DESIGN SIMULATION AND EVALUATION OF PHOTOVOLTAIC PLANT

A THESIS SUBMITTED TO THE GRADUATE SCHOOL OF APPLIED SCIENCES OF NEAR EAST UNIVERSITY

BY
UWINEZA LAETITIA

In Partial Fulfillment of the Requirements for the Degree of Master of Science in Electrical Electronics Engineering

NICOSIA, 2018

Laetitia UWINEZA: DESIGN SIMULATION AND EVALUATION OF PHOTOVOLTAIC POWER PLANT

Approval of Director of Graduate School of Applied Sciences

Prof. Dr. Nadire ÇAVUŞ

We certify this thesis is satisfactory for the award of the degree of Masters of Science in Electrical and Electronics Engineering

Examining Committee in Charge:

Prof. Dr. Mehrdad Tarafdar HAGH	Supervisor, Department of Electrical and Electronics Engineering, NEU
Prof. Dr. Seyed Hossein HOSSEINI	Department of Electrical and Electronics Engineering, TABRIZU
Assist. Prof. Dr. Lida EbrahimVAFAEİ	Department of Mechanical Engineering, NEU

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Name, Last name:
Signature:
Date:

ACKNOWLEGMENTS

I take this opportunity to express my sincere appreciation to my supervisor Prof. Mehrdad Tarafdar Hagh for his guidance and encouragement throughout the course of this thesis and also the staffs of Electrical Electronics Engineering department Near East University, especially my adviser, Dr. Sartan Kaymak and the Head of Department Prof. Dr. Bülent Bilgehan.

To my parents Mukashyaka Dorothee, Kaburame Janvier and my brother Muhawenimana Jean de DIEU, whose constant prayers, love, support, and guidance have been my source of strength and inspiration throughout these years, words alone can't express how grateful I am for the support you gave me.

To my parents…

ABSTRACT

Electric energy production using renewable energy sources (RES) has seen an upscale in recent years because of the numerous advantages of RES; non pollutant, raw materials are free, environmentally friendly and cost efficient. To maximize production and efficiency, types of RES are correlated to geographical locations with abundance of such types of resources.

The goal of this thesis is to design, simulate and evaluate photovoltaic power plant in Rwanda using PVsyst software and the load estimation for the two communities based on the average primary load profile of each categories . According meteorological data, Rwanda has one of the best solar irradiation data in Eastern Africa. Using solar irradiation map, a suitable location is chosen for our plant, calculation of PV arrays and arrangements (series or parallel) are done to determine the right number of panels, to maximize ac power production, and highly efficient inverters are selected. The design data is used for simulation to determine the annual energy production. The simulation will be done for three scenarios; fixed panels, single axis tracking and two axis tracking systems.

Keywords: Design; simulation; evaluation; load estimation; photovoltaic.

ÖZET

yenilenebilir enerji kaynakları (YEK) kullanarak elektrik enerjisi üretimi nedeniyle YEK sayısız avantajları, son yıllarda bir lüks gördü; sigara kirletici, hammadde çevre dostu ve düşük maliyetli, özgürdür. üretimini ve verimliliğini maksimize etmek için, RES türleri kaynaklarının bu tür türlerinin bolluğu ile coğrafi konumlara ilişkilidir. Bu tezin amacı, tasarım simüle ve PVsyst yazılım ve her kategoriden ortalama birincil yük profiline göre iki toplum için yük tahmini ullanarak Ruanda fotovoltaik enerji santralini . Meteorolojik verilere göre, Ruanda, uygun bir konum bizim bitki için güneş ışınlama harita kullanarak Doğu Afrika'da en iyi güneş ışınlama verilerinin birini seçilir etti, PV dizisi ve düzenlemelere (seri veya paralel) hesaplanması AC güç üretimini maksimize etmek için, paneller hemen sayısını belirlemek için yapılır ve yüksek verimli çeviriciler seçilir. tasarım verilerini yıllık enerji üretimini belirlemek için simülasyon için kullanılır. simülasyon üç senaryo için yapılacaktır; Sabit panel, tek eksenli izleme ve iki eksenli izleme sistemleri. Seçilen sitesinde aylık ortalama güneş radyasyonu ve PV sistem bileşenlerinin özellikleri hakkında bilgiler farklı internet siteleri tarafından sağlanacaktır, PVGIS Afrika, farklı kitaplar, bilimsel araştırma makaleleri, dergilerin (Fotovoltaik Coğrafi Bilgi Sistemi). tasarım verilerini yıllık enerji üretimini belirlemek için simülasyon için kullanılır. simülasyon üç senaryo için yapılacaktır; Sabit panel, tek eksenli izleme ve iki eksenli izleme sistemleri. Seçilen sitesinde aylık ortalama güneş radyasyonu ve PV sistem bileşenlerinin özellikleri hakkında bilgiler farklı internet siteleri tarafından sağlanacaktır, PVGIS Afrika, farklı kitaplar, bilimsel araştırma makaleleri, dergilerin (Fotovoltaik Coğrafi Bilgi Sistemi). tasarım verilerini yıllık enerji üretimini belirlemek için simülasyon için kullanılır. simülasyon üç senaryo için yapılacaktır; Sabit panel, tek eksenli izleme ve iki eksenli izleme sistemleri. Seçilen sitesinde aylık ortalama güneş radyasyonu ve PV sistem bileşenlerinin özellikleri hakkında bilgiler farklı internet siteleri tarafından sağlanacaktır, PVGIS Afrika, farklı kitaplar, bilimsel araştırma makaleleri, dergilerin (Fotovoltaik Coğrafi Bilgi Sistemi).

***Anahtar Kelimeler*:** Tasarım; simülasyon; değerlendirme ;ve yük tahmini;fotovoltaik.

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LIST OF ABREVIATIONS

AC: Alternating current

CSP: Concentrated solar power

DC: Direct current

DPVP: Distpachable photovoltaic plants

DVD: Digital versatile disk

GTO: Gate turn off thyristors

LFS: Line focusing systems

LVRT: Low voltage ride through

MPPT: Maximum power point tracking

MW : Megawatt

PFS: Point focusing systems

RPC: Reactive power compensation

SCADA: Supervisory control and data acquisition

SEGS: Solar electric generating system

STATCOM: Static synchronous compensator

SVC: Static volt ampere reactive compensation

THD: Total harmonic distortion

CHAPTER 1
INTRODUCTION

1.1 Introduction

Energy is the principal catalyst required in the socio-economic development of every nation and as such, the lack of this useful commodity can severely hinder its successful development. They are various forms and sources of energy but electric power or energy is the most critical form of energy required as a radical stimulus for rapid socio-economic development of a nation. Some of the methods (not limited to) of generating electric power are by the use of generators, electrochemistry, photovoltaic effects etc. The most common method of generating electric power in Africa is hydroelectric power stations and thermal power plants.

Rwanda is located in central and east Africa and is bordered by Tanzania, Burundi, Democratic Republic of the Congo and Uganda. Rwanda is found in the area described as the region of African Great lakes. The west and east demography's are mostly mountains and savannas respectively; also there are numerous lakes in the country. The population of Rwanda is young and mostly located in rural settings. The capital city of Rwanda is Kigali and the country occupies an area of 26,340Km^2 with geographical co-ordinates 1.9403° S, 29.8739° E. The national population as at 2016 was 11,917,508. The rural population at as the same time was 70% of the national population. The gross domestic product and gross domestic product per capita are $8,376,048,904.58 and $702.84 respectively (Landi et al .,2013).
Rwanda being a third world country in Africa is faced with the challenge of providing cheap, reliable and a well-distributed network of electric power across urban and rural areas of the country. The state of electric power infrastructure is not the best as such a lot needs to be done urgently to improve the generation, transmission and distribution of electric power in Rwanda. There have been numerous government policies and programs to rapidly expand the installed capacity from 45MW of electric energy in 2006 to 563MW by 2018. 70% of the national population should have access to electric power, a plan the government hopes to achieve by 2018 (Nzeyimana , 2003). As part of government' s efforts to increase installed capacity

from 45MW to 563MW by 2018, the rate of expansion has seen a rapid increase between the last five years. Between February and December of 2015, the Rwanda's electric power generation capacity increased from 153MW to 186MW with national peak demand at 105MW(Irechukwu et al., 2017), The generation capacity as at January 2017 is 208MW(Irechukwu et al., 2017) .

Table1.1 shows the various generating components which constitute the installed capacity of electric power in Rwanda. Hydroelectric power provides most of the Rwanda's electricity whilst solar energy provides less than 6% of electric power (Werner et al.,2011)

Table 1.1: Electric power capacity in Rwanda (Werner et al . ,2011)

Name	**Year Installed**	**Capacity MW**
Hydro Power		
Ntaruka Power Station	1959	11.5
Mukungwa Power Station	1982	12
Mukungwa II Power Station	2010	2.5
Nyabarongo I power station	2014	28
Rukarara hydroelectric	2010	9.5
Rusizi I Hydroelectric	1958	30
Rusizi II Hydroelectric	1989	44
Total		137.5
Thermal Power		
Kivuwatt Power station	2015	25
Kibuye Power Plant 1	2012	3.5
Gishoma Thermal Power	2016	15
Total		43.5
Renewable energy (Solar)		
Ngoma Solar Power Station		2.4
Rwamagana Solar Power Stat.	2015	8.5
Total		10.9

1.1 Thesis Problem

Rwanda just like any other third world country faces the enormous challenge of providing electricity to every citizen no matter their location in the country. Statistically 70% of Rwanda's population is of rural setting and these types of communities create problems of the increased cost of transmission and transmission losses.

The national population of Rwanda is 11.92 million (2016) with only 19.80% of the population having access to electricity which means that roughly 10 million of the population do not have access to electric power. The rate of urban electrification is 67% but the rate of rural electrification is an abysmal 5% (Landi et al., 2013).The electric power sector of Rwanda is bedeviled with two principal problems;

a. Short fall in generation i.e. demand far exceeds supply
b. Reduced or poor rural coverage

As part of government's goal of increasing access to electricity, the enormous advantage of solar energy such as non-pollutant, readily available, environmentally friendly and ease of installation can be efficiently tapped to help achieve this goal. As such, this research work seeks answers to the potential of building photovoltaic power plant in the district of Kirehe.

1.2 The Aim of Thesis

The main objective of this thesis is a proposal which seeks to help reduce the electric power deficit of Rwanda thereby increasing socio-economic development of the country. This will be achieved by designing, simulation and evaluation of a photovoltaic power plant using PVsyst software.

Undoubtedly, the use PVsyst software as a tool for solar photovoltaic power plant simulation can be considered a good choice because of its extensive application in research works by academia and photovoltaic industry players. The proposed photovoltaic plant will be situated at Kirehe district, Eastern Province; this is because of the favorable weather conditions for solar photovoltaic park installation

1.3 The Importance of Thesis

The importance of this thesis is to provide an engineering based proposal to help address the deficit in electricity generation in Rwanda. The proposal seeks to provide an advantageous methodology of electric power generation; photovoltaic power plant. When this proposal is implemented, cheap efficient and reliable electric power will be provided to millions of household in Rwanda. This method of electric power generation has several advantages such as:

a. Non pollutant
b. Cost of fuel is eliminated
c. Cost effective maintenance
d. Variety of location for installation
e. Reduced electricity tariffs
f. Payback period is much less-than plant life span

1.4 Limitation of Study

Even though this research was conducted with outermost care, the possibilities of shortcomings and limitations are unavoidable. First and foremost the research was conducted using PVsyst software hence the ability to control the research is limited to the structure of the software. Also the data used is limited to a specific period of not more than 15 years and the data sourcing methodology is satellite -based not ground- based instruments. The performance and efficiency of modules and other components are manufacturer-related problems as such can seriously limit our research. The output of our research is heavily dependent on the weather hence a serious limitation.

1.5 Overview of the Thesis

This thesis is categorized into five chapters:

Chapter 1: Introduction This chapter is made of introduction, Thesis Problem, The aim of Thesis, The important of Thesis and overview of the thesis.

Chapter 2: Solar energy and its application

Explanation of solar energy, history of solar energy, isolation, Photovoltaic system and concentrated solar power are made in this section, also advantages of solar energy is mentioned

Chapter 3: On-grid and off-grid systems Photovoltaic Power Plant Design

Chapter 4: Photovoltaic Power Plant Design

Chapter 5: PV power plant simulation using PVsyst

Chapter 6: Conclusion and recommendation

CHAPTER 2

SOLAR ENERGY AND ITS APPLICATION

2.1 Solar Energy

The Sun is considered to be a black body which produces and radiates enormous amount of energy into the solar system at a speed of 3.0 x 10^8m/s^2 i.e. the speed of light. Solar energy is produced by a method called nuclear fusion where hydrogen gas is converted into helium gas at very high temperatures of between 10^6 to 15^{6} ^{0}C (Nzeyimana ,2003). In an hour, 4.3 x 10^{20} J of solar energy reaches the earth's atmosphere; this amount of energy is enough to support the energy requirements of planet earth up to a year. Solar energy is naturally produced and replenished; thus making solar energy part of renewable energy sources.

In the solar system, planets rotate around the sun and as such, half of the earth is without sunlight at specific times of the year. Solar energy reaches the universe in electromagnetic waves. These waves are differentiated by their spectrum which is the length of the frequency of the waves. The length or range of spectrum determines the magnitude of energy it possesses; Spectrum with shorter wavelength has more energy than spectrums with a longer wavelength. On the earth's surface, only wavelengths ranging from 0.29µm to 2.3µm can be detected (Van Niekerk and Hall ,2013). When the solar energy reaches the earth's atmosphere, the majority are bounced backed into space, green plants absorb some for photosynthesis, solar energy helps in evaporation of water bodies resulting in rainfall, whilst the remaining is unutilized. The unutilized solar energy is enough to provide energy to sustain the ever-increasing energy demands of the world. This can be achieved main by using smart energy harvesting methods and also efficient utilization of energy. Global radiation is the sun's radiation which reaches the earth's atmosphere. It is composed of three parts known as Direct (beam) radiation, diffuse radiation and Albedo radiation. Figure 1.2 shows the global horizontal radiation of Rwanda.

2.2 Brief History of Solar Energy

The background of solar energy can be traced to the inception of the solar system. Energy derived from the sun has been applied to various relevant forms by mankind and nature such as photosynthesis, drying, preserving, illumination, and fire etc. Various researches and studies were carried out in the 18^{th} century to convert solar energy into electricity; notable among them was the discovery in 1839 by Alexander Becquerel, also Charles Greeley Abbott, a French scientist developed the steam engine powered by solar energy (Nzeyimana, 2003). The technology of converting solar energy into electric power by means of photovoltaic panels was birthed at Bell Laboratories in 1954 by the following scientist D.M. Chapin, C.S. Fuller and G.L. Pearson.

2.3 Solar collectors

Solar collectors are devices which absorb the sun's radiations (energy) and converts it into other forms of energy e.g. electricity. Also, solar collectors can be described as the methodology of solar energy harvesting. A typical example is the traditional solar water heater technology found in most homes in Cyprus; which is still being used today but with a touch modernization. The various photovoltaic power systems can be considered as solar collectors.

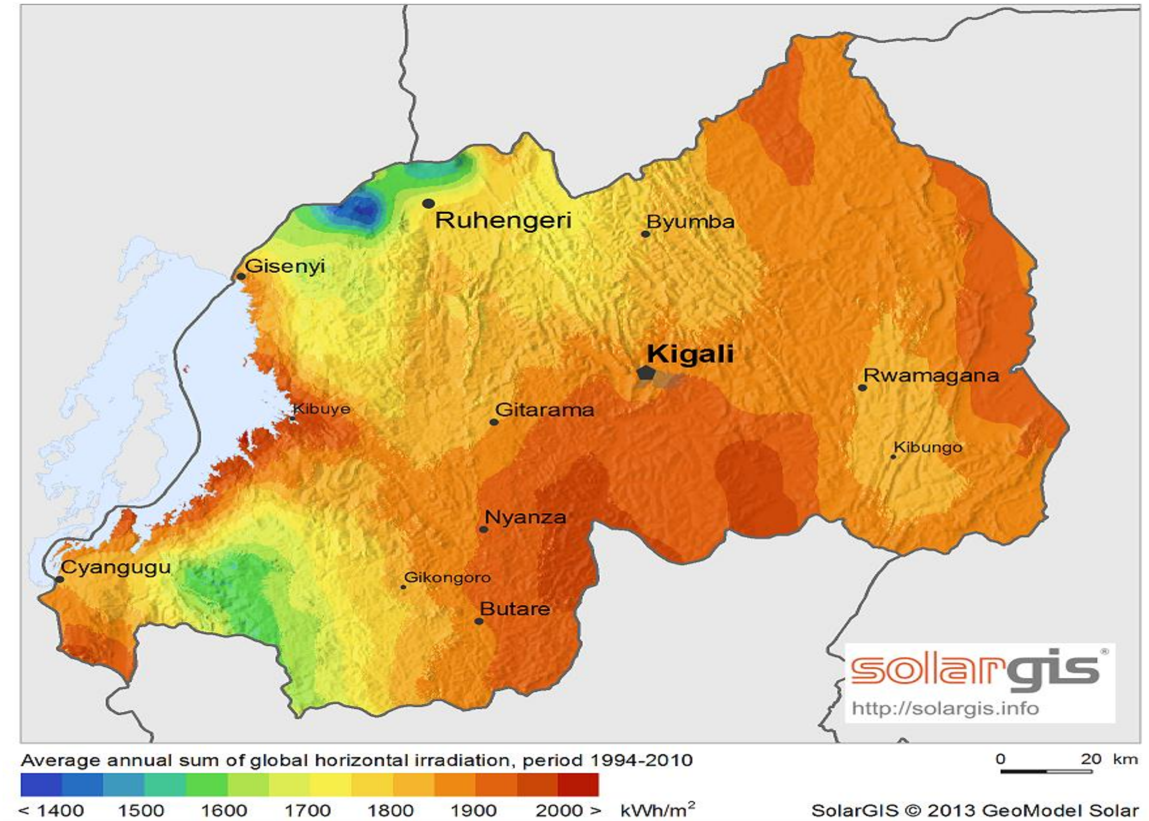

Figure 2.1: Global horizontal radiation of Rwanda (Nzeyimana, 2003)

2.4 Solar Photovoltaic Systems

The word Photovoltaic can be broken down into two parts; photo and voltaic which means light and voltage respectively. Photovoltaic signifies electric voltage caused by sunlight. The photovoltaic system is the conversion of solar energy into electrical energy by using semiconductor cells. Crystalline silicon (SC) is used to manufacture photovoltaic cells from semiconductor materials. CS has numerous advantages such as durable, reliable, noise-free and fuel free material to produce electricity. PV cells have a lifespan of 30 years plus (Goodrich et al ., 2012). Residential.PV cells are formed by the combination of P-type and N-type semiconductor materials separated by junction called p-n junction. Research into photovoltaic technology started over on hundred years ago. Selenium was the first element that has the ability to convert solar into electricity. A scientist Charles Fritts developed the first Selenium based solar electric cell (Goodrich et., 2012).

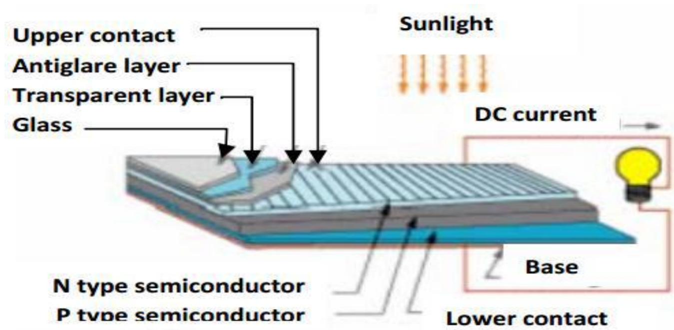

Figure2.2: Typical PV Cell (Goodrich et al.,2012)

2.5 Types of PV Cells

They are 3 basic types of solar PV cells. Silicon found commonly from sand is the main material used in making PV cells. PV cells manufactured from silicon materials can be are arranged into three categories.

2.5.1 Monocrystalline silicon panel

It is the most effective and commonly utilized commercial solar PV cells because of its powerful conversion efficiency of 15%. It requires a small area to produce much power when compared to other cells. Its power production magnitude is four times that of thin film cell having the same cell area and under same weather conditions. Also, it has a longer life span of between 25 – 30 years but has the disadvantage of being much expensive (Goodrich et al.,2012).

Figure2.3: Monocrystalline silicon panel (Guda and Aliyu ,2015)

2.5.2 Polycrystalline silicon Panel

Polycrystalline silicon cells have other names such as poly-Si or polysilicon, multicrystalline. It has a lower efficiency of 13%, cheaper to manufacture when compared to monocrystalline. It requires more space for less power production. Polycrystalline silicon cell produces 130W of electric power using an area of m^2 and $1000W/m^2$ of solar irradiance. It has a shorter life cycle of 20 – 25 years.

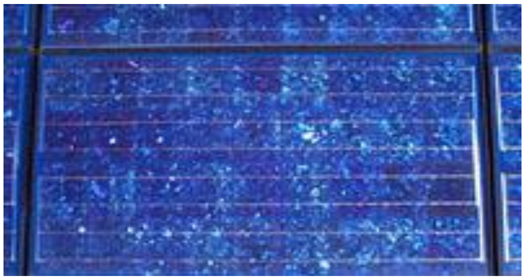

Figure 2.4: Polycrystalline silicon Panel(Guda and Aliyu 2015)

2.5.3 Thin film silicon

The thin film silicon cells are considered to be the subsequent batch of PV cells. It requires less material for its production and consumes less power. Thin film cells are cheaper when liken to crystalline cells. Typical efficiency is about 7% making it the least efficient. It can function perfectly well at lower irradiance, thin film silicon are made from non-crystalline silicon.

Figure 2.5: Thin film silicon Panel (Guda and Aliyu, 2015)

2.6 Photovoltaic System Component

Depending on the type of photovoltaic system or design requirements, a number of components are connected together to constitute PV system. These components are panels, charge controller, inverter, and storage unit (battery). Solar water pumps designed for irrigation purposes not require inverters because the pump uses direct current (dc) power. Also, commercial or grid-connected PV system will require other components such transformers etc. The above-mentioned components are applicable to standalone PV systems which provide electric power for homes and small offices.

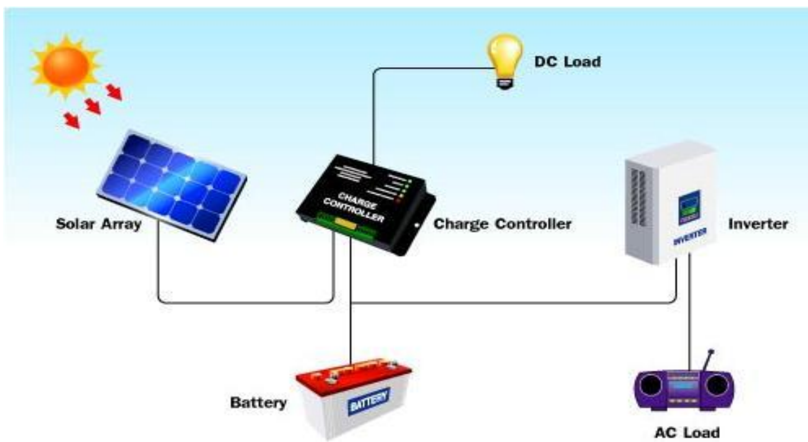

Figure 2.6: Photovoltaic component(Guda and Aliyu, 2015)

2.6.1 Photovoltaic module/panel

The photovoltaic panel is the main device which converts solar irradiance into electric power. The panel is formed by connecting a number of PV cells together. An array is formed when modules are connected either in series, parallel or a combination of series and parallel; these connections are done depending on the required output characteristics. PV systems are usually worked at multiples 12 volts (Guda and Aliyu, 2015).

2.6.2 Charge Controller

The charge controller (also known as voltage regulator) is the intermediary device between the panels and other PV system components such storage unit and inverter. Its purpose is to control the power flow between these components thereby protecting them. The basic function of a charge controller is to regulate battery voltage.

2.6.3 Inverter

The power produced by the panels is DC, therefore the inverter changes direct current (DC) to alternating current (AC) making it suitable to be used by most home appliances.

2.6.4 Storage unit/Batteries

The storage unit is composed of batteries; its function is to store excess electric power. These batteries are classified as deep cycle batteries; they are able to withstand continues charging and discharging. They are different from car/vehicle batteries

2.7 Types of PV System

Photovoltaic systems are classified according to construction type and function or purpose of the installation. Basically, there are three types of photovoltaic systems; standalone, grid-connected and hybrid PV systems. There are other types of PV system such direct PV system which does not have any an inverter to convert dc power to ac power.

2.7.1 Standalone PV System

Standalone photovoltaic systems can be categorized into two groups; DC standalone or AC standalone or DC/AC standalone system. Basically, standalone systems are not connected to the utility or grid. Components of standalone systems are modules, charge controllers, storage unit, and inverter. Standalone systems are the most common type of PV systems around the world; they are mostly installed in homes and small business/office premises. Countries having good PV regulations are turning most standalone systems into the grid-connect system. The metering system is connected to by the home and grid, and excess power from the PV system is sold to the utility provider and increase of power demand exceeds production, power is sourced from the utility.

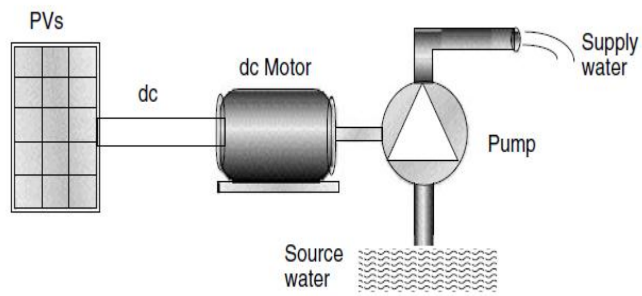

Figure 2.7: standalone PV systems (El-Dein et al .,2013)

2.7.2 Grid-connected PV system

The grid-connected can be a standalone system which is connected to the grid or large or medium scale photovoltaic plants called PV power plants. These plants are usually mega-watts installation and cover large hectares of land. PV power plants have other components such as power condition units which shape (frequency and power quality issues) the power into the desirable state before connecting to the grid (Azoumah et al ., 2010).

2.7.3 Hybrid PV systems

The hybrid PV systems is a combination of PV systems and other forms of energy producing units such as diesel or gas generators, wind turbines and hydro plants. The purpose of these other units is to complement the PV system during unfavorable weather conditions and most at night.

2.8 PV Cell Equivalent Circuits

Figure 8 shows the simplest equivalent representation of the solar cell. The circuit consists of a current source I_{ph} parallel to a diode D and shunt resistance R_{sh}, all together connected to a series resistance R_s. The current source is an ideal source which provides current proportional to solar flux which it is revealed to.

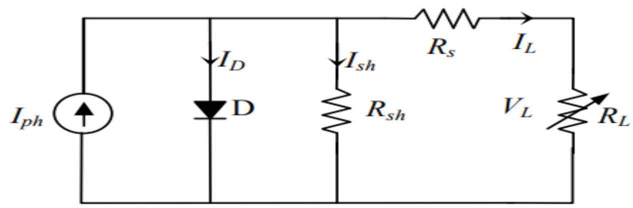

Figure 2.8: Pv cell equivalent circuit (El-Dein et al .,2013)

2.8.1 PV module connection

There are three ways of connecting photovoltaic modules; series, parallel and combination of series and parallel connection. Each of the connecting methods depends on specific array output requirements. Connecting modules in series increases the voltage but maintain current whilest connecting in parallel maintains voltage but increases the current. Parallels and series combination depends on several factors such as array power output, the capacity of inverters and power conditioning components etc (El-Dein et al. , 2013).

2.8.2 Concentrated Solar Power

The technology of concentrated solar energy can be traced as far back as 200 BC; Archimedes used curved to converge the sun's radiation to a point. This idea was used to start fires. Diocels who was a Greek mathematician explained the parabolic trough's optical property in 2nd century BC. In 1746, Comte de Buffon outlined Heliostat design development. In 1878, Augustin Mouchot, at the universal exhibition in Paris, displayed a dish propelled by steam engine system. A much better breakthrough in CSP technological research occurred in Egypt in 1913 when Frank Schuman successfully built parabolic trough powered pumping system. But the actual CSP industry started in 1980s in California in U.S.A; 354MW of nine SEGS (Solar Electric Generating System) were built during these periods and still functioning today (Lovegrove , 2012).

Concentrated solar power is based on the principle of concentrating solar radiation to a specific point where heat from the sun's radiation is used to power steam turbine to produce electricity. Mirrors or lenses are used in focusing the sun's radiation. There is a similar technology called concentrated photovoltaic but in this case, multi-junction solar cells are used to produce electric power; both technologies are similar in the sense that solar radiation is concentrated to a point (El-Dein et al., 2013). CSP is renewable energy thus prevent the destructive effects of using fossil fuels and nuclear reactions for electric power generation. CSP has the advantage of being able to produce power in the absence of solar radiation when fitted with thermal storage system; this added benefit seriously increases the capacity factor when liken to photovoltaic systems. CSP technology can be categorized into two groups; line-focusing systems (LFS) and Point-focusing systems (PFS). LFS is made up Fresnel plants and parabolic trough; they have single axis tracking network whilst PFS is made up of the solar tower and solar dish plants which uses double axis tracking system (Lovegrove , 2012)

2.8.3 Parabolic trough

The parabolic trough technology is composed of mirrors or lenses designed into parabolic shapes. At the center of the parabolic-formed mirror is a tube equal in length to the mirror. The tube contains fluid which absorbs solar energy (thermal) and transports it to the steam turbine for power generation or storage unit. Basically parabolic trough technology is made of the thermal receiver, solar collector (lenses, mirror or highly published surface), and storage unit and generator system. Figure 10 shows the parabolic-shaped mirrors with tubes containing thermal receivers. Because of rotation of the earth, the sun's position is not stationary thus parabolic trough system are incorporated with solar tracking system to maximize efficiency at all times of the day. Synthetic oil, molten salt or water/steam is used as the heat receiver and choice depends on plant design requirements (Lovegrove, 2012).

Figure 2.9: Parabolic Trough (Lovegrove, 2012)

2.8.4 Linear fresnel

The linear Fresnel technology and method of operation is similar to the parabolic technology; the difference being that the linear Fresnel uses flat mirrors or slightly curved mirrors (mostly at the edges) and also the tube containing the thermal receiver is elevated to a good height and the inverted. Figure 9 shows the linear Fresnel technology. It has the benefit of requiring small land area and also being relatively cheap when compared to parabolic trough technology (Jacobson and Delucchi ,2011).

Figure2.10: Linear Fresnel reflector(Jacobson and Delucchi,2011)

2.8.5 Solar tower technology

The solar tower technology is also known as the central receiver. It has five principal components; Heliostats, thermal storage, heat and exchange, receiver and controls. Heliostats (an array of mirrors) concentrate the sun's energy onto a central receiver located on the pinnacle of a tower of appreciable height. The central receiver can be referred to as an interface between the source of energy (sun) and the generation unit; it transfer heat from the sun to the generator. The heat absorbed by the receiver is used to convert water into steam to propel steam generators. Molten salt acts thermal storage unit. Figure 2.11 illustrates the central receiver technology.

Figure 2.11: Solar tower technology(Lovegrove,2012)

2.8.6 Stirling dish technology

The Stirling dish technology combines parabolic trough and solar tower technologies. The physical structure of the Stirling dish resembles satellite receiver. The main components of the Stirling dish are: a collector, receiver, and an engine. Mirrors are shaped into a satellite dish and the receiver and engine are placed as shown in Figure 2.12. The collector (mirror) concentrates the sun’s energy onto the receiver which transfers the energy to the engine. Advantages of the Stirling technology are:

- The close proximity of the engine to the receiver reduces heat loss during heat transfer.
- Due to its small generation capacity, Stirling dish can be employed as distributed generations
- It can be used in regions with water difficulties because it employs dry cooling technology (Azoumah et al., 2010).

Figure2.12: Stirling dish technology (Azoumah et al.,2010)

CHAPTER 3
GRID CONNECTION AND OFF-GRID CONNECTION

3.1 Grid Connection

An electric grid is a system of interconnected network which is used in supplying electric power to the consumer i.e. from the point of generation to distribution. It's made up of consumer, generating stations, substations, and different levels of magnitude of voltage transmission lines; from mega-volts to volts (Kaplan et al . ,2009) . Grid connection or grid-tied photovoltaic power plants has increased tremendously over recent years. PV systems together with other renewable energy sources have become visible contributors in electricity generation and distribution (Wang and XU, 2010).This is as a result of harmful effects of fossil fuels such as greenhouse gas emission causing global warming to environment. PV energy is clean, reliable and a non-pollutant as such most developed countries have stated or are already investing heavily in photovoltaic systems and other forms of renewable energy. Most African countries are yet to take full advantage of PV system even though the weather conditions favorable supports photovoltaic systems.

Grid connections of photovoltaic systems can be categorized into two sections; transmission level connection and distribution level connection. In the transmission level connection, a centralized PV park usually with power in mega-watts (MW) is properly conditioned with suitable devices such as inverters, transformers etc. before connecting to the grid, most transmission level connections are done from commercial PV farms. Photovoltaic power plants with capacity beyond 5 kW_p are called DPVP (Dispatchable photovoltaic plants); they are so-called because they can easily regulate output power at the behest of the grid operator (Wang and XU , 2010) .In the distribution level connection, either standalone PV systems or small scale commercial PV systems are tied to the grid after suitable conditioning has been done; rooftop PV systems can also be connected to the grid in countries having proper grid codes, regulations/regulators or standards. The difference between transmission level connection and distribution level connections is that the latter tends to produce grid related constraints such power quality issues (Li et al., 2012).Three phase photovoltaic systems can be connected to the grid at transmission and distribution levels whilst single phase photovoltaic systems can only be connected to the grid at the distribution level. Grid connection of photovoltaic systems is heavily dependent on one principal component called inverter; other peripheral devices such as transformers, protection units etc. are used as well.

The inverter is a power electronic device which changes direct current (dc) to alternating current (ac). The inverter is made up semiconductor switches; transistors (IGBT, MOSFET BJT etc.), diodes, thyristors, gate turn-off thyristors (GTO), Triode, passive and active elements, appropriate circuitry and a control mechanism. There are several types of inverters; conventional inverters, matrix converters, etc. prominent among the types is the multilevel inverter which is made up of two types; symmetrical and asymmetrical. Multilevel inverter is the connection of a number of H-bridge (single or three phases) to produce several levels of voltage at the output. The goal of most multilevel inverter designers is to produce several number of dc levels at the output of an inverter using limited number switches and dc sources. The multilevel inverter has seen rapid application over the years because of its numerous advantages. Single phase H-bridge inverter circuit is shown in Figure 3.1 and three phase inverter is shown in Figure 3.2.

3.2 Single Phase H-bridge Inverter

Single phase H-bridge inverter can be categorized into two groups; Single phase half H-bridge inverter and Single phase full H-bridge inverter. The single phase full H-bridge inverter is shown in Figure 3.1. It’s made up of four transistor switches connected anti-parallel with a single diode each, the purpose of the diode is to provide alternative path for current flow. The switching topology for the single phase H-bridge inverter is shown in Table 3.1.

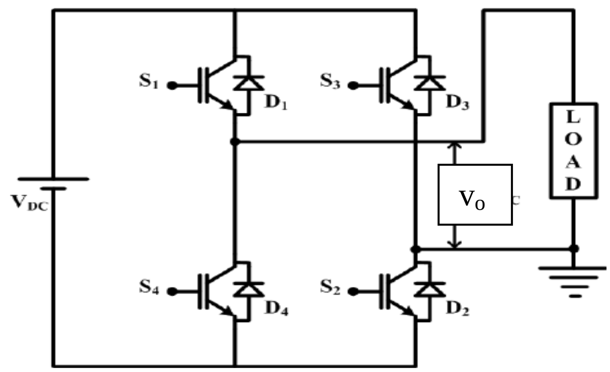

Figure 3.1: Single Phase H-bridge Inverter (Kaplan et al., 2009).

Table 3.1: Table for Single Phase full H-bridge Inverter (Kaplan et al., 2009)

	Switches				
State	S_1	S_2	S_3	S_4	Output voltage V_o
1	1	1	0	0	V_o
2	0	0	1	1	$-V_o$
3	1	0	1	0	0
4	0	1	0	1	0

3.3 Three Phase H-bridge Inverter

The three phase H-bridge inverter is made up of two types; half bridge and full bridge inverter. Three phase full bridge inverter is shown in Figure 3.2. It's made up of six transistor switches connected anti-parallel with a single diode each, the purpose of the diode is to provide alternative path for current flow. Two switches are connected in series and three of such series connection is connected in parallel. The switching topology for the three phase H-bridge inverter depends on the firing angle. Basically the principle of operation of the three phase inverter is that only one switch can be on amongst the series connection for duration of time. Example Q_1 and Q_2 cannot be on at the same time neither can Q_3 and Q_4 be on at the same time, also all three switches at the upper (Q_1, Q_2, Q_3) level or lower (Q_2, Q_4, Q_6) cannot on or off at the same time.

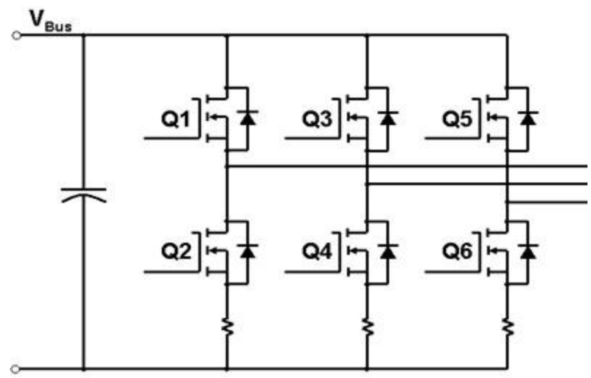

Figure 3.2: Three Phase Full H-bridge Inverter (Kaplan et al., 2009)

The inverter used in photovoltaic systems is an essential device which has multiple functions such voltage inverting, grid connection, power quality monitoring. This is inverter is also referred to as PV inverter. The PV inverter monitors the condition of the photovoltaic array and its own operating status to enhance grid connection. The control setup furnishes Supervisory control and data acquisition (SCADA) with the following; (MPPT) maximum power point tracking supervision, smooth connection to grid, (LVRT) low voltage ride through, Island mode, dynamic volt-ampere reactive supervision. The PV inverter has protective systems which insulate the switches from irregular current stress (di/dt) and voltage stress (dv/dt) by instantly obstructing triggering pulse.

3.4 Reactive Power Compensation

Photovoltaic energy is heavily dependent on modules and inverter type weather conditions at the location of the plant. Due to these reasons the output of photovoltaic systems can vary swiftly with changes in weather. The large and rapid fluctuation can affect the balance and safety of electrical grid as reactive power compensation (RPC) is needed to solve this problem. RPC method boosts power quality and also limits space consumption. Several field proven RPC methodologies such as static synchronous compensator (STATCOM), static volt-ampere reactive compensation (SVC) will help in power factor compensation, harmonic elimination, voltage imbalance, over and under voltage (Kaplan et al., 2009).

Figure 3.3: NR Electric's SVC system (Yan et al., 2014)

3.5 Photovoltaic Substation

A new substation called Photovoltaic Digital Step-Up Substation has been proposed by NR Electric; this substation has been tested in the field using over 250 substations and has proven to very useful and efficient when compared to the conventional substation. Photovoltaic digital step-up substation is applied to small and medium scale solar parks for electric power grid integration. Photovoltaic digital step-up substation is made up of intelligent primary devices and a network of secondary devices. Fiber-optic is used as a medium for data acquisition and sharing amongst intelligent equipment. The fiber-optic used is of IEC 61850 conventions.

Phase monitoring devices can be sited in the photovoltaic power system to analyze and monitor the dynamic response of the system; this will be achieved in real time. The output of the PV system is greatly dependent on input fuel (sunlight); this fuel is a natural occurring substance and as such the quantity is really not known. Photovoltaic power prediction is an important factor to be considered in grid-tied PV system; this will help in monitoring and stabilizing the power grid. Also power stability control network can be installed to help mitigate against transient stability, load flow and voltage stability (Yan et al., 2014).

3.6 Off-Grid Connection

Off-grid systems offers the possibility to usher in vast amount of electric power produced mainly from renewable energy sources such wind and solar which will greatly to help in curbing depletion of ozone layer and as such constitute healthy environmental practices. This will also lead to economic growth in mainly under-deprived and under-developed countries. An off-grid system or network can be defined as self-sustaining power producing network devoid of the conversional utility. A combination of hydro, wind or solar are the basic fuel used in electric power generation of off-grid system. A hybrid system of RES and diesel generators are used to produce power in emergency situations due to disruption in weather conditions. An off-grid system should meet the following conditions:

a. An independent system devoid of external reliance
b. Efficient production and consumption system
c. Availability of energy storage system (ESS)
d. Use mostly renewable energy sources
e. Management of active side
f. Ability to serve new types of load(Kubalik et al.,2014)

Off-grid and grid-tied photovoltaic power plants are similar but with a few differences being; after power is produced at the PV array, its converted to ac power then connected to the utility in the case of grid-tied PV systems. In the case of off-grid PV systems, photovoltaic array power is stored in energy storage systems or supplied to the consumer via microgrids. Off-grid PV systems is a very broad and controversial area because of the factors to be considered when describing off-grid photovoltaic systems. Off-grid systems are mainly homes, institutions or communities which are not connected to the main power utility of a country, this mainly due to cost of extending grid infrastructure, location or terrain and economic status of the country. In communities where the main/national grid is not extended to, a microgrid can be developed to power reliable power for the community.

A microgrid grid a distinct electric energy grid made up of distributed generations and energy storage systems.Microgrids are either grid connected or islanded mode.Distributed generations are small to medium size electric power generation units which are usually fueled by renewable energy sources.

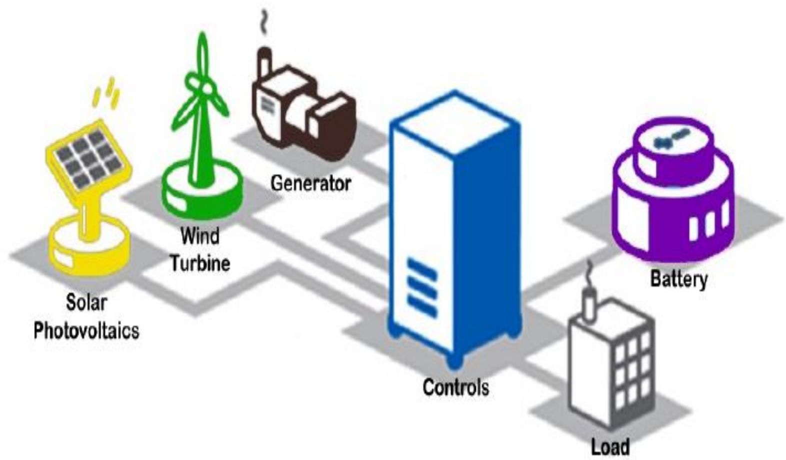

Figure 3.4: Microgrid layouts (Disfani, 2015)

3.7 Power Quality in Off-grid Systems

Power quality which is also known as electric power quality can best be described using the following parameters in electrical systems; waveform, frequency and voltage. Power quality can be said to be acceptable if the power flow is consistent and falls within the authorize scope of voltage, waveform and frequency. Therefore the power supplied to a consumer at point of load connection should be in compatible with load power characteristics. Any interruption in these parameters renders the quality of power poor which can have devastating effect on load rendering loads to malfunction and leading to financial loses (Saini and Kapoor, 2012). The power quality of an electrical system is dependent on a number of factors such as; duration of supply i.e. short or long term, harmonics distortions, voltage variations and transients. Harmonics distortion is the deformation of voltage or current waveforms in electrical systems caused by the introduction of harmonics by the use power electronic converters and non-linear loads. The effects of harmonics in electrical systems are power factor reduction, flickering, over heating of electrical, early breakdown of transformers and uninterrupted power supplies, system capacity reduction due to overheating, electrical fires, damage to sensitive loads, frequent circuit breaker triggering. Total harmonic distortion is also known as THD is the overall harmonics present in an electrical system. The total harmonic distortion of an electrical systems expressed in voltage terms is a ratio of the square root sum of rms voltage of individual components to fundamental rms voltage (Hojabri and Toudeshki, 2013).

$$\text{THD}=\frac{\sqrt{V_1^2+V_3^2+\ .\ .\ .+V_n^2}}{V_1} \tag{3.1}$$

Where

V_1 = rms voltage fundamental component

V_3 = rms voltage of third component

V_n = rms voltage of the n^{th} component

Expressing the total harmonic distortion in percentage terms will give us:

$$\text{THD}=\frac{\sqrt{V_1^2+V_3^2+\ .\ .\ .+V_n^2}}{V_1} \text{ x } 100\ \% \tag{3.2}$$

3.8 Energy Storage Systems

The efficient harnessing of renewable energy sources such solar energy is greatly dependent on the ability to store produced power. The output power of a PV system depends heavily on weather conditions and as such power supply can vary at any given time. To be able to efficiently supply the required power and also efficiently utilize produced power, energy storage systems are required for off-grid photovoltaic systems. In case of our research, the required energy storage system is the type called large scale energy storage systems or grid energy storage. Several energy storage systems have been developed and are being used to store energy either in small to medium and large scales. Some examples of energy storage systems are:

a. Compressed Air
b. Liquid Air
c. Batteries
d. Flywheel
e. Hydrogen
f. Power to gas
g. Pumped water
h. Super conducting magnetic energy
i. Molten salt

Newly designed and developed energy storage systems for large scale off-grid photovoltaic power plants has been installed on an island called Ta‘ū; one of the five islands of American Samoa. 1.4MW solar power plant made up 5328 panels was installed on the island together with Tesla Powerpack energy storage system. A total of 60 Powerpacks with 6MWh of storage capacity was installed to store energy during excess production and provide energy during low-production of electric power. The power pack takes 7 hours to fully charge when the plant is producing power optimally and power for three days even when the plant is not producing power. The tesla Powerpack is an ideal energy storage system that can be applied in our power design if we choose to go off-grid completely.

Figure 3.5: MW PV Plant in Tau, American Island (solar City) (Hojabri and Toudeshki, 2013)

Figure 3.6: 6MWh Power pack storage unite (solar City) (Hojabri and Toudeshki, 2013)

CHAPTER 4

DESIGN OF PHOTOVOLTAIC POWER PLANT

4.1 PV Power Plants

A power plant is an industrial installation used for electric power generation. Power plants also known as generating stations, powerhouse, generating plants, power stations uses a number of generators to produce electric power, mechanical energy is converted into electrical power by means of rotating parts in the generators.

PV power plants on the other hand do not use generators but use solar photovoltaic modules to produce electric power. PV power plants also called solar parks are made up of thousands of PV modules, used to develop photovoltaic systems to produce large scale power either for grid integration or islanded mode. PV power plants produce electricity by converting solar energy directly into electricity via solar cells. The nameplate capacity of photovoltaic power plants differs from countries to countries. These variations are MW_p (megawatt-peak) which refers the Dc power produced at the array, MW_{AC} is the ac power produced at inverter output and finally MVA known as mega volts-amperes (Landi et al., 2013).

The efficient performance of photovoltaic systems depends on several factors such weather conditions (ambient and cell temperatures), the type of PV modules and inverters, the efficiency and STC conditions of PV modules and inverters etc. PV power plant design is heavily dependent on the nameplate capacity of the module, and inverter efficiency and weather conditions at location.

4.2 Kirehe District

The district of Kirehe is located in the Eastern Province of Rwanda. It's made up of 12 sectors; Gahara, Gatore, Kigarama, Nyarubuye, Nyamugari, Nasho, Mushikiri, Musaza, Mpanga, Mahama, Kirehe, and Kigina. Kirehe district has sufficient solar radiation to support the construction of photovoltaic power plants. Data sourced from National Aeronautical and Space Administration (NASA) website using geographical coordinates; longitude 30.654878 and latitude -2.280087 shows average (22-year period; Jul 1983 - Jun 2005) monthly global horizontal radiation of 5kWh/m^2/day and peak sun hours of approximately 5 hours per day. The warmest annual average temperature found in Kirehe district is 22.4^{o}C at longitude of 30.2E and latitude of 2.2S (Werner et al., 2011).Table 4.1, shows an aerial view of Kirehe community accessed from Google maps.

Table 4.1: Solar radiation (Werner et al.,2011)

Month	**Air temperature °C**	**Daily solar radiation horizontal kWh/m^2/d**	**Wind speed m/s**	**Cooling degree-days °C-d**
January	23.8	5.67	3.6	424
February	24.4	5.91	3.7	404
March	23.1	5.45	3.7	409
April	22.2	5.25	3.6	365
May	21.9	5.17	3.5	373
June	22.2	4.86	3.5	368
July	22.6	4.73	3.5	391
August	22.2	4.81	3.5	379
September	21.5	4.98	3.6	349
October	21.2	4.57	3.6	350
November	21.2	4.63	3.5	350
December	22.2	5.16	3.4	381
Annual	22.4	5.10	3.6	4533

4.3. Load Estimation

Electric load consumption varies with time, consumer type and location of consumer. Thus all electric power suppliers should factor in the variation of load during load estimation. Efficient load estimation of a community can be done by using previous consumer bills (load information) over a period of time say one year and secondly collating data of gadgets a consumer has. The latter methodology is applied in communities without grid connections or newly developing communities. Load information is a data which shows how a community or a consumer uses electric power by the hour, day, month and year. There are several ways of formulating load data according to the specifications of the applicant. The main factors for load data descriptions are dimension (amperes, Kilovolts, cos ϕ), system location, time and class of customer (residential, services, industry). The constant availability of electric power and the cost of electric power are two important factors which determines the consumption patterns of customers. The electric load demand of communities in Kirehe is segmented into four broad categories:

- Household/domestic sector which includes (lighting, TV, Radio, fridge etc.)
- Commercial loads (flour milling machine, mini shops, unisex hair dressing saloons etc.)
- Community load which consists of (elementary school lighting, desktop computer, printer)
- Health clinic which includes (vaccine refrigerator, communication radio, television, microscope, computer and printer, DVD player, lighting systems).

The results of electric load estimation for the two communities under study in Kirehe are shown in Tables 4.2 and 4.3 respectively. These are the chosen communities where electric power will be provided by means of photovoltaic power plants. The estimated power for the two communities are 500kW for community 1 and 302.232kW for community2, thus 0.802232MW (802.232kW) in total. Table 4.2 and Table 4.3 are made up of the categories of electric load consumers which constitute the communities under study. Each community is made up of the following categories; Upper class, middle class, lower class, Commercial, Administration post, Medical center, Primary school, Secondary school, Church, Small manufacturing. Tables 4.4 up to Table 4.13 are samples of each category providing detailed explanation of how electric load estimation for the two communities was achieved.

Figure 4.1: Google map picture of Kirehe sector

Table 4.2 : Community 1

Categories	Number Of households	Required Power kW	Total Power (KW)	Power used Per Day Kwh/day	Total Power Kwh/day
Upper Class	100	3.255	325.5	16.69	1669
Medium Class	50	2.386	118.4	14.75	737.5
Lower Class	100	0.064	6.4	0.6	60
Commercial	5	2.336	11.6	49.620	248.1
Administration	1	0.585	0.585	3.870	3.870
Medical center	2	1.125	2.25	17.5	35
Primary school	2	2.730	5.46	12.36	24.72
Secondary school	2	6.460	12.94	41.2	82.4
Church	3	0.58	1.74	1.91	5.73
Small manufacturing	5	4.08	20.4	29.310	146.55
Total	270		500 KW		3012.87

Table 4.3: Community 2

Categories	Number Of households	Required Power kW	Total Power (KW)	Power used Per Day Kwh/day	Total Power Kwh/day
Upper Class	60	3.225	195.3	16.690	1001.4
Medium Class	30	2.368	71.04	14.75	442.5
Lower Class	80	0.064	5.12	0.6	48
Commercial	2	2.336	4.672	49.62	99.24
Administration	1	0.585	0.585	3.87	3.87
Medical center	1	1.125	1.125	17.5	17.5
Primary school	1	2.73	2.73	12.36	12.36
Secondary school	2	6.46	12.92	41.2	82.4
Church	1	0.58	0.58	1.91	1.91
Small manufacturing	2	4.08	8.16	29.310	58.62
Total	180		302.232 KW		1767.8

Table 4.4: Upper class family

Appliances	No.in use	Power(W)	Total Power(w)	Hrs/day	Wh/days	Hour/day
Lamps	10	11	110	5	550	05:00-06:00 18:00-22
Mobiles	5	5	25	2	50	05:00-07:00
Radio	2	10	20	12	240	05:00-17:00
TV	1	120	120	3	360	18:00-21:00
DVD	1	30	30	3	90	18:00-21:00
Computer	2	100	200	2	400	17:00-19:00
Refrigerator	1	500	500	24	12000	00:00-24:00
Iron	1	1000	1000	1	1000	09:00-10:00
Water pumps	1	500	500	1	500	08:00-09:00
AC	1	750	750	3	1500	13:00-15:00
Total			3255 watts		16690	

Table 4.5: Medium class family

Appliances	No in use power	Power(w)	Total power (w)	Hrs/day	Wh/days	Hours /days
Lamps	8	11	88	5	440	05:00-06:00 18:00-22:00
Mobiles	4	5	20	2	40	05:00-07:00
Radio	1	10	10	12	120	05:00-17:00
TV	1	120	120	3	360	18:00-21:00
DVD player	1	30	30	3	90	18:00-21:00
Computer	1	100	100	2	200	17:00-19:00
Refrigerator	1	500	500	24	12000	00:00-24:00
Iron	1	1000	1000	1	1000	09:00-10:00
Water pumps	1	500	500	1	500	08:00-09:00
Total			2368 W		14750	

Table 4.6: Administration post

Appliances	**No in use**	**Power(w)**	**Total power(W)**	**Hrs/day**	**Wh/day**	**Hours/day**
Lamps	10	11	110	2	220	17:00-19:00
Mobiles	5	5	25	2	50	07:00-09:00
Television	1	120	120	8	960	09:00-17:00
DVD player	1	30	30	8	240	09:00-17:00
Computer	3	100	300	8	2400	09:00-17:00
Total			585 W		3870	

Table 4.7: Lower class family

Appliance	**No in use**	**Power(w)**	**Total power**	**Hrs/day**	**Wh/days**	**Hours/day**
Lamps	4	11	44	5	440	05:00-06:00 18:00-22:00
Mobiles	2	5	10	2	40	05:00-07:00
Radio	1	10	10	12	120	05:00-17:00
Total			64 W		600	

Table 4.8: Commercial/community purposes

Appliances	**No in use**	**power**	**Total power**	**Hrs/day**	**Wh/day**	**Hours/day**
Lamps	6	11	66	5	330	05:00-06:00 18:00-22:00
Mobiles	2	5	10	2	20	05:00-07:00
Radio	1	10	10	12	120	05:00-017:00
TV	1	120	120	3	360	19:00-22:00
DVD player	1	30	30	3	90	19:00-22:00
Computer	1	100	100	7	700	08:00-17:00
Refrigerator	2	1000	2000	24	48000	00:00-24:00
Total			2336 W		49620	

Table 4.9: Medical center

Appliances	No in use	power	Total power	Hrs/day	Wh/days	Hours/days
Lamps	10	11	110	15	1650	08:00-23:00
Mobiles	5	5	25	2	50	05:00-07:00
TV	1	120	120	8	960	09:00-17:00
DVD player	1	30	30	8	240	09:00-17:00
Computer	3	100	300	8	2400	09:00-17:00
Microscopes	2	20	40	5	200	09:00-14:00
Refrigerator	1	500	500	24	12000	00:00-24:00
Total			1125 W		17500	

Table4.10: Primary school

Appliances	No in use	Power	Total power	Hrs/day	Wh/days	Hours/days
Lamps	30	11	330	2	660	17:00-19:00
Mobiles	50	5	250	2	500	12:00-14:00
TV	1	120	120	8	960	18:00-20:00
DVD player	1	30	30	8	240	09:00-17:00
Computer	20	100	2000	5	10000	09:00-14:00
Total			2730 W		12360	

Table 4.11: Secondary school

Appliances	No in use	Power	Total power	Hrs/day	Wh/days	Hours/day
Lamps	50	11	550	5	2750	05:00-06:00 18:00-22:00
TV	1	120	120	3	360	19:00-22:00
DVD player	1	30	30	3	90	19:00-22:00
Computer	50	100	5000	7	35000	09:00-15:00
Water pumps	1	500	500	4	2000	06:00-10:00
Total	1	500	6400 W	4	41220	06:00-10:00

Table 4.12: Community church

Appliances	No in use	Power	Total power	Hrs/day	Wh/day	Hours/day
Lamps	20	11	220	3	660	17:00-20:00
Mobiles	2	5	10	4	200	12:00-16:00
TV	1	120	120	3	360	19:00-21:00
DVD player	1	30	30	3	90	19:00-21:00
Computer	2	100	200	3	600	09:00-14:00
Total			580 W		1910	

Table 4.13 : Small manufacturing unit

Appliances	No in use	Power	Total power	Hrs/day	Wh/day	Hours/day
Lamps	5	11	55	4	220	08:00-21:00
Mobiles	3	5	15	4	60	12:00-16:00
3- phase motors	1	3000	3000	8	24000	08:00-21:00
1-phase motors	1	1000	1000	5	5000	08:00-21:00
Radio	1	10	10	3	30	15:00-18:00
Total			4080 W		29310	

4.3.1 Average daily load profile

The maximum electricity load of the community occurs from 19:00 hour till 22:00 hour this is due to most of the families would expect to be at home enjoying radio and television besides night light use and some small manufacturing will be working during that time and commercial.

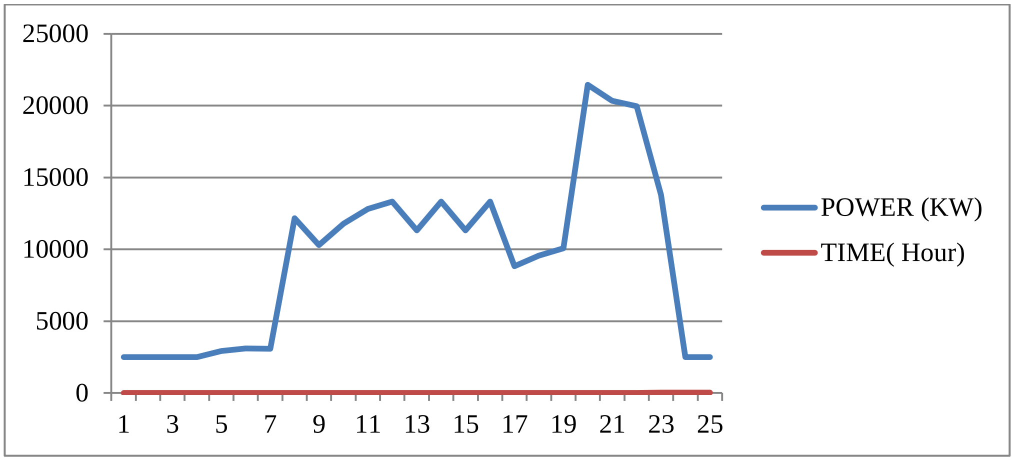

Figure 4.2: Average daily loads

4.4 PV Power Plant Design

Sun power or energy is the fuel used in producing electricity by means of photovoltaic systems. Energy from the sun comes in two forms; heat and light. Solar thermal technologies use the heat aspect of sun's energy to produce power whilst solar PV technologies use the light (photons) from the sun in producing power. The power consumption demand for the two communities derived after load estimation is 802.232kW/day. From engineering perspective, it's not right to produce the exact quantity of power required by a consumer/community thus we will design 1MW PV power plant; excess power produced will be injected into the grid. Consumption of power will increase when power is constantly available and affordable. Increase in economic activities will also lead to increase in power consumption thus the need to design 1MW plant.

4.4.1 PV panel/module

Samsung PV-MBA1BG250 (250W) monocrystalline silicon solar panel is proposed for the construction of 1MW PV power plant and also used for simulation in PVsyst software. The datasheet specifications of PV-MBA1BG250 are: STC and PTC power ratings of 250W and 225.7W respectively. Open circuit voltage V_{oc} is 37.8V, short circuit current I_{sc} is 8.68A, maximum point current and voltage (I_{mp}, V_{mp}) are 8.15A and 30.7V respectively, Nominal operating cell temperature is 45^0C, made of 60 cells, area is 1644mm (length) x 992mm (width), weight is 20.2kg and efficiency is 15.33% with 5 years guaranty and 90% and 80% efficiency guaranty for 10 and 20 years respectively.

The following steps will help us to accurately design the required PV power plant of 1MW capacity.

4.4.2 Energy required from the PV panels

$$\text{Pdc,STC} = \frac{\text{Pac}}{\text{conversion efficiency}} = \frac{1\text{MW}}{0.75} = 1.33\ \text{Mw} \qquad (4.1)$$

Conversion efficiency: 75 % estimate the impacts of temperature, inverter efficiency, module mismatch, and dirt to come up with conversion efficiency from dc to ac.

P_{dc}(STC): is the dc power of the array obtained by simply adding the individual module ratings under standard test conditions.

P_{ac}: AC power.

Capacity of PV panel total W_P = P (MW) / (h/day of "peak sun") (4.2)

Capacity of PV panel total W_P =1.3MWh /5(h/day)= 0.26MW_p

$$\text{The number of PV modules needed} = \frac{\text{total watt peak rating}}{\text{PV module rated output}} \qquad (4.3)$$

The number of PV panels needed = 1.3MW / 250W=5200 modules

Energy (kWh/year) = P_{ac} (kW) * (h/day of "peak sun") * 365 days (4.4)

Energy (kWh/year) =1.3MW * 5 h/day * 365days

Energy (kWh/year) = 2.3725GW/year

4.4.2 Inverter selection/string

Sunny tripower 15000TL inverter is what we selected for our design. Sunny tripower 15000TL is manufactured by System Mess Anlagentechnik, SMA Solar Technology AG

(Germany). Sunny tripower 15000TL has the following technical information for the dc input side: maximum dc power is 15340W, maximum input voltage 1000V, maximum power point voltage range is 360V-800V, rated input voltage 600V; minimum input voltage 150V, maximum input current is 40A/12.5A. For the ac output side; European efficiency and maximum efficiency are 97.8% and 98.2% respectively, rated power is 15000W at 230V 50Hz frequency, nominal AC voltage at different variations: 220/380V or 230/400 and 240/415V.

$$\text{Inverter size} = \frac{1\text{MW} * 130}{100} = 1.3\text{MW} \tag{4.5}$$

$$\text{Number of inverter} = \frac{\text{inverter size}}{\text{rated power of inverter}} \tag{4.6}$$

$$\text{Number of inverter} = \frac{1.3\text{MW}}{15000\text{W}} = 86.66 \text{ inverters} \approx 87 \text{ inverters}$$

$$\text{Number of modules in series} = \frac{\text{maximum open circuit voltage of inverter}}{\text{open circuit voltage of each PV module}} \tag{4.7}$$

$$\text{Number of modules in series} = \frac{600}{37.8} = 15 \text{ modules}$$

Size of an array is 15 Modules which are in series 4 of such array are connected in parallel to produce one string of inverter.

$$\text{Total No. of Arrays in the solar field} = \frac{\text{total No. of modules}}{\text{number of module in array}} \tag{4.8}$$

$$\text{Total No. of Arrays in the solar field} = \frac{5200 \text{ modules}}{15\text{modules}} = 325\text{Arrays}$$

The selected inverter must be large enough to handle the total amount of watts peak requirement, the inverter size should be 25%–30% bigger than total watts requirement. Per the technical information of the our chosen inverter, the field connection of modules to the inverter is as follows; 15 panels having voltage of 30.7V and current of 8.15A are connected in series to produce 460.5V voltage and 8.15A current. Four of such array connections are connected in parallel to produce a voltage of 460.5V and current of 32.6A, this produces one string of connection for one inverter. Per the module-inverter calculations, a total of 87 inverters will be required to efficiently convert dc power to ac power. There are different types of inverters for various purposes. Examples are micro-inverters, string inverters and central inverters. To determine the best inverter type for a specific application, several factors such as cost, type of PV system; grid connection, standalone, hybrid etc. needs to be evaluated. Considering cost, ease of installation and efficiency, 3-phase string inverters are the best practical option.

4.3 Plant Area

A total of 5200 panels/modules are used in the design of our photovoltaic power plant. Each module has an area of 1.631m^2 (1644mm x992mm) therefor the total generating area of the plant is 8480.41m^2 whilst the total area the plant will be bigger than the generating area of the plant. The generating area of the plant is an important factor in determining the amount of energy to be produced and also analyzing the performance of the plant.

Table 4.15 : Photovoltaic module circuit

Types	**Sizes**
Photovoltaic modules	250 w
Number of PV modules	5200 modules
Sunny tripower 15000TL	15000 w
Number of inverters	87 inverters
Number of modules in series	15 modules
Size of an array	15 modules
Total number of arrays in solar field	325 arrays
Module area	1.631m^2
Land required for PV modules	8480.41m^2

CHAPTER 5
PVSYST SIMULATION

5.1 PVsyst Software

The simulation aspect of our research is divided into two parts; simulation for fixed module orientation and simulation for tracking system composed of east-west tracking, this is achieved by using PVsyst software. PVsyst 6.6.8 edition is used. André Mermoud, a graduate (1971) of university of Geneva in Switzerland is the author and founder of PVsyst software and PVsyst SA respectively. PVsyst is made up of four sections; preliminary design, project design, databases and tools. In the project design section, there are four subsections or systems; grid-connected, standalone, pumping and dc grid. The grid connected subsection is our area of concern because the desire of our project is to design grid connected photovoltaic. Using satellite based meteorological data by NASA, simulation will be done to determine the yearly energy output for the two case scenarios; the flowchart for simulation is shown in Figure 5.1.

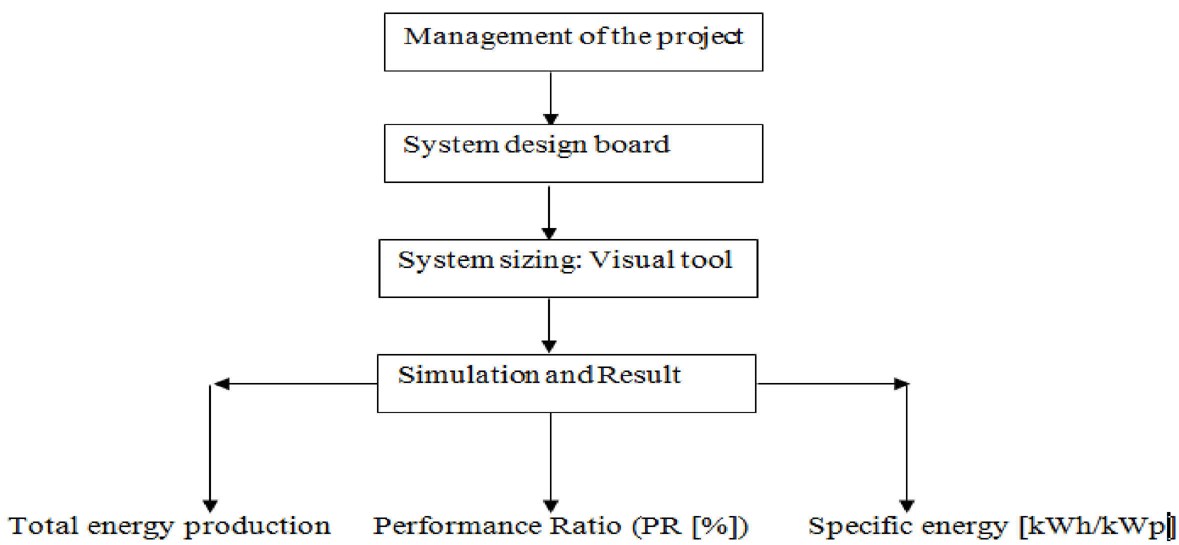

Figure 5.1: Flowchart of PVsyst system programing

5.1.1 Site Location

The proposed PV power plant will be sited at Kirehe which is in the Eastern Province of Rwanda. Kirehe district has sufficient solar radiation to support the construction of photovoltaic power plants. Data sourced from National Aeronautical and Space Administration (NASA) website using geographical coordinates; longitude 30.654878 and latitude -2.280087 shows average (22-year period; Jul 1983 - Jun 2005) monthly global horizontal radiation of 5kWh/m^2/day and peak sun hours of approximately 5 hours per day. The warmest annual average temperature found in Kirehe district is 22.4^{o}C at longitude of 30.2E and latitude of 2.2S.

5.1.2 Orientation

According to weather and landscape terrain of Kirehe, the photovoltaic panels will be inclined at an angle of 30^0 to south at fixed position. This angle of orientation is as a result of previous research works; the optimal absorption of irradiance is at its peak at this angle and as such maximum power is produced at the array output.

5.1.3 Horizon

The horizon line drawing for Kirehe is shown in Figure 5.2; it's a graph of sun's height versus azimuth angle. There's a correlation between the suns height at specific hours of the day and the azimuth angle. The geographical site details of Kirehe are: longitude of 30.2E and latitude of 2.2S altitude 111m and albedo 0.20.

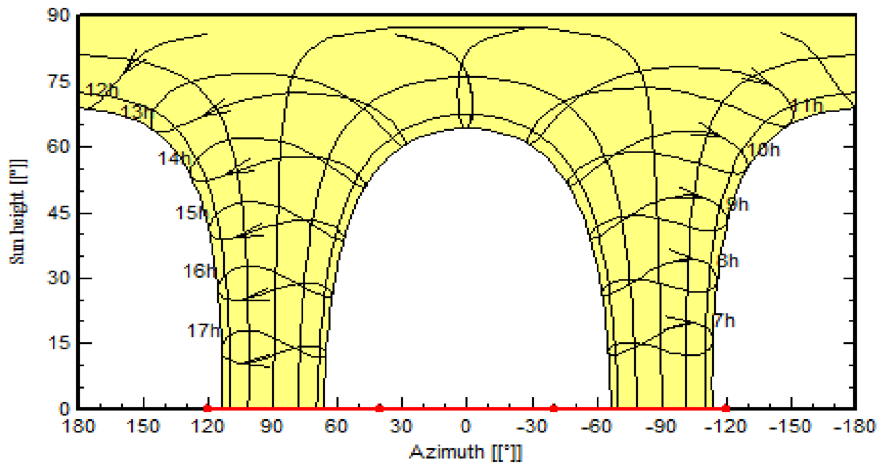

Figure 5.2: Horizon line drawings for Kirehe

5.1.4 Detailed losses

Experimental and simulation research by PVsyst over the years has led to standard values for detailed losses in photovoltaic power plants. These standard values can be changed according to the designer's specifications. Factors that affect losses in PV systems are: thermal loss factor, ohmic losses, module quality and mismatch, soiling loss, IAM Losses, Ageing etc. PVsyst set standard losses are used for our simulation.

5.1.5 System sizing : visual tools

For our simulation design, 1300kWp nominal power composed 5200 modules with an area of 8480.41m^2 and 86 group of SMA inverters are used. The proposed panels and inverters that we want to use in construction Kirehe power plant is selected for simulation. The data provided below is generated by PVsyst; no shading was defined because the landscape of the location of the plant is made up of more shrubs and grasses.

1. **Orientation parameters**

Field type: **Fixed Tilted Plane**

Plane tilt/azimuth = **30° / 0°**

2. **Compatibility between System defintions**

Full system orientation **tilt/azim = 30° / 0°**

1 sub-array PNom = 1301 kWp, modules area = 8489 m²

No Shading field defined

3. **System parameters**

Sub-array #1	**PV Array**
PV modules:	347 strings of 15 modules in series, 5205 total
Pnom = 250 Wp	Pnom array = 1301 kWp, Area = 8489 m²
Inverters (15.0 kWac)	87 MPPT Main inputs, Total 1

4. **Shading scene parameters**

   No shading scene defined

5.1.6 Near shading

Kirehe PV power plant is not affected by any shading type; there are no buildings, tress or mountains to cast shadow/shade onto the panels at certain time periods of the day. The landscape is lowland with little shrubs. Figure 5.3 shows the satellite imagery for Kirehe.

Figure 5.3: Proposed Site for Kirehe Power Plant

5.1.7 System

The system feature in PVsyst allows you to design your PV power plant according your specifications. Detailed information of desired output power, type of module to use; manufacturer and output power W_p, type of inverter according to manufacturer and size, shading effects, inverter sizing, economic analysis, etc. should be entered into system. According to the load estimations made in the previous chapter, 1.3MW photovoltaic power plant needs to be built in Kirehe. The plant will be made up of 5200 modules. The module selected for simulation is Samsung PV-MBA1BG250: STC and PTC power ratings of 250W and 225.7W respectively. Open circuit voltage V_{oc} is 37.8V, short circuit current I_{sc} is 8.68A, maximum point current and voltage (I_{mp}, V_{mp}) are 8.15A and 30.7V respectively, Nominal operating cell temperature is 45^0C, made of 60 cells, area is 1644mm (length) x 992mm (width). A simplified diagram showing the building blocks of the systems in PVsyst is shown below. The 'user E needed' in the diagram refers to the energy used by plant; lighting, data acquisitions and peripheral needs.

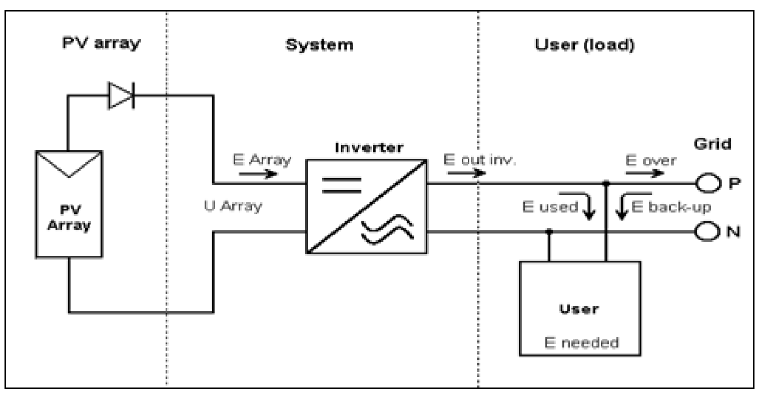

Figure 5.4: simplified diagram of simulation

5.2 Simulation and Results

As stated in the beginning of chapter 5, the simulation is done for two case scenarios; fixed module orientation and tracking system orientation. Detailed report is presented for both cases; these reports are located in the appendix of our thesis. In the report a number of parameters are presented, the three main parameters which describes the produced energy and losses in the systems are:

- Normalized production (per installed kWp)
- New simulation variant
- Losses diagram

5.2.1 Normalized production (per installed kWp)

Figure 24 shows the graph of normalized productions per each installed kilowatt power (kWp); 13001kWp nominal power. Figure 5.5 displays three other factors; systems losses, collection losses, useful energy produced which are very useful indicators; which determines the performance of the plant in terms of energy production. From the graph, the highest useful energy produced occurred in May, June, July and August, with July recording the highest; 5.1kWh/kWp/day. The highest system losses and collection losses occurred in the period of June and July. Though photovoltaic systems depend on sun light for electric power production, the heat energy associated with sunlight affects PV system performance negatively. This means that for every 1^0 C of temperature beyond the STC value, the power of the panel is reduced by -0.44%/K (Ozerdem,2015). Collection losses are the losses which occur during conversion of irradiance into power, it’s a ratio of how much irradiance is received and how much of that irradiance is converted into power. System losses also occur in the irradiance conversion chain but it’s mostly caused by mechanical losses, inverter losses etc. system losses can be greatly reduced with higher module and inverter efficiency, quality and short cabling systems. The percentage difference between losses (system + collection = 0.72) and useful energy produced (3.98) is 18.09%; which is an ‘acceptable’ loss in PV systems.

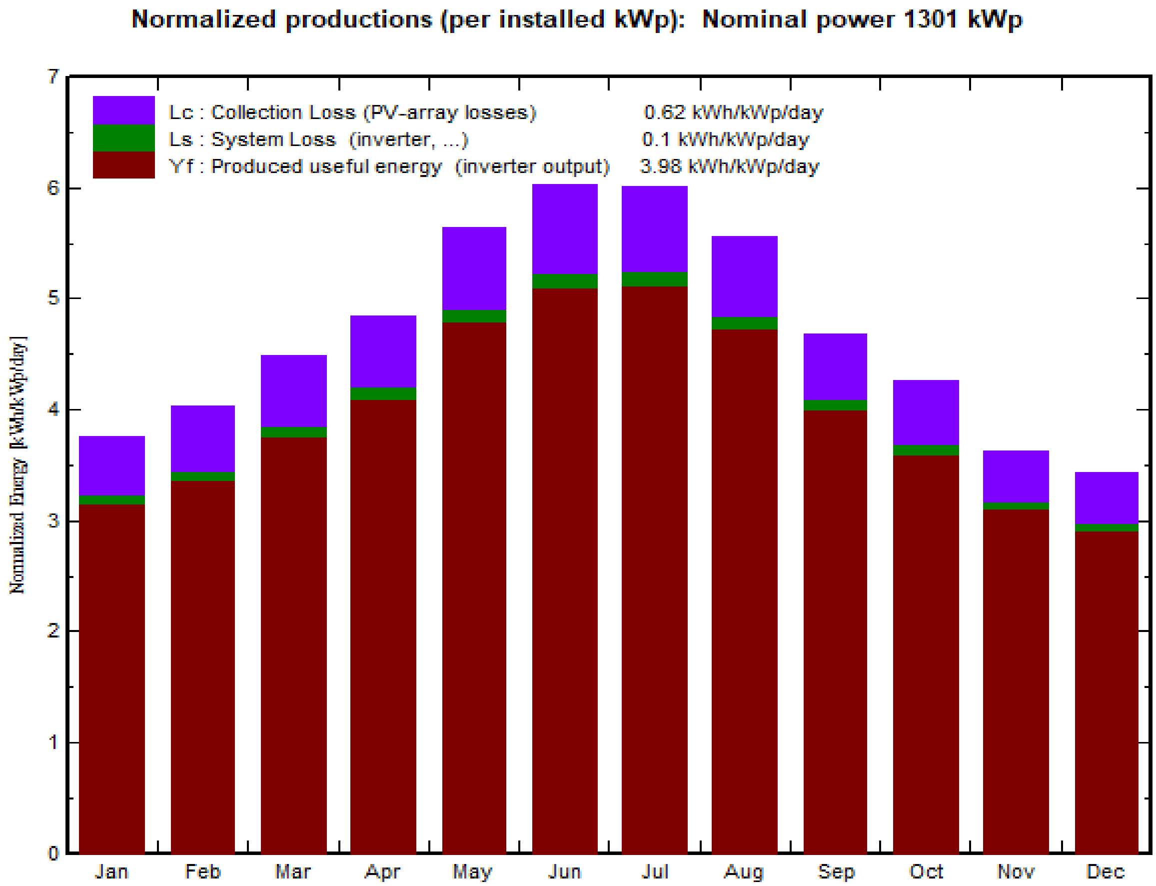

Figure 5.5: Nominal power 1301kWp (Normalized productions)

5.2.2 Performance ratio

The performance ratio is a quantity which is defined as the ratio of effective energy produced at the array output with respect to energy produce by an ideal PV system under the same conditions. Usually standard test conditions (STC) are used with the same amount of irradiance incident on 'global plane'. The performance ratio of PV systems comprises of system and array losses. Array losses are wiring, mismatch, module quality, shading effects, photovoltaic conversion rate, IAM. From Figure 5.6, the overall performance ratio of our system is 84%; there wasn't much difference in the monthly performance even though the system and collection losses for June and July were considerable high.

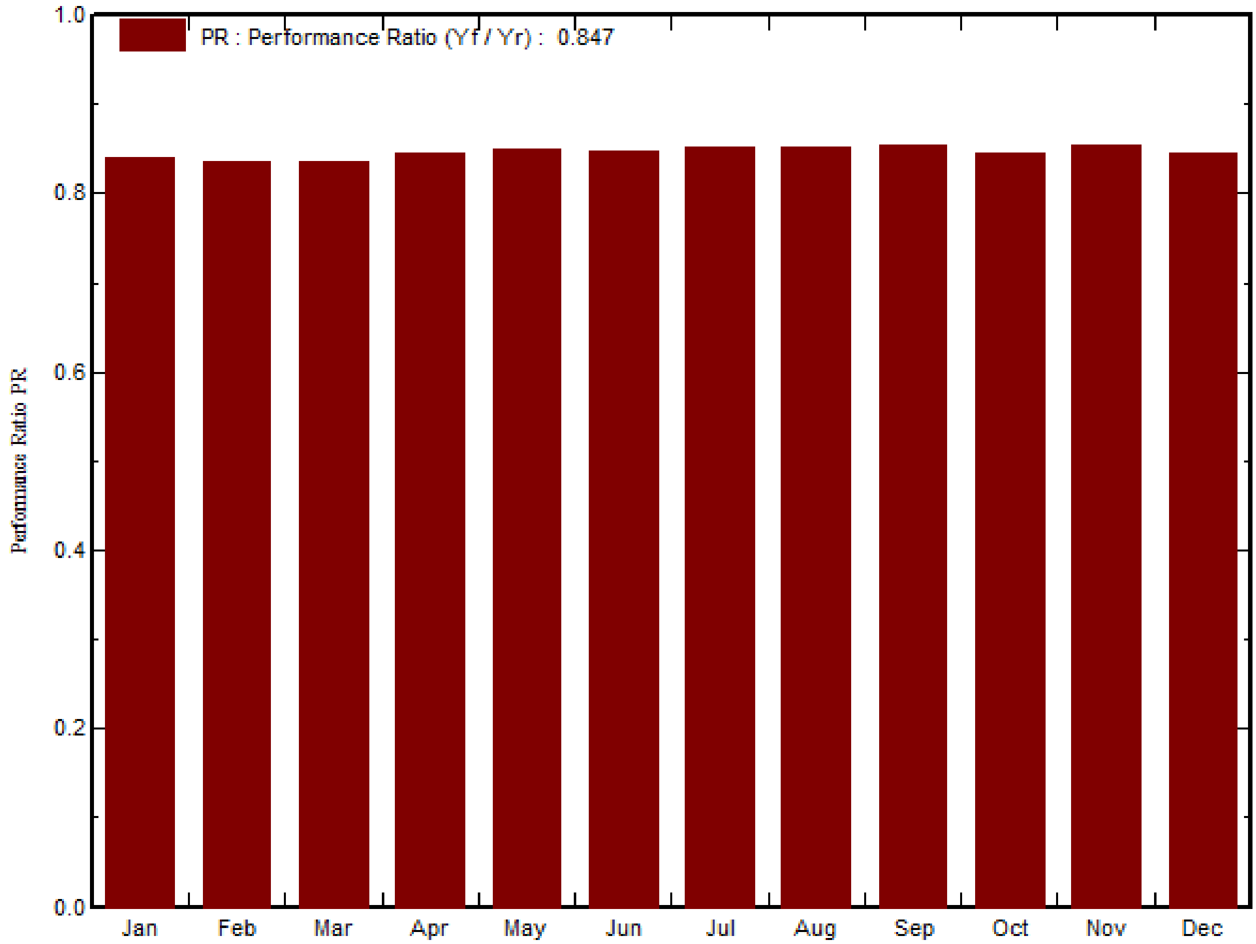

Figure 5.6: Performance ratio

5.2.3 New simulation variant

Balances and main results of our simulation for Kirehe PV power plant is shown in Table 16. From the table, maximum monthly energy production occurred in July; 211856kWh and least occurred in December; 120194Wh. The yearly effective energy produced at the array output (EArray) is 1938963kWh. However it should be noted that EArray is dc power. After converting the dc power to ac power, then we have E-Grid, energy connected to the grid. Yearly energy connected to the grid is 1892338kWh. The difference between E-Array and E-Grid determines the efficiency of the inverter (97.6%). The graph of daily energy production is given in the appendix of the thesis, from January to December.

Table 5.1: Balances and main results

	GlobHor kWh/m^2	DiffHor kWh/m^2	T Amb ^{0}C	GlobInc kWh/m^2	GlobEff kWh/m^2	EArray kWh	E_Grid kWh	PR
January	154.7	73.03	21.28	116.7	111.0	130856	127597	0.840
February	136.4	68.81	22.19	112.9	108.0	125946	122856	0.836
March	152.9	70.41	22.11	139.3	134.4	155327	151455	0.835
April	146.0	71.79	20.81	145.6	141.1	164146	160176	0.846
May	159.1	69.11	20.49	174.8	170.2	197879	193189	0.849
June	158.7	61.46	19.48	180.7	176.5	204408	199478	0.849
July	165.2	63.22	19.19	186.3	181.9	211856	206791	0.853
August	165.3	74.14	19.55	172.1	167.5	195642	191029	0.853
September	148.6	82.10	20.03	140.6	135.7	159858	156158	0.854
October	155.0	77.97	21.01	132.1	126.7	148733	145165	0.845
November	136.8	82.36	20.42	108.9	103.9	124117	121207	0.855
December	142.5	77.59	21.18	106.6	101.3	120194	117238	0.845
Year	1821.2	871.99	201.64	1716.6	1658.2	1938962	1892339	10.16

Legends:

GlobHor - Horizontal global irradiation

DiffHor – Horizontal diffuse irradiation

T Amb- Ambient Temperature

GlobInc - Global incident in collector Plane

EArray- Effective energy at array output

E_Grid - Energy injected into grid

PR – Performance ratio

5.2.4 Loss diagram

The loss diagram for Kirehe PV power plant is illustrated in Figure 5.7. The loss diagram is the sum of various losses that occur right form irradiance conversion to grid connection of produced energy. Losses which makes up the loss diagram can be categorized intro three groups; conversion and module losses, conductor and accessories losses and finally inverter losses. From Figure 26 the yearly energy produced at STC is 2159MWh, but ‘real’ power injected into the grid is 1892MWh yearly; this represents 12.37% total loss in the PV power plant.

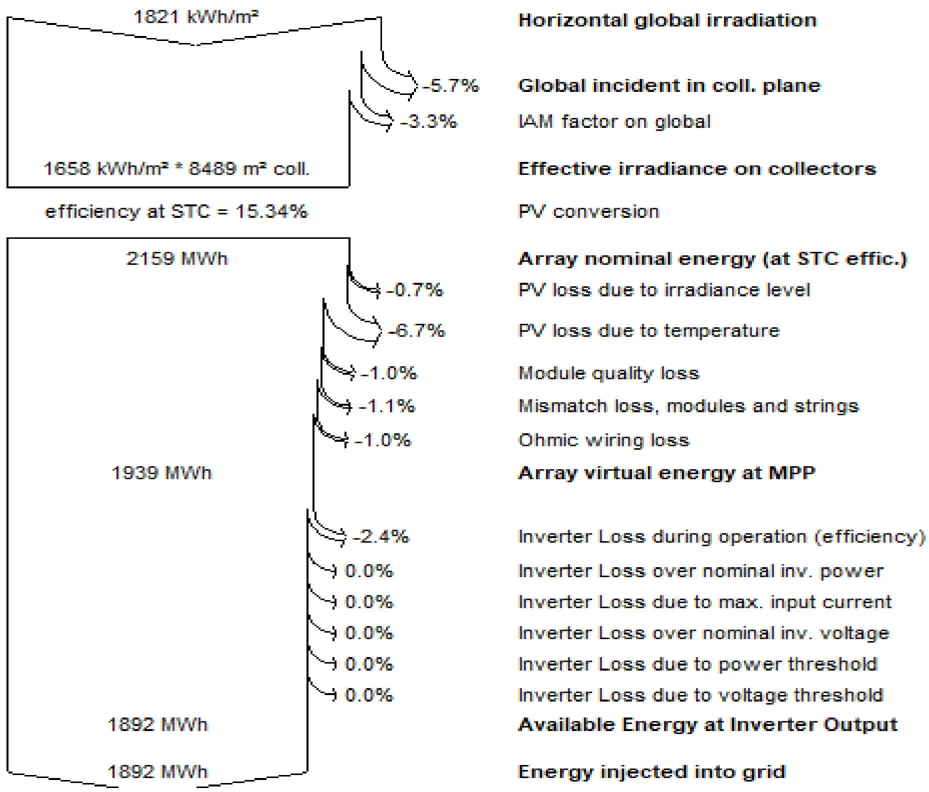

Figure 5.7: Loss diagram

Table5.2 **,**represents detailed system losses on monthly basis. The sum of the various losses (ModQual, MisLoss, OhmLoss, EArMPP and InvLoss) is 2047050kWh. This does not mean 2047050kWh is a ‘loss’, this is because the fuel; irradiance for PV systems is free, also ModQual represent module quality loss and it illustrates the percentage of irradiance that can be converted to electric power. Although increasing the efficiency of modules will greatly reduce MdQual losses, thus reducing total losses in the plant.

Table 5.2: Detailed System Losses

	ModQual KWh	MisLoss KWh	OhmLoss KWh	EArrMPP KWh	InvLoss KWh
January	134	1466	977	130856	3259
February	129	1412	1042	125947	3091
March	1602	1745	1522	155336	3881
April	1694	1845	1688	164197	4021
May	2044	2226	2176	197959	4770
June	2114	2302	2435	204562	5084
July	2190	2384	2453	211931	5140
August	2020	2200	2109	195719	4689
September	1647	1794	1443	159865	3708
October	1532	1668	1277	148733	3568
November	1276	1390	848	124117	2910
December	1236	1346	808	120194	2957
Year	20000	21780	18778	1939415	47077

Legends:

ModQual- Module quality losses

MisLoss- Module mismatch loss

OhmLoss- Ohmic wiring loss

InvLoss- Inverter Loss

EArrMPP- Array energy at maximum power point

5.3 Tracking System

Solar tracking system is an improvement on fixed module orientation, the goal of all types of tracking systems is to maximum energy production by being in 90^0 alignment with the sun at all times of the day. Basically there are two types of tracking system in PV power plants; single axis and double axes tracking systems. Under these two basic types of tracking systems; there are a number of different types of tracking system by virtue of geographical tracking examples, East -west tracking, North - south tracking, vertical or horizontal tracking etc.

Adding tracking systems to the design of the plant will increase energy production but will also add extra cost to the plant. Examples of solar PV tracking power plants are 105MW plant in Punjab, India and 206MW single axis tracking system in California USA. The various figures and tables represents simulation results for incorporating two axes tracking system East – West frame to the design of Kirehe photovoltaic power plant. The same result parameters obtained for the fixed angle orientation is also acquired for the two axes tracking system, analysis of the two systems will determine difference in levels of energy production between the two systems and economic feasibility. The results parameters are;

- Normalized production
- Performance ration
- Balances and main results table
- Loss diagram
- Detailed system losses

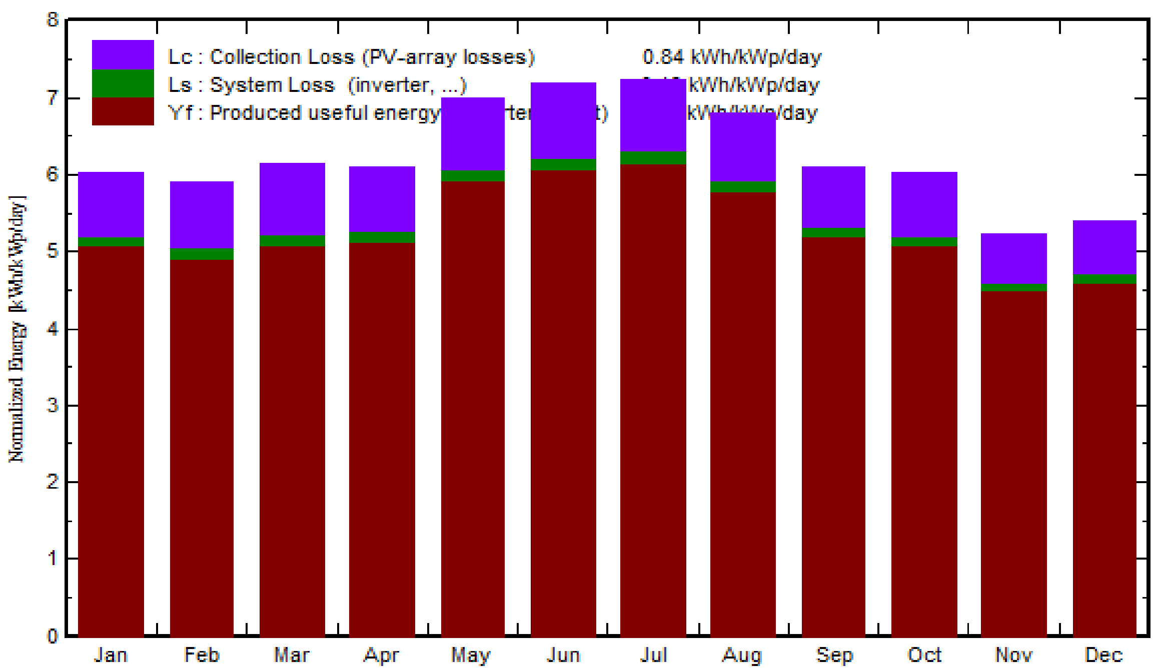

Figure 5.7: Normalized productions for tracking system

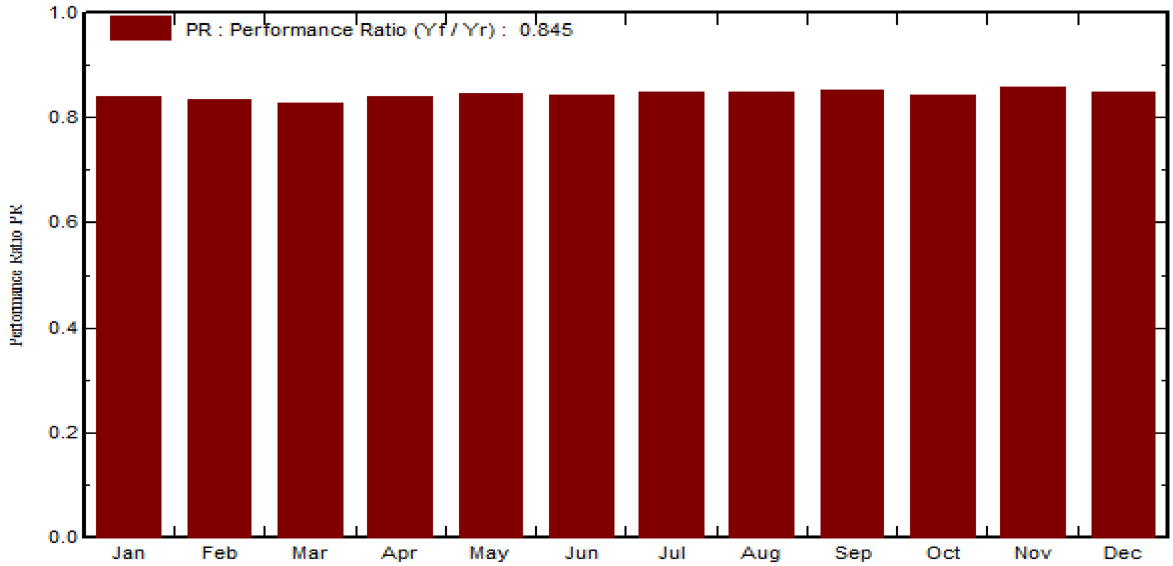

Figure 5.8: Performance ratio for tracking system

Table 5.3: Balances and main result for tracking system

	GlobHor KWh/m^2	DiffHor KWh/m^2	T Amb ^{0}C	GlobInc KWh/m^2	GlobEff KWh/m^2	EArray KWh	E_Grid KWh	PR
January	154.7	73.03	21.28	187.1	183.5	209686	204539	0.840
February	136.4	68.81	22.19	165.3	162.5	183810	179269	0.833
March	152.9	70.41	22.11	190.4	187.4	210595	205272	0.828
April	146.0	71.79	20.81	183.2	180.4	205551	200474	0.841
May	159.1	69.11	20.49	216.2	213.8	244981	239075	0.847
June	158.7	61.46	19.48	215.7	213.1	242594	236590	0.843
July	165.2	63.22	19.19	224.5	221.7	254185	247956	0.849
August	165.3	74.14	19.55	210.7	207.6	238624	232884	0.849
September	148.6	82.10	20.03	182.6	179.3	207388	202484	0.852
October	155.0	77.97	21.01	186.7	183.4	209821	204740	0.843
November	136.8	82.36	20.42	156.9	153.4	179527	175365	0.859
December	142.5	77.59	21.18	167.5	163.7	189986	185465	0.851
Year	1821.1	871.99	20.64	2287.4	2249.5	2576747	2514113	0.845

Table 5.4: Detailed System Losses for tracking system

	ModQual KWh	**MisLoss KWh**	**OhmLoss KWh**	**EArrMPP KWh**	**InvLoss KWh**
January	1711	1863	1477	166021	3940.371
February	1593	1734	1516	154417	3717.678
March	1840	2004	1929	178240	4387.992
April	1951	2124	2190	188786	4681.403
May	2483	2704	3113	239997	5981.896
June	2488	2710	3365	240276	6312.009
July	2598	2829	3390	250943	6309.119
August	2355	2564	2806	227736	5544.633
September	1838	2001	1746	178181	4116.760
October	1851	2016	1805	179403	4202.462
November	1496	1626	1126	145367	3293.328
December	1524	1660	1149	148097	3415.456
Year	23726	25838	25611	2297465	55903.106

Legends:

ModQual- Module quality losses

MisLoss- Module mismatch loss

OhmLoss- Ohmic wiring loss

InvLoss- Inverter Loss

EArrMPP- Array energy at maximum power point

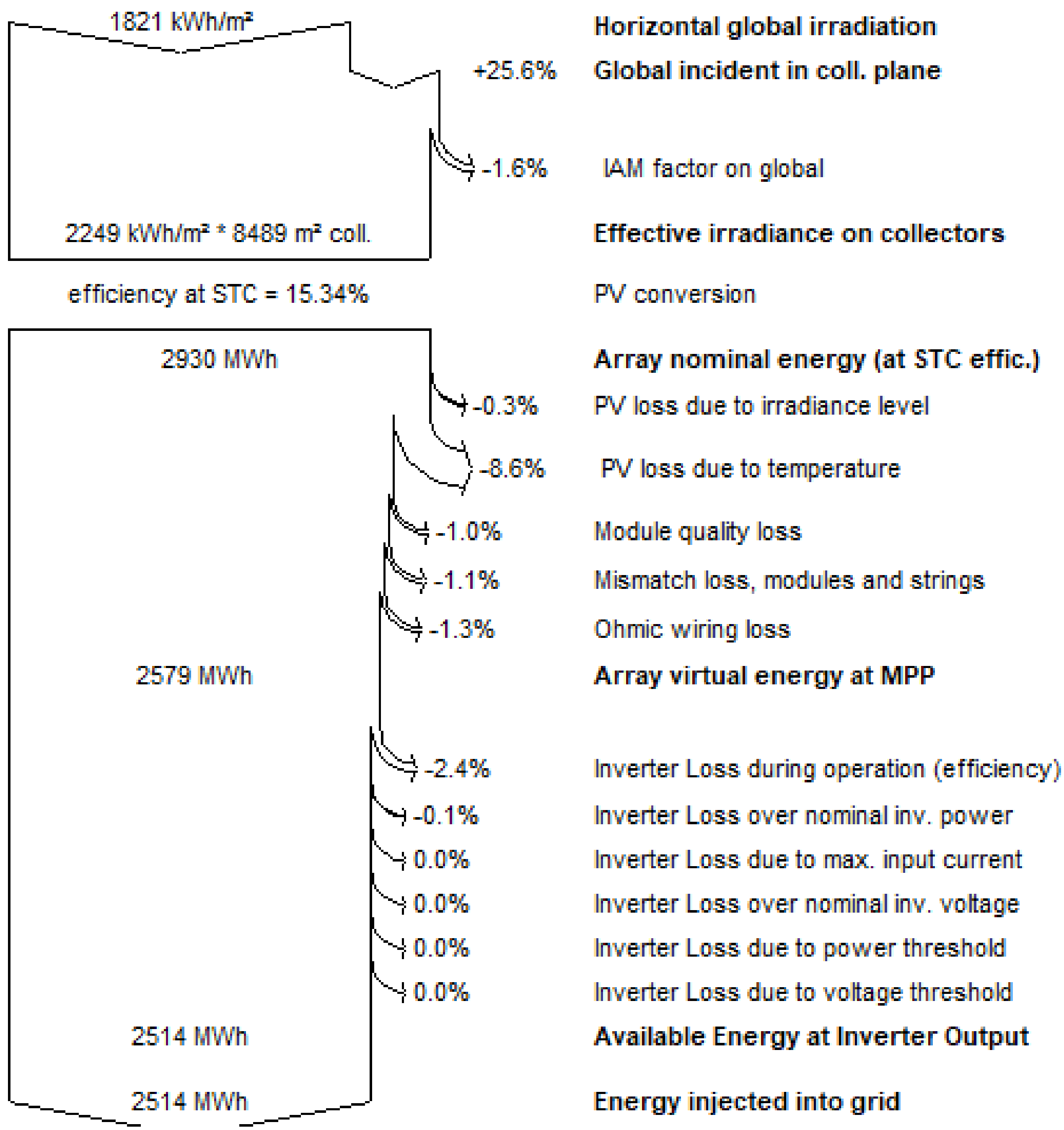

Figure 5.9: Loss diagram for tracking system

5.4 Economic Analysis

PV systems are often considered as a clean energy solution which is friendly to environment ,however ,on the other hand ,PV systems are also valuable in financial issues .With effective design and operation , PV system may pay back its investment and have further profit .Some PV systems have lower cost than other type of generations. To decide the cost and value of a PV system ,an economic analysis is conducted by designers.

5.4.1 Initial cost

Financial costs include initial costs ,maintenance costs ,repair costs and replacement costs.Initial cost involves the stage of design ,engineering ,devices and installation of the PV system .The prices of equipment are obtained from manufacturer or sellers. The different cost between a system that is installed by self and a system that requires professional installation of the devices .Then the total cost is thought to be the total cost to be initial cost at the beginning of life of the system .

Table5.5: Economic gloss

Economic parameters	**Fixed system**	**Tracking system**
Module cost	910 000€	910 000€
Support cost	832 000€	832 000€
Dual axis tracking motor and wiring	0 €	733 915.5 €
Inverter and wiring	260 000€	260 000€
Transport and mounting	641 269€	641 269€
Investment cost	2 643 269 €	3 143 184 €
Annuities	212 103 €/yr	252 217.2162 €/yr
Maintenance cost	34 201€/yr	34 201€/yr
Total yearly cost	246 304€/yr	286 904€/yr
Energy cost	0.13 €/yr	0.13 €/yr
Payback period	11 years	10 years

PVsyst software give access to define the installation cost and operation cost of PV power plant for grid connected only ,this value in table for grid connected ,we got it through from PVsyst simulation and we set lifetime to be 20 years of the system .

Based on the information given by the above Table .the approximated cost for the PV system size of 5200 modules of Samsung PV-MBA1BG250 in PVSYST is 91 000 euros , and the support cost of module in PVSYST it give me 832 000 euros. The cost of 87 inverter   Sunny tripower 15 000TL and its installation in PVSYST software is 260 000 euros ,Transport and mounting cost in PVsyst is 641 269 euros then the PVsyst software add the cost of modules 91000 euros plus the support cost of 832 000 plus cost of inverter and its installation   260 000 euros and the transport and mounting cost 6 412 269   euros the total summation of this cost it is the total investments which is equal to 2 643 269 euros .We set that If government of Rwanda take the loan for investment of 2 643 269 euros which is going to be paid in 20 years with rate of 5% each year it will supposed to pay 212 103 euros /yr as it was calculated by PVsyst

By my manual calculation also annuities is equal :

$$A= \frac{r(\ PV)}{1-(1+r)*power\ -n} \qquad (5.1)$$

$$A=\frac{0.05*2643269}{1-(\ 1+0.05)power-20} = 212\ 103 \text{ euros/yr}$$

r :Rate of period

n:Duration

PV :Present value

The PVsyst provide maintenance cost of 34 201 euros /yr, The total yearly cost is equal to annuities of 212 103 euros/yr plus maintenance cost of 34 201 euros/yr   will be equal to 246 304 euros/yr.The analysis in PVsyst software is based on the current system cost that are used in Rwanda . We set the energy cost in PVsyst   to be 0.13euros/Kwh as it is in Rwanda ,The yearly energy of fixed system in PVSYST   is 1918 000Kwh/yr .

For tracking system we assumed the some cost value to be the same as it is for fixed system ,module cost is 910 000 euros, support cost is 832000 euros ,inverter and wiring cost is 260000 euros transport and amounting cost is 641 269 euros but I added the cost of dual axis solar tracking system , it has the following characteristics (https://www.amazon.com/ECO-WORTHY-Dual-Solar-Tracking-System/dp/B00JYAIS9W Retrieved 21 April 2018**).**

- Complete solar tracking kits: 12V 6" & 12" Linear Actuator & Remote Controller & Mounting Accessories. Linear Actuator: 12V motor has gearbox and is rated to hold up to 330 lbs. when not moving. An all-metal housing and is water-resistant and sealed against dust for rugged durability.
- Dual axis controller: control dual axis linear actuator to make the solar panel to follow the Sunlight, keep the solar panel always face the sunlight. Smart weather detector,
- Material: Mounting pole is made from galvanized iron tube .Mounting arms are all made from Aluminum
- Perfect tracking mounting kit for solar panel system, improve solar power efficiency.

The cost of one dual axis solar tracking system is $499.00 & FREE Shipping and I changed it in euro it is 423.25 euro in that cost they will provide the cable and other components . One dual axis solar tracking system can hold approximately three modules (https://www.amazon.com/ECO-WORTHY-Dual-Solar-Tracking-System/dp/B00JYAIS9W Retrieved 21 April 2018)**.** The total modules is 5200 modules ,We will need 1734 dual axis solar tracking by taking 5200 modules divide by three , the total cost is equal 423.25 euros times 1734 modules ,the cost of dual axis solar tracking will be 73 3915.5 euros , then I sum up the total cost ,I get investment cost of 3 143 184 € .

$$A = \frac{0.05 * 3143184}{1-(1+0.05) power - 20} = 252\ 217.\ 2162\ €/yr$$

we assumed that the maintenance cost will be the same as it is for fixed system because there is the advancement in technology and reliability in electronics and mechanics ,the maintenance cost is 34 201€/yr .

Total yearly cost =maintenance cost +annuities (5.2)

Total yearly cost =34 201€/yr+252 217.2162 €/yr=286 418.216 €/yr

The energy cost is 0.13€/kwh as it is in Rwanda. The yearly energy production of tracking system from PVsyst Software it is 2 514 113 Kwh/yr.

5.4.2 Payback period

The payback period of a plant is the duration or time for which the plant is able to generate revenue from production to the meet the cost of installation. Economic analysis from PVsyst puts the cost of the plant at 2 643 269 million euros. To determine the payback period of the plant, the price the consumer pays for 1kWh of power will be used to determine revenue generation pattern of the plant. Analysis of yearly revenue generation and cost of the plant will ascertain the payback period of the plant. However I choose 20 years lifespan .

Revenue of fixed system per year = yearly energy * cost of energy (5.3)

Revenue of fixed system per year =1918000Kwh/yr *0.13€ /kwh=249340€

Revenue of tracking system per year=2514113Kwh/yr*0.13€/kwh=326834€

$$\text{The payback period for fixed system} = \frac{\text{the total investment}}{\text{generated revenue}} \quad (5.4)$$

$$\text{The payback period for tracking system} = \frac{2643269 \text{ euro}}{249340 \text{ euro}} = 11 \text{ years}$$

$$\text{The payback period for tracking system} = \frac{3143184}{326834.69 \text{ euros}} = 10 \text{ years}$$

This payback period it excludes maintenance cost and other cost incurred during operation of the plant.

As the result the tracking system is best option because it can increase the amount of electricity generated by photovoltaic modules even though it is expensive because of extra cost of tracking motor but you can get profit in short period than fixed system you can be able to payback the investment in short time than fixed system .

CHAPTER 6
CONCLUSION

6.1 Conclusion

Solar energy continues to play very important role in the generation and distribution of clean, affordable, sustainable and environmentally friendly electric power. Comparing photovoltaic system to other solar energy based technology make PV systems the most promising technology for electric power generation. This is because it cheap and does not require very cumbersome installation processes.
Rwanda just like any other third world country faces the enormous challenge of providing electricity to every citizen no matter their location in the country and economic status. The national population of Rwanda is 11.92 million (2016) with only 19.80% of the population having access to electricity which means that roughly 10 million of the population do not have access to electric power.

The main objective of this thesis is a proposal which seeks to increase electric power supply and at same time reduce the huge electric power deficit of Rwanda thereby increasing socio-economic development of the country. This will be achieved by designing, simulation and evaluation of a 1.3MW photovoltaic power plant using PVsyst software. The research was segmented into two parts; load estimation of the communities where power is to be provided and simulation using PVsyst.

Simulation results acquired for the proposed Kirehe PV power plant puts the yearly grid connected power at 1892338kWh for fixed module orientation and 2514113kWh for tracking systems; this represents 28.2211% increase which is very significant amount of power in PV systems. Performance ratio of 85% for both cases and losses of 12.37% -15.29 % are good indicators of PV power plants under optimal operations. Undoubtedly, the use PVsyst software as a tool for solar photovoltaic power plant simulation can be considered a good choice because of its extensive application in research works by academia and photovoltaic industry players. From the various simulation results obtained for the two case scenarios (fixed module and tracking system) of our research, we can conclude that technically and economically, the construction of PV power plant at Kirehe is feasible and poses no danger to the environment.

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APPENDICES

APPENDIX 1

FIXED SYSTEM

PVSYST V6.68		07/04/18	Page 1/3

Grid-Connected System: Simulation parameters

Project :	**New Project**			
Geographical Site	**Kirehe**		Country	**Rwanda**
Situation	Latitude	-2.27° S	Longitude	30.65° E
Time defined as	Legal Time	Time zone UT+2	Altitude	1504 m
	Albedo	0.20		
Meteo data:	**Kirehe**	Meteonorm 7.1, Sat=100% - Synthetic		

Simulation variant :	**New simulation variant**	
	Simulation date	07/04/18 20h03

Simulation parameters	System type	**No 3D scene defined**		
Collector Plane Orientation	Tilt	30°	Azimuth	0°
Models used	Transposition	Perez	Diffuse	Perez, Meteonorm
Horizon	Free Horizon			
Near Shadings	No Shadings			
PV Array Characteristics				
PV module Si-mono	Model	**PV-MBA1BG250**		
Original PVsyst database	Manufacturer	Samsung SDI. Co. Ltd.		
Number of PV modules	In series	15 modules	In parallel	347 strings
Total number of PV modules	Nb. modules	5205	Unit Nom. Power	250 Wp
Array global power	Nominal (STC)	**1301 kWp**	At operating cond.	1159 kWp (50°C)
Array operating characteristics (50°C)	U mpp	410 V	I mpp	2828 A
Total area	Module area	**8489 m²**	Cell area	7413 m²
Inverter	Model	**Sunny Tripower 15000TL-10**		
Original PVsyst database	Manufacturer	SMA		
Characteristics	Operating Voltage	150-800 V	Unit Nom. Power	15.0 kWac
Inverter pack	Nb. of inverters	86 * MPPT 0.80	Total Power	1290 kWac
PV Array loss factors				
Thermal Loss factor	Uc (const)	29.0 W/m²K	Uv (wind)	0.0 W/m²K / m/s
Wiring Ohmic Loss	Global array res.	2.4 mOhm	Loss Fraction	1.5 % at STC
Module Quality Loss			Loss Fraction	1.0 %
Module Mismatch Losses			Loss Fraction	1.0 % at MPP
Strings Mismatch loss			Loss Fraction	0.10 %
Incidence effect, ASHRAE parametrization	IAM =	1 - bo (1/cos i - 1)	bo Param.	0.05
User's needs :	Unlimited load (grid)			

Grid-Connected System: Main results

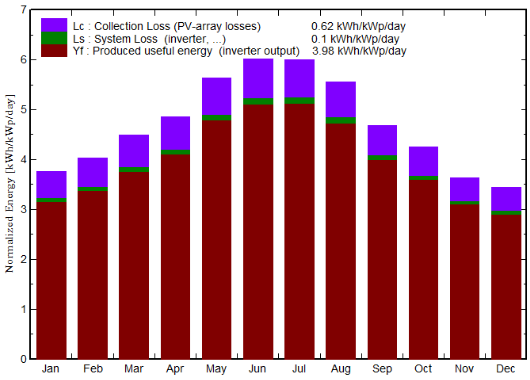
Project : **New Project**

Simulation variant : **New simulation variant**

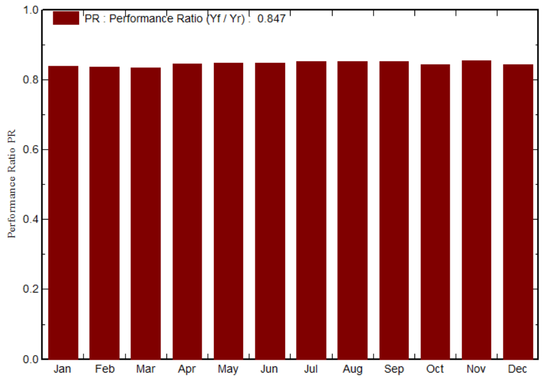
Main system parameters	System type	**Grid-Connected**		
PV Field Orientation	tilt	30°	azimuth	0°
PV modules	Model	PV-MBA1BG250	Pnom	250 Wp
PV Array	Nb. of modules	5205	Pnom total	**1301 kWp**
Inverter	Model	Sunny Tripower 15000TL-10		15.00 kW ac
Inverter pack	Nb. of units	86.0	Pnom total	**1290 kW ac**
User's needs	Unlimited load (grid)			

Main simulation results				
System Production	**Produced Energy**	**1892 MWh/year**	Specific prod.	1454 kWh/kWp/year
	Performance Ratio PR	84.72 %		

Normalized productions (per installed kWp): Nominal power 1301 kWp



Performance Ratio PR



New simulation variant

Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_Grid MWh	PR
January	154.7	73.03	21.28	116.7	111.0	130.9	127.6	0.840
February	136.4	68.81	22.19	112.9	108.0	125.9	122.9	0.836
March	152.9	70.41	22.11	139.3	134.4	155.3	151.5	0.835
April	146.0	71.79	20.81	145.6	141.1	164.1	160.2	0.846
May	159.1	69.11	20.49	174.8	170.2	197.9	193.2	0.849
June	158.7	61.46	19.48	180.7	176.5	204.4	199.5	0.849
July	165.2	63.22	19.19	186.3	181.9	211.9	206.8	0.853
August	165.3	74.14	19.55	172.1	167.5	195.6	191.0	0.853
September	148.6	82.10	20.03	140.6	135.7	159.9	156.2	0.854
October	155.0	77.97	21.01	132.1	126.7	148.7	145.2	0.845
November	136.8	82.36	20.42	108.9	103.9	124.1	121.2	0.855
December	142.5	77.59	21.18	106.6	101.3	120.2	117.2	0.845
Year	1821.1	871.99	20.64	1716.6	1658.1	1939.0	1892.3	0.847

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

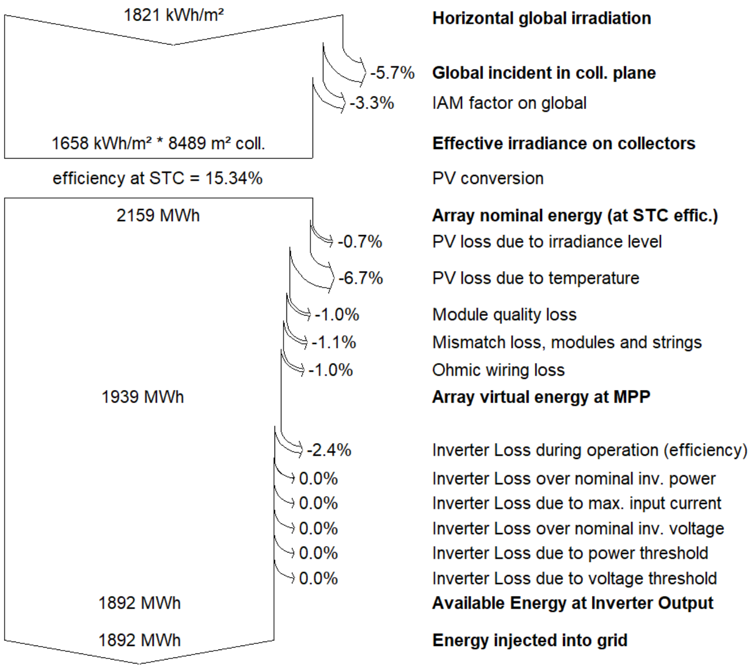
Grid-Connected System: Loss diagram

Project : **New Project**

Simulation variant : **New simulation variant**

Main system parameters	System type	**Grid-Connected**		
PV Field Orientation	tilt	30°	azimuth	0°
PV modules	Model	PV-MBA1BG250	Pnom	250 Wp
PV Array	Nb. of modules	5205	Pnom total	**1301 kWp**
Inverter	Model	Sunny Tripower 15000TL-10		15.00 kW ac
Inverter pack	Nb. of units	86.0	Pnom total	**1290 kW ac**
User's needs	Unlimited load (grid)			

Loss diagram over the whole year



APPENDIX 2

TRACKING SYSTEM

PVSYST V6.68		08/04/18	Page 1/3

Grid-Connected System: Simulation parameters

Project :	**New Project**			
Geographical Site	**Kirehe**		Country	**Rwanda**
Situation	Latitude	-2.27° S	Longitude	30.65° E
Time defined as	Legal Time	Time zone UT+2	Altitude	1504 m
	Albedo	0.20		
Meteo data:	**Kirehe**	Meteonorm 7.1, Sat=100% - Synthetic		

Simulation variant :	**New simulation variant**			
	Simulation date	08/04/18 16h51		

Simulation parameters	System type	**No 3D scene defined**		
Tracking two axis, frame E/W	Frame axis azimuth	0°		
Frame Rotation Limitations	Minimum Tilt	10°	Maximum Tilt	80°
Tracker's tilt on frame	Minimum Phi	-60°	Maximum Phi	60°
Models used	Transposition	Perez	Diffuse	Perez, Meteonorm
Horizon	Free Horizon			
Near Shadings	No Shadings			
PV Array Characteristics				
PV module Si-mono	Model	**PV-MBA1BG250**		
Original PVsyst database	Manufacturer	Samsung SDI. Co. Ltd.		
Number of PV modules	In series	15 modules	In parallel	347 strings
Total number of PV modules	Nb. modules	5205	Unit Nom. Power	250 Wp
Array global power	Nominal (STC)	**1301 kWp**	At operating cond.	1159 kWp (50°C)
Array operating characteristics (50°C)	U mpp	410 V	I mpp	2828 A
Total area	Module area	**8489 m²**	Cell area	7413 m²
Inverter	Model	**Sunny Tripower 15000TL-10**		
Original PVsyst database	Manufacturer	SMA		
Characteristics	Operating Voltage	150-800 V	Unit Nom. Power	15.0 kWac
Inverter pack	Nb. of inverters	86 * MPPT 0.80	Total Power	1290 kWac
PV Array loss factors				
Thermal Loss factor	Uc (const)	29.0 W/m²K	Uv (wind)	0.0 W/m²K / m/s
Wiring Ohmic Loss	Global array res.	2.4 mOhm	Loss Fraction	1.5 % at STC
Module Quality Loss			Loss Fraction	1.0 %
Module Mismatch Losses			Loss Fraction	1.0 % at MPP
Strings Mismatch loss			Loss Fraction	0.10 %
Incidence effect, ASHRAE parametrization	IAM =	1 - bo (1/cos i - 1)	bo Param.	0.05
User's needs :	Unlimited load (grid)			

Grid-Connected System: Main results

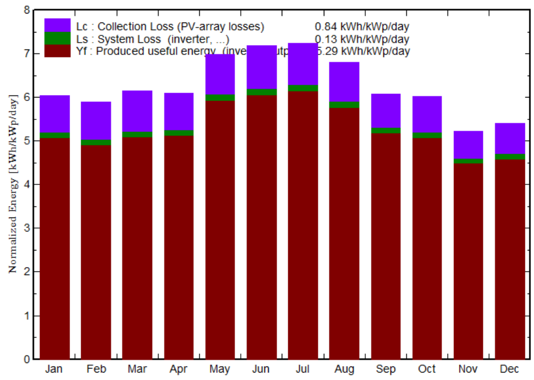
Project : **New Project**

Simulation variant : **New simulation variant**

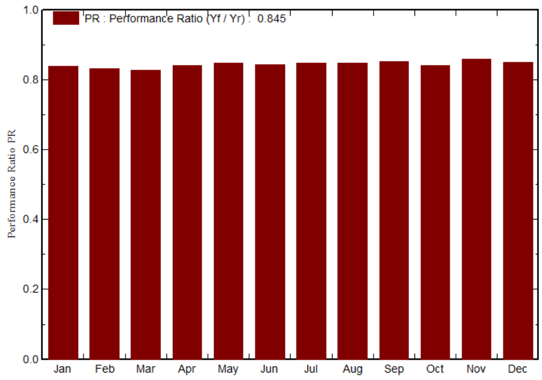
Main system parameters	System type	**Grid-Connected**		
PV Field Orientation	tilt			
PV modules	Model	PV-MBA1BG250	Pnom	250 Wp
PV Array	Nb. of modules	5205	Pnom total	**1301 kWp**
Inverter	Model	Sunny Tripower 15000TL-10		15.00 kW ac
Inverter pack	Nb. of units	86.0	Pnom total	**1290 kW ac**
User's needs	Unlimited load (grid)			

Main simulation results				
System Production	**Produced Energy**	**2514 MWh/year**	Specific prod.	1932 kWh/kWp/year
	Performance Ratio PR	84.47 %		

Normalized productions (per installed kWp): Nominal power 1301 kWp



Performance Ratio PR



New simulation variant

Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_Grid MWh	PR
January	154.7	73.03	21.28	187.1	183.5	209.7	204.5	0.840
February	136.4	68.81	22.19	165.3	162.3	183.8	179.3	0.833
March	152.9	70.41	22.11	190.4	187.4	210.6	205.3	0.828
April	146.0	71.79	20.81	183.2	180.2	205.6	200.5	0.841
May	159.1	69.11	20.49	216.8	213.8	245.0	239.1	0.847
June	158.7	61.46	19.48	215.7	213.1	242.6	236.6	0.843
July	165.2	63.22	19.19	224.5	221.7	254.2	248.0	0.849
August	165.3	74.14	19.55	210.7	207.6	238.6	232.9	0.849
September	148.6	82.10	20.03	182.6	179.3	207.4	202.5	0.852
October	155.0	77.97	21.01	186.7	183.4	209.8	204.7	0.843
November	136.8	82.36	20.42	156.9	153.4	179.5	175.4	0.859
December	142.5	77.59	21.18	167.5	163.7	190.0	185.5	0.851
Year	1821.1	871.99	20.64	2287.4	2249.5	2576.7	2514.1	0.845

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

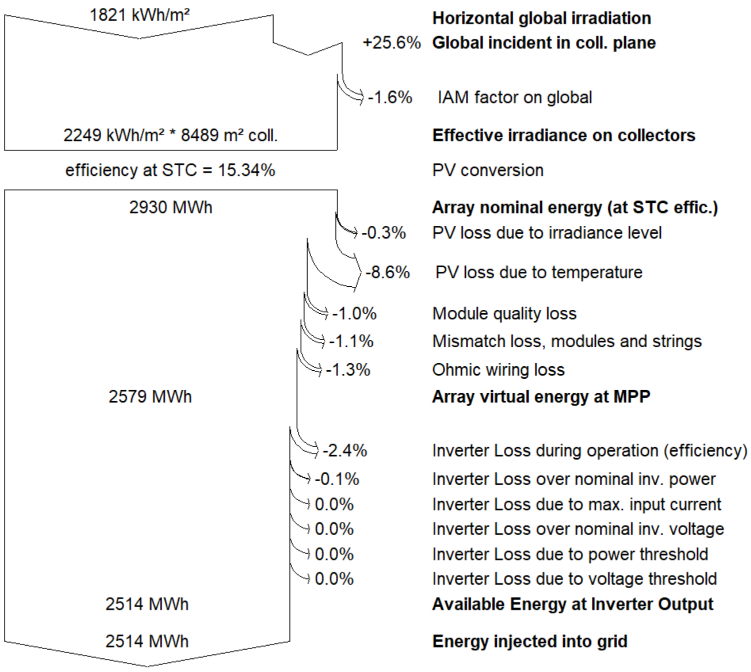
Grid-Connected System: Loss diagram

Project : **New Project**

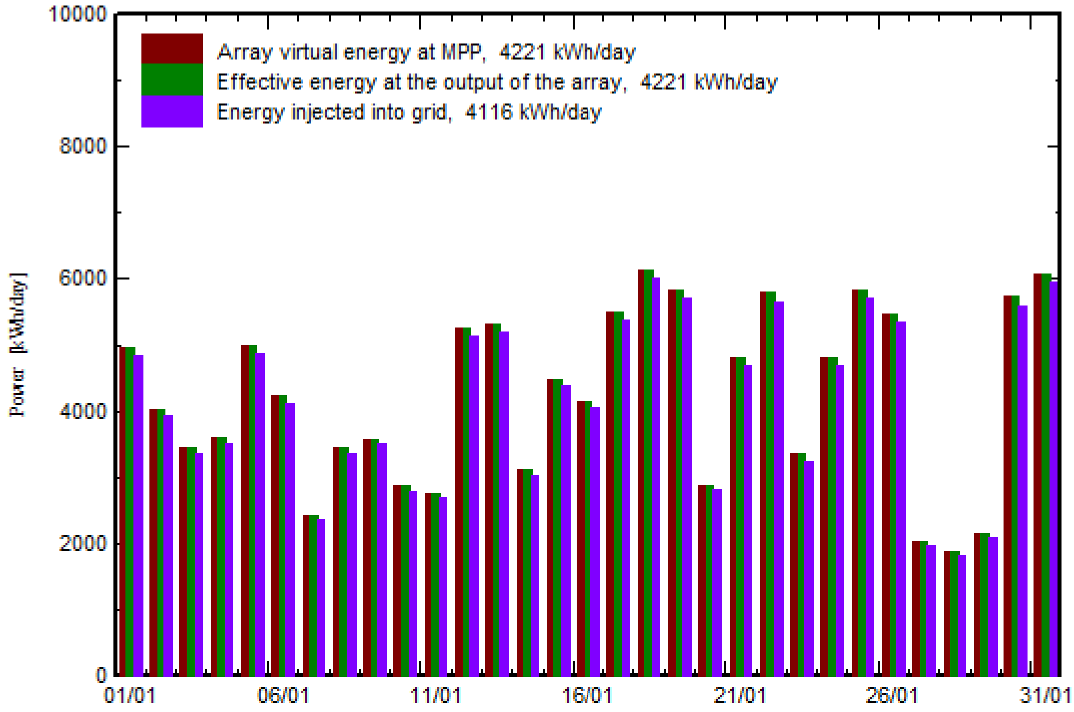
Simulation variant : **New simulation variant**

Main system parameters	System type	**Grid-Connected**		
PV Field Orientation	tilt			
PV modules	Model	PV-MBA1BG250	Pnom	250 Wp
PV Array	Nb. of modules	5205	Pnom total	**1301 kWp**
Inverter	Model	Sunny Tripower 15000TL-10		15.00 kW ac
Inverter pack	Nb. of units	86.0	Pnom total	**1290 kW ac**
User's needs	Unlimited load (grid)			

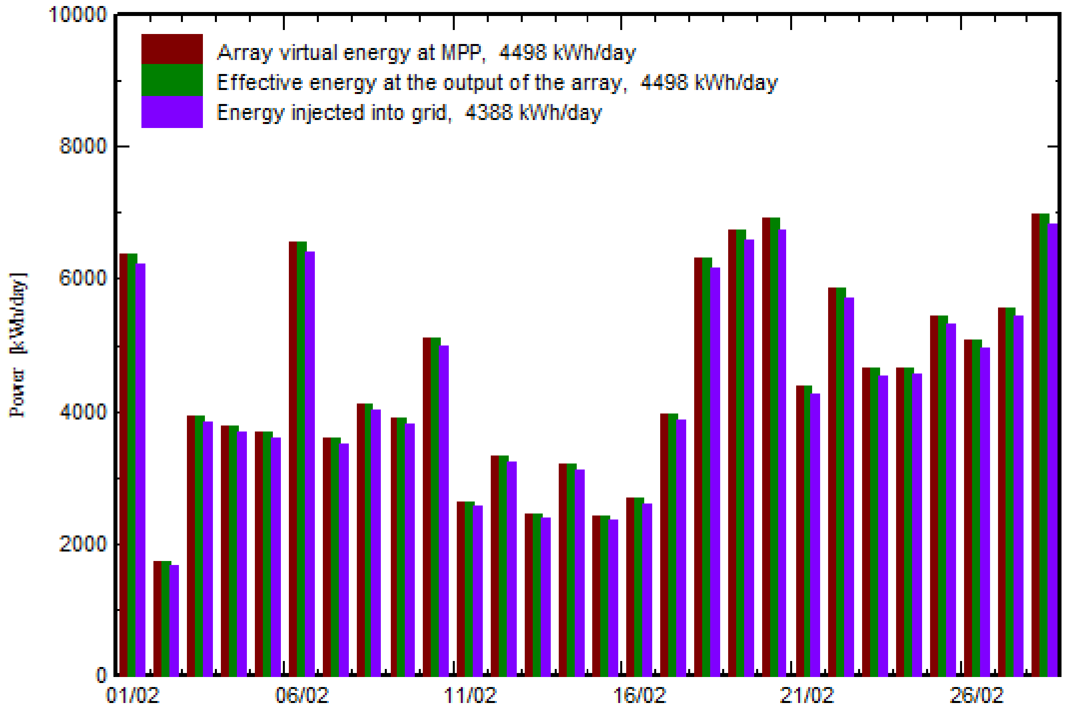
Loss diagram over the whole year

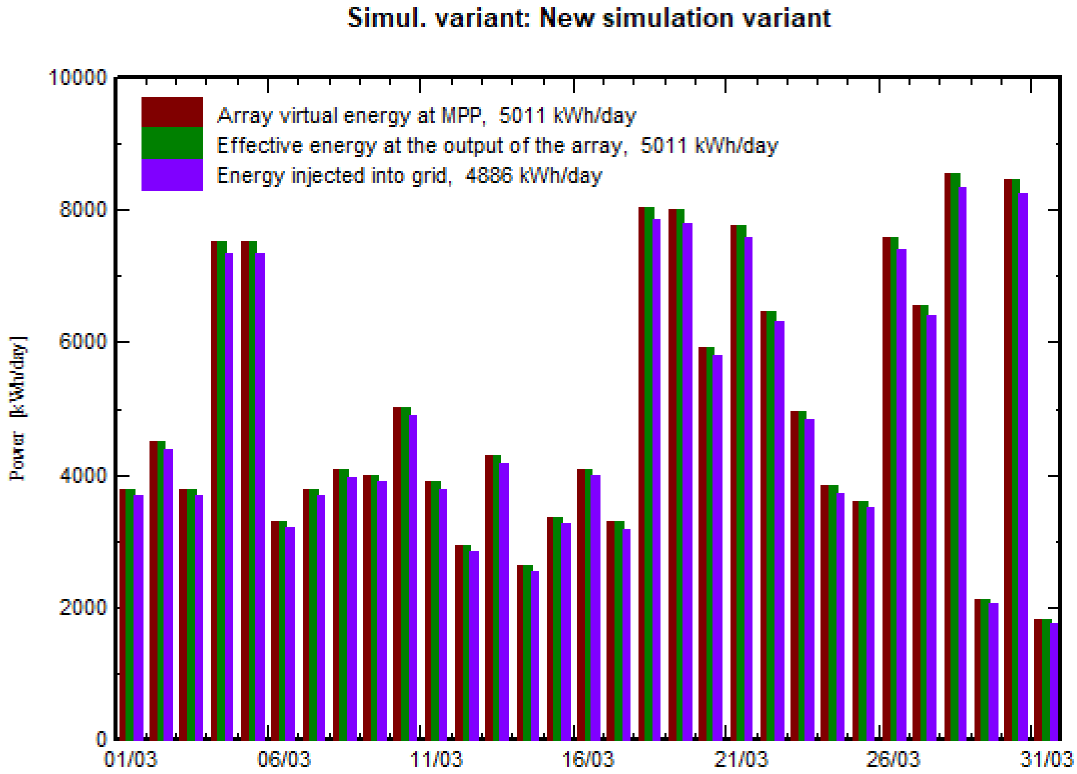


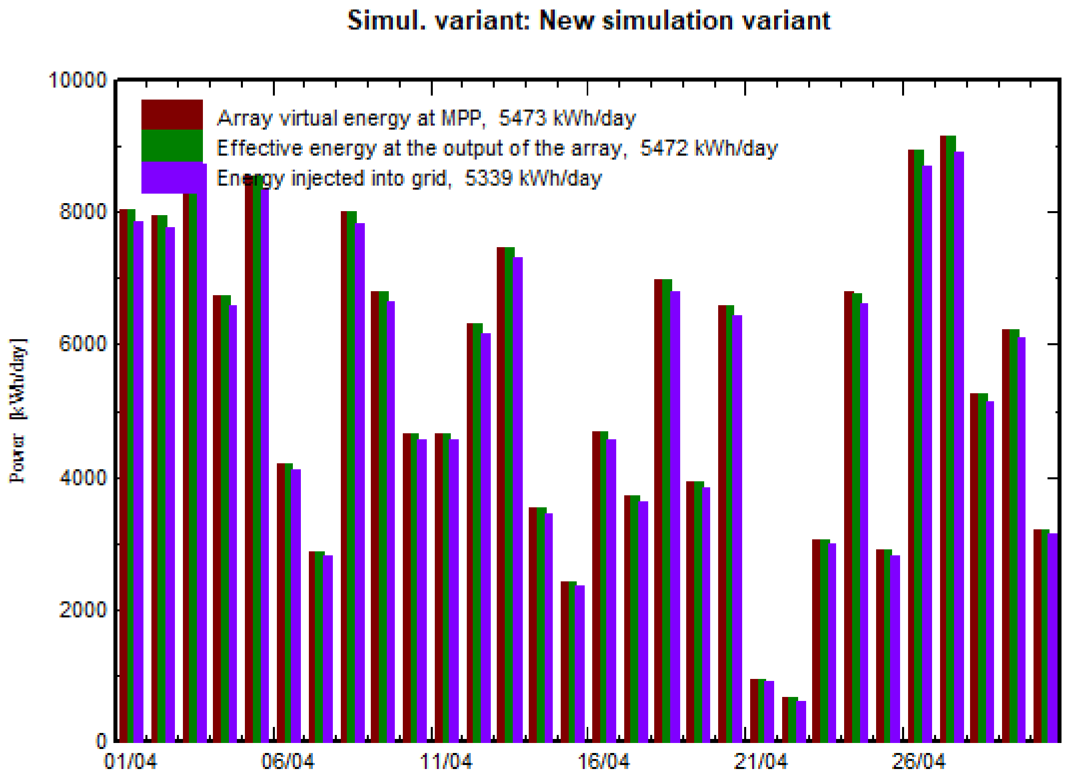
Simul. variant: New simulation variant



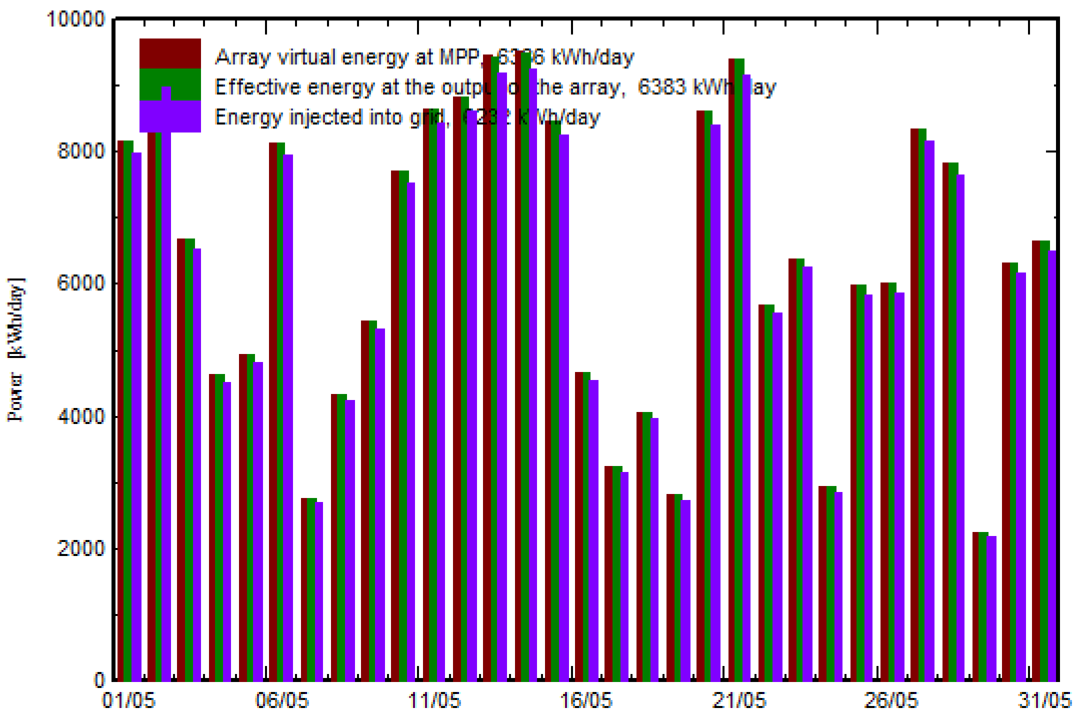
Simul. variant: New simulation variant



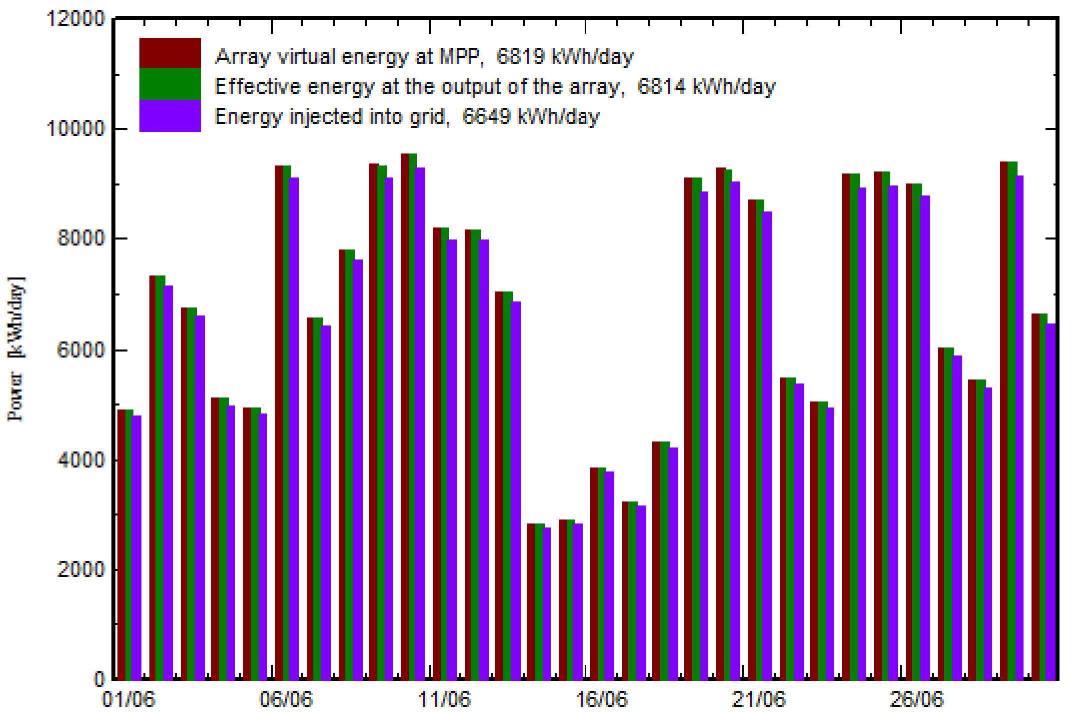

Simul. variant: New simulation variant
Array virtual energy at MPP, 5011 kWh/day
Effective energy at the output of the array, 5011 kWh/day
Energy injected into grid, 4886 kWh/day
Power [kWh/day]
10000
8000
6000
4000
2000
0
01/03
06/03
11/03
16/03
21/03
26/03
31/03


Simul. variant: New simulation variant
Array virtual energy at MPP, 5473 kWh/day
Effective energy at the output of the array, 5472 kWh/day
Energy injected into grid, 5339 kWh/day
Power [kWh/day]
10000
8000
6000
4000
2000
0
01/04
06/04
11/04
16/04
21/04
26/04

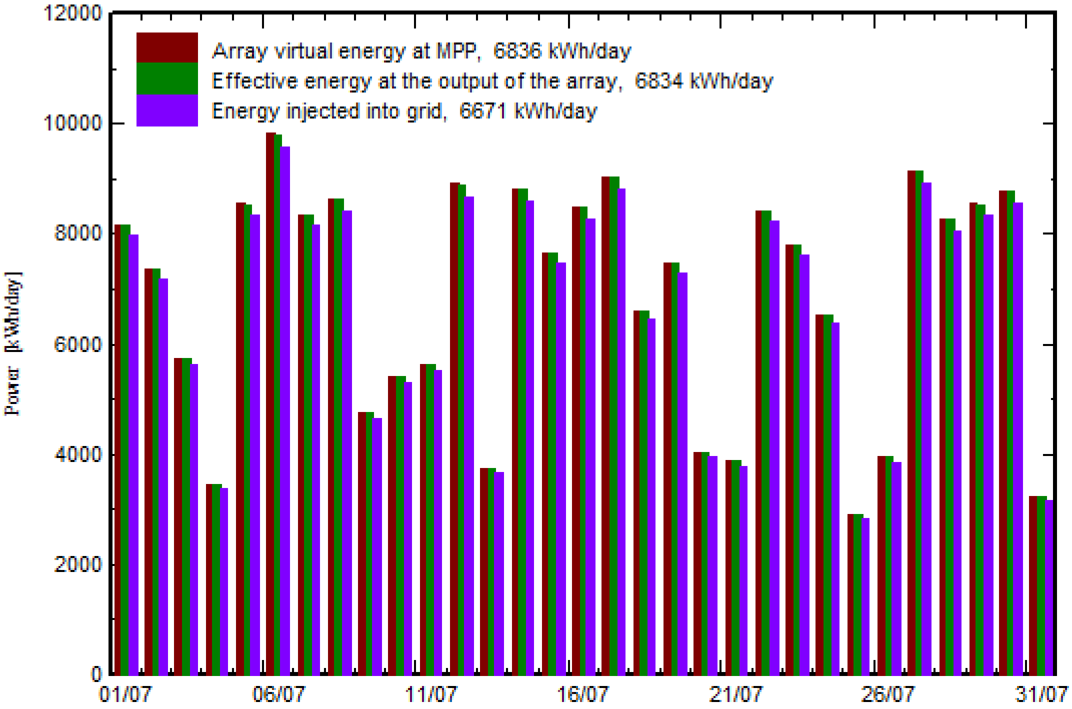
Simul. variant: New simulation variant



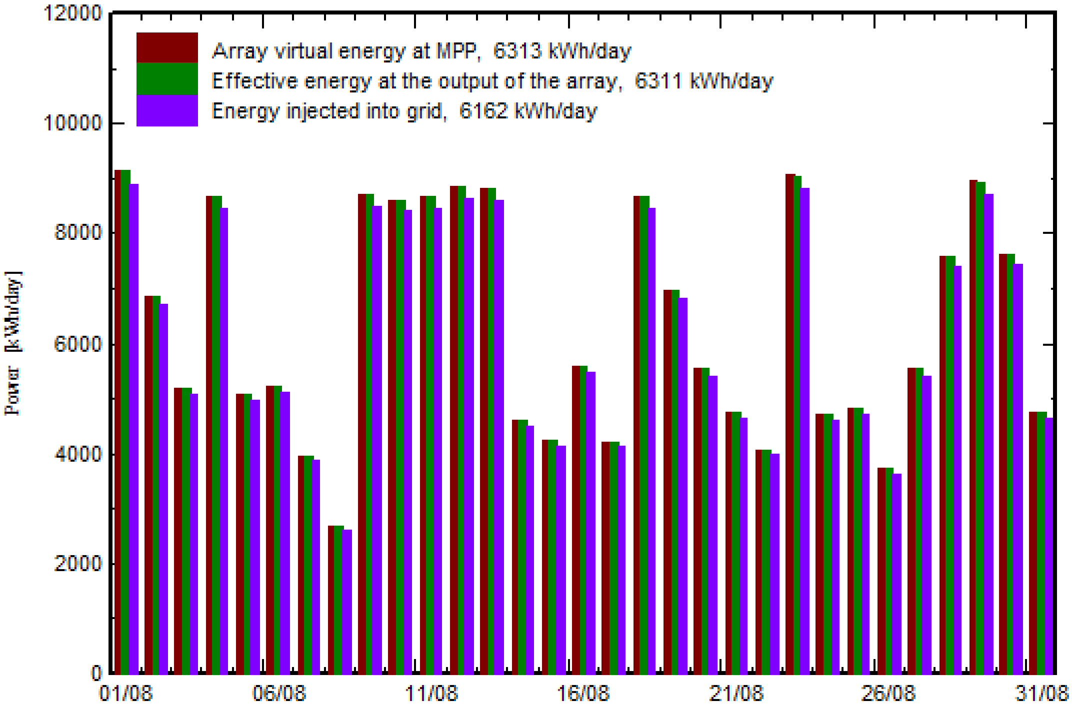
Simul. variant: New simulation variant



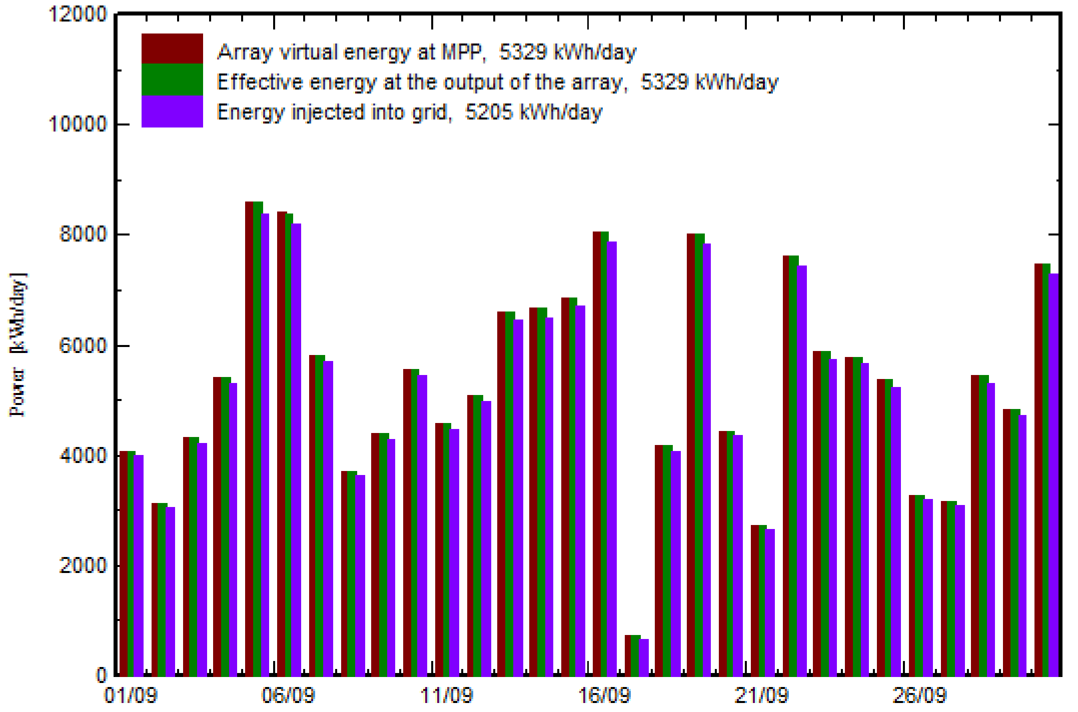
Simul. variant: New simulation variant



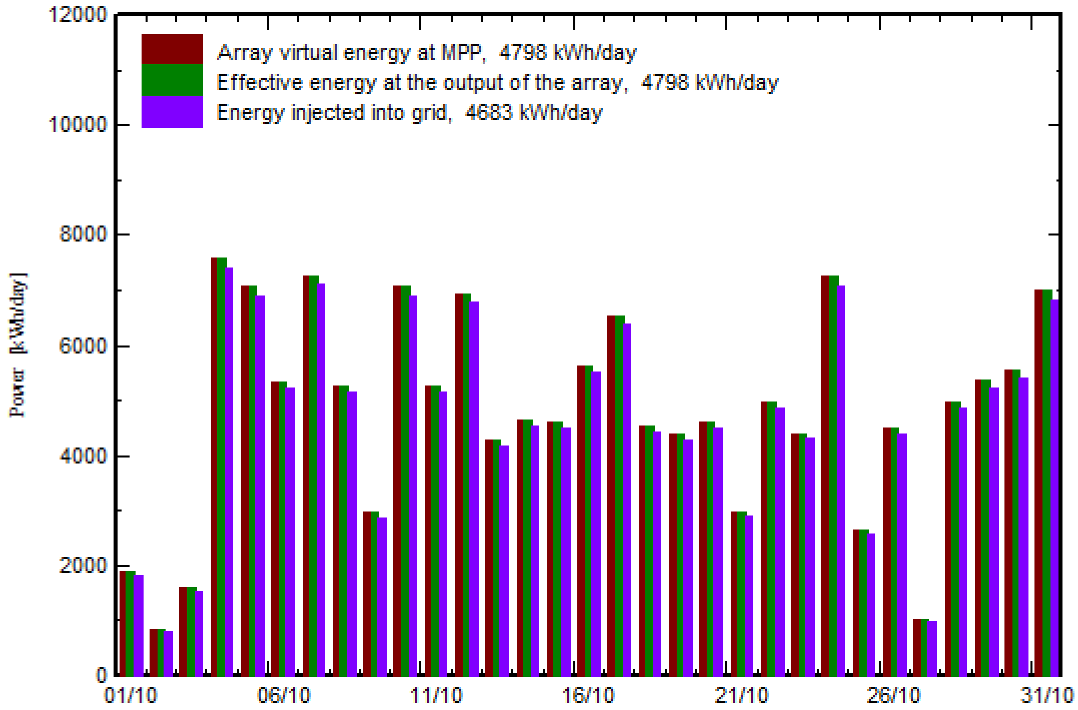
Simul. variant: New simulation variant

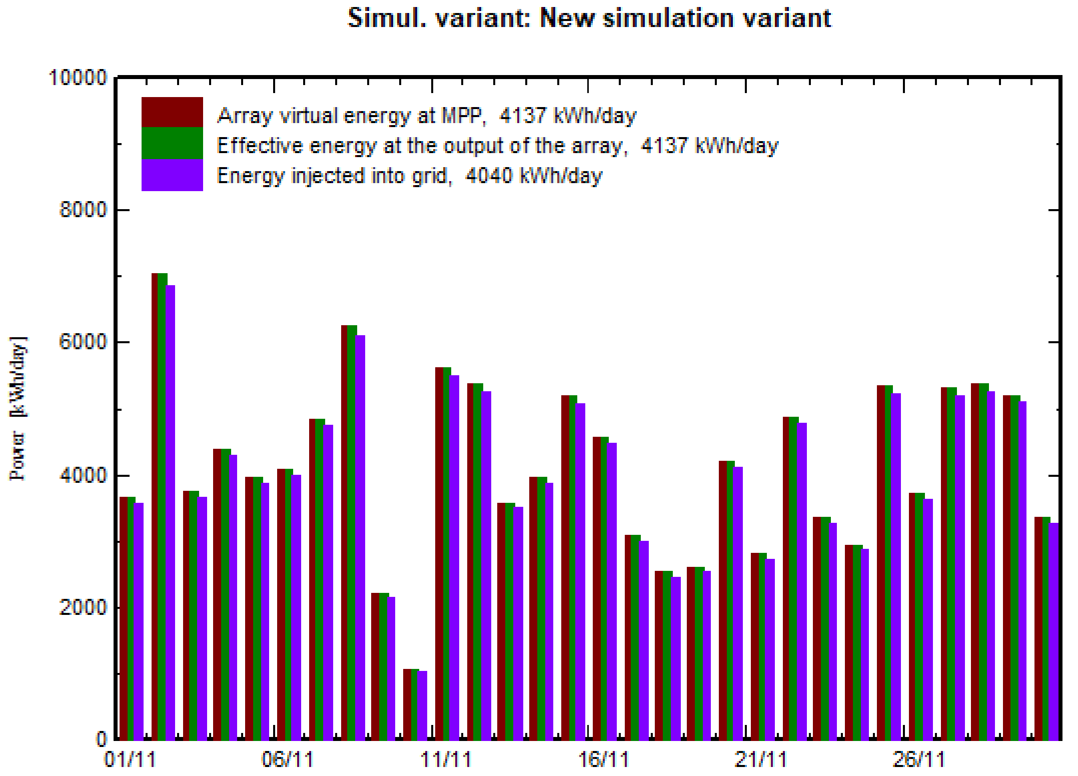


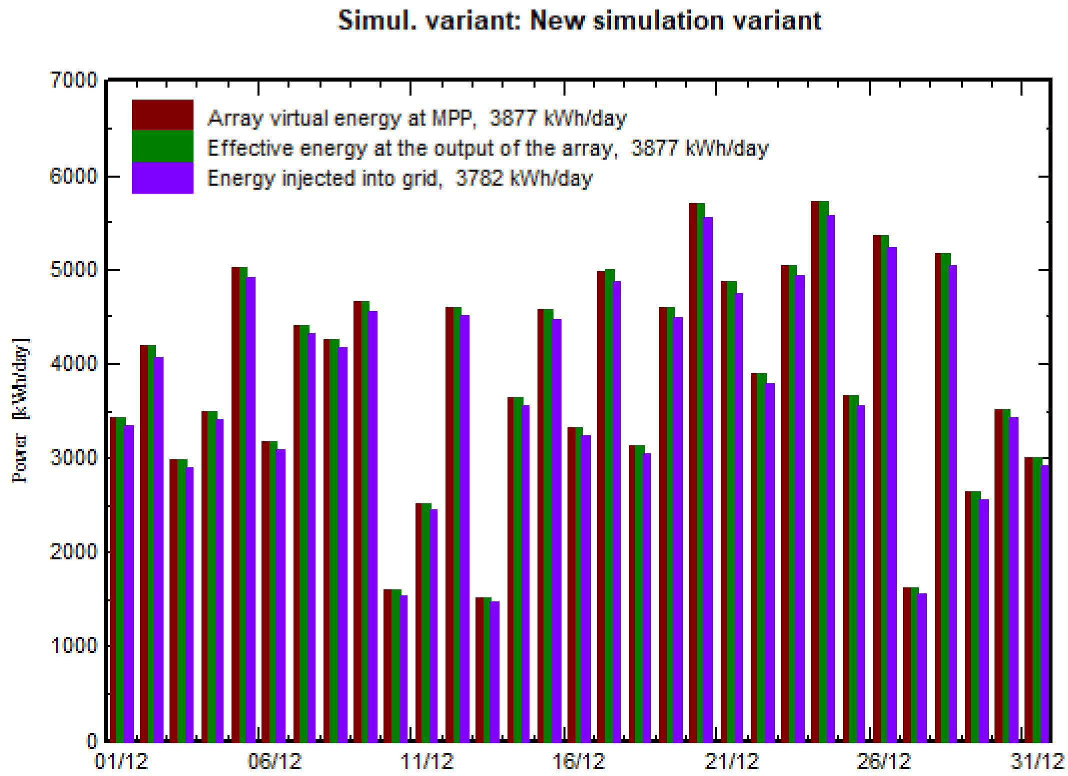
Simul. variant: New simulation variant



Simul. variant: New simulation variant

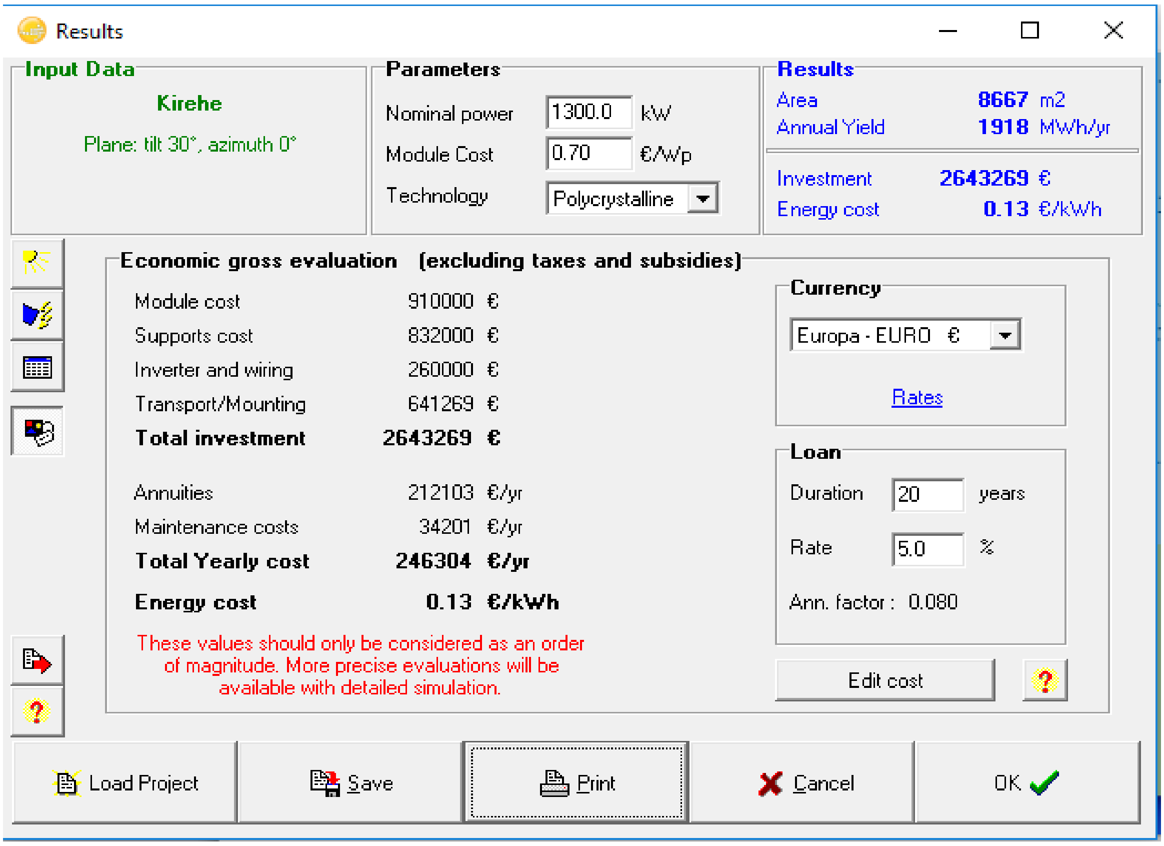


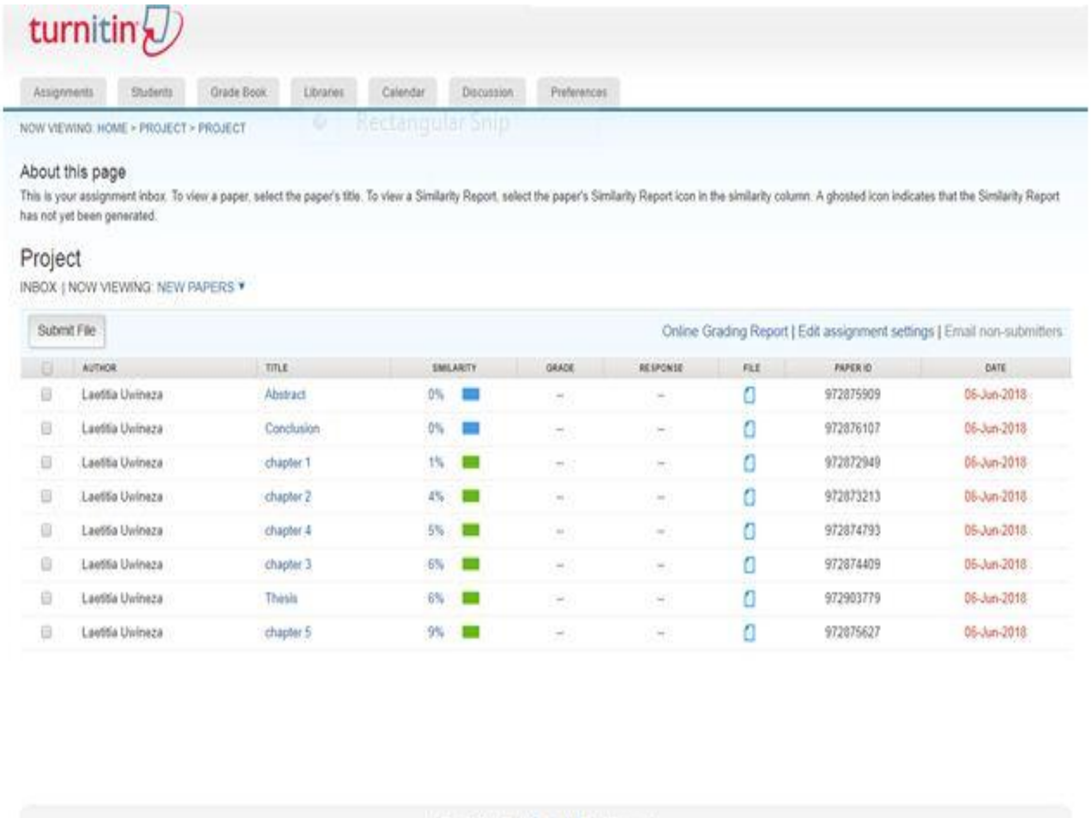

Simul. variant: New simulation variant
Array virtual energy at MPP, 4137 kWh/day
Effective energy at the output of the array, 4137 kWh/day
Energy injected into grid, 4040 kWh/day
Power [kWh/day]
10000
8000
6000
4000
2000
0
01/11
06/11
11/11
16/11
21/11
26/11


Simul. variant: New simulation variant
Array virtual energy at MPP, 3877 kWh/day
Effective energy at the output of the array, 3877 kWh/day
Energy injected into grid, 3782 kWh/day
Power [kWh/day]
7000
6000
5000
4000
3000
2000
1000
0
01/12
06/12
11/12
16/12
21/12
26/12
31/12

APPENDIX 3

ECONOMIC ANALYSIS

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