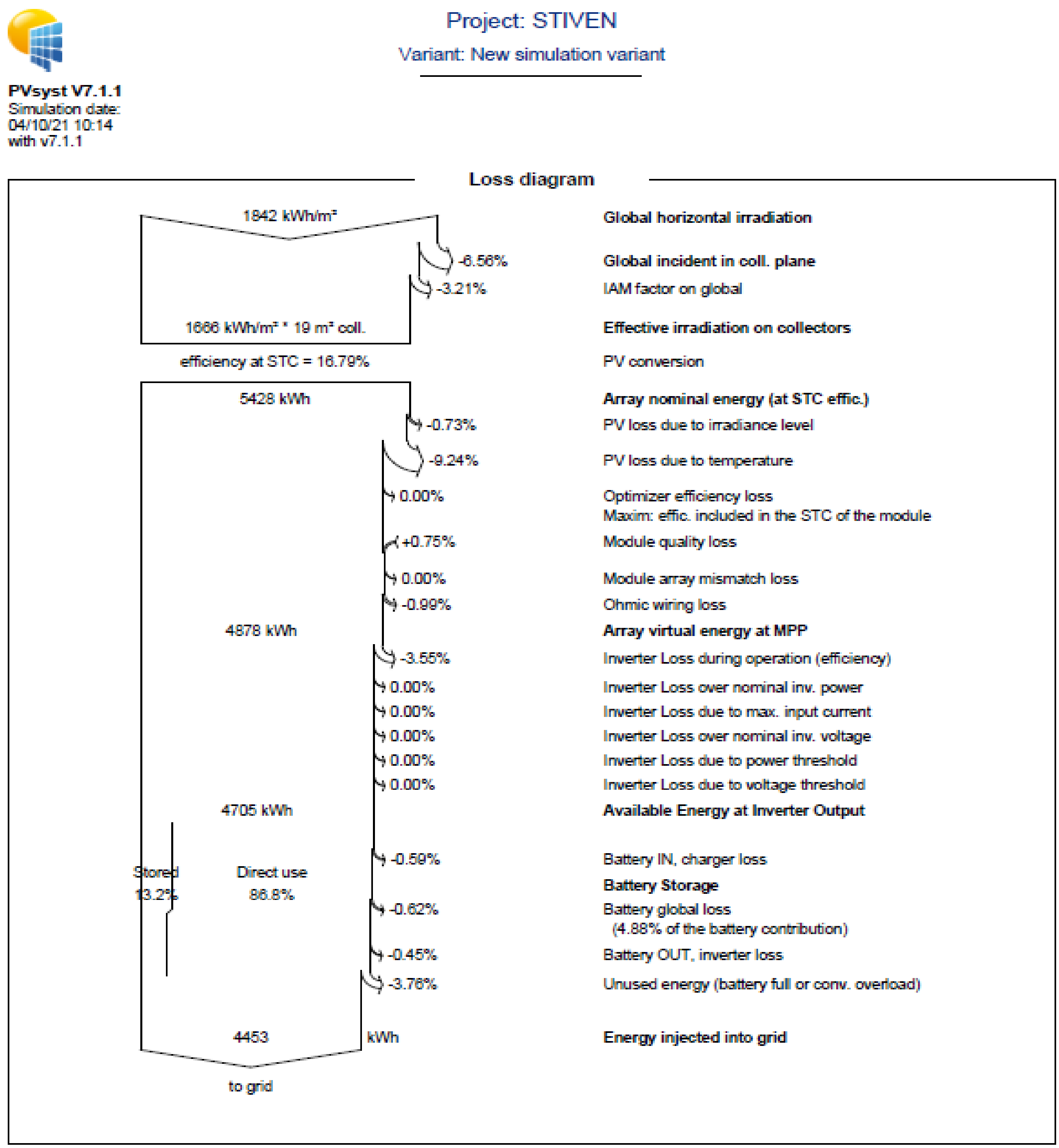

Figure.4.3: unused energy generated from the PV system and stored energy in the battery.

4.2. Economic analysis

In this chapter is the analysis of the system in general and the results obtained from the simulations of the hybrid system in homer software.

In the above chapter 3, the optimization model design that have been used to evaluate the optimum system configuration of the grid connected solar PV system is the hybrid optimization model for electric renewable (HOMER),The results obtained is discussed in this chapter.

4.2.1. Grid connected solar PV system configuration

The figure.4.4 presents the system configuration with the components and the model in HOMER. The system is simulated with possible arrangements for PV system either with storage or no storage, and the other sensitivity values like solar irradiation and financial costs.

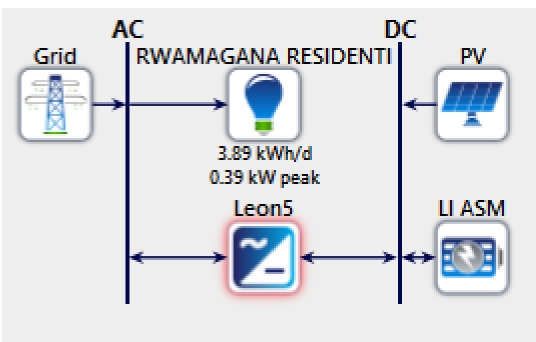

Figure.4.4: grid connected solar PV system configuration

4.2.2. Results of the simulations

Table.4.3 summarizes the results of the system model describing two scenarios, one using grid connected solar PV without storage another using grid connected solar PV with battery storage.

The main criteria we consider in the simulation results is the net present cost and levelized cost of energy for the system with storage and for the system without the storage in grid connected solar PV.

Table.4.3: optimization results of grid connected solar PV configuration with storage and no storage

Export...

Optimization Results

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

Architecture							Cost					System
					PV (kW)	LI ASM	Leon5 (kW)	NPC ($)	Operating cost ($/yr)	Initial capital ($)	O&M ($/yr)	Ren Frac (%)
					12.0		3.00	-$19,841	-$1,741	$2,664	-$1,760	93.2
					11.9	1	3.00	-$18,899	-$1,714	$3,260	-$1,749	93.3

Further description of the results obtained from the above simulation in table.4.3 is below.

- Scenario 1: Grid connected solar PV without battery storage, here the installation cost is very low compared to the second scenario but the LCOE is very low
- Scenario 2: grid connected solar PV with storage battery, here the installation cost is high but the LCOE is very high

For each scenario, we have found the parameters below which help us for further analysis

- Total net present cost (NPC)
- Levelized cost of electricity (LCOE)
- Operating cost of electricity/expenditures (OPE)

4.2.3. Economic analysis of the results

With the table.4.3, show that the total cost of the system which use grid connected solar PV without battery storage is low compared to the system which use grid connected solar PV with battery storage, the homer optimizer show that the difference values is in initial capital which is equal to $2,664 for the system of grid connected solar PV without battery and $3,260 for the system with battery means the difference is $596 which is very low different compared to the energy lost in grid connected solar PV without battery which is equal to 17.25% of the total generating power from the PV system, whereas for the system with battery have a minimum of 3.76% of unused energy.

4.3.Discussion

From the PVsyst simulation results show that the percentages of unused energy generated by the PV system in grid connected solar PV without battery storage is 17.25% of the total generated energy from the PV which correspond to the 936.33Kwh annually, whereas the energy which is not used for the grid connected solar PV with the battery storage is equal to 3.76% of the total generated energy from the PV system which is equal to 204.09KWh annually.

The simulated result from homer pro software, show that the grid connected solar PV system with battery storage have the NPC of $18,898.76 and the initial capital investment which is $3,260 this system can feed the demand at a LCOE of 0.1411$/KWh with 93.2% renewable fraction. Whereas for grid connected solar PV without the battery storage have the NPC of $19,841.22 and the initial capital investment which is $2664, this system with no battery can feed the demand at a LCOE of 0.1478$/KWh with 93.3% renewable fraction.

CHAPTER FIVE

CONCLUSION AND RECOMANDATION

5.1. Conclusions

The solar potential in Rwamagana is very good, with average horizontal solar radiation of 4.81KWh/m^2/day and the clearness index of 0.481, show that is the favorable place for solar PV system implementation.

The simulated results from PVsyst software of grid connected solar PV with and without battery storage show that the unused energy generated from the PV system is very low at 3.76% when using the system with battery storage compared to the system without storage where the loss increases up to 17.25% of unused energy generated from the PV system.

with the system with battery storage, which allow the consumer to store the energy generated from the PV system and hence reducing the energy lost in the system, this will help to maximize the use of own generated power from the PV system and minimize the dependability of the consumer to the grid, hence the demands will be minimized and the owner of the system will sell the surplus to the grid, hence the electricity tariff will be reduced in general due to the minimization of connecting diesel power plants to support the grid in time of peak hours.

The owner of grid connected solar PV will also benefits by using his own generated power without buying the electricity from the utility grid.

For the simulated results from Homer software, show that the initial cost of grid connected solar PV with battery storage is $596 higher than the one without using the battery, but the NPC (net present cost) of grid connected solar PV without battery is $19,841.22 which is much money compared to $18,898.76 of the system with battery.

The system of grid connected solar PV with battery storage can feed the demands at LCOE (levelized cost of energy) of 0.1478$/KWh whereas the one without the battery storage feed the demands at LCOE (levelized cost of energy) of 0.1411$/KWh, it is seen that the best system configuration according to the LCOE is the use of grid connected solar PV with battery storage because it has very low LCOE compared to the grid connected solar PV without battery.

After the results we obtain from different simulations and analysis of those results, we can conclude that grid connected solar PV system with battery storage is an optimum system configuration to optimize the electricity costs by optimizing the generated energy lost in the PV system, this will help the consumer to maximize the use of his own generated power and this will reduce the monthly bill the consumer pay to the utility grid, also with the implementation of this system in residential houses in Rwanda will help to reduce the electricity tariff in general because the dependability of the use of diesel power plants to supports the grid will be reduced after the optimization and maximization of the use of energy generated from the PV system.

5.2. Recommendations

The availability of solar in our country is sufficient, the exploitation of this sources of energy is still low compared to other form of energy like hydro and thermal sources, but solar energy is the cheapest sources of energy in terms of operation cost and maintenance costs, once you install the system you continue using the system freely.

The government need to ease and encourage the investors to invest in the solar energy system, especially to starts connecting the singles houses to the grid, to facilitate the consumer who wants to install the PV system to buy and install the system at favorable price, to facilitate and evaluate the technical condition and right to connect to the national grid for the residential consumer.

In the future when the use of grid connected solar PV is developed it would be better to implement the system of peer to peer in Rwanda which will decrease the dependability of consumer to the grid and increase the amount of power surplus sent to the grid which will help the national grid especially in time of peak hour.

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