PERFORMANCE EVALUATION OF SERHATKOY PV POWER PLANT

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To my mom: Theresa Ansah…

ABSTRACT

Solar energy continues to play pivotal role in the delivery of clean and affordable source of generating electricity. Photovoltaic is the most promising technology amongst the types/methods of producing electricity from solar energy. The aim of this thesis is to evaluate the performance of Serhatkoy PV power plant. The results of the analysis will be useful in expanding the existing solar park or replicate such facility in locations with favorable weather conditions, evaluate the investments made, plan maintenance and estimate the efficiency of production. PVsyst software is used to model Serhatkoy PV power plant and simulation done to determine the performance ratio using meteorological data provided by NASA. Also the capacity factor is determined and the PR calculated using SAM formula proposed NREL. The payback period of the plant is also estimated using revenue generated and exchange rate between Turkish lira and Euro.

Keywords: Solar energy, photovoltaic systems, performance ratio, Capacity factor, payback period

Özet

Güneş enerjisi temiz ve ekonomik enerji ürertiminde önemli bir rol oynamaya devam etmektedir. Fotovoltaik güneş enerjisi üretim teknolojileri içerisinde gelecek vadeden önemli bir yer işgal etmektedir. Bu tez çalışması Serhatköy PV santralının performansını değerlendirmek için gerrçekleştirilmiştir. Bu tez konusu olan analizler ile ulaşılan sonuçlar bu santralın muhtemel genişletilmesi, veya gelecek yatırımlar için bu bölgenin uygunluğu yanı sıra mevcut yatırımın değerlendirilmesi ve bakım ve verim çalışmalarının planlanmasına yardımcı olacaktır. Santralın modellenmesinde PVsyst yazılımı kullanılmış ve simulasyon NASA tarafından yayınlanan meteoroloji verileri kullanılarak performans oranını hesaplama amacı ile gerçekleştirilmiştir. Kapasite katsayısı da hesaplanarak performans katsayısı NREL tarafından sunulan SAM formulü ile belirlenmiştir. Santralın geri ödeme süresi ise Türk lirası ile Euro arasındaki kur farkı da göz önüne alınarak ve yaratılan özvarlıklar dikkate alınarak hesaplanmıştır.

Anahtar kelimeler: Güneş Enerjisi, fotovoltaik sistemler, performans katsayısı, kapasitekatsayısı, geri ödeme süresi.

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LIST OF ABBREVIATIONS

DC: Direct Current

MPPT: Maximum Power Point Tracking

PSCAD: Power System Computer Aided Design

NREL: National Renewable Energy Laboratory

SAM: System Advisor Model

PV: Photovoltaic System

CSP: Concentrated Solar Power

STC: Standard Test Condition

CF: Capacity Factor

PR: Performance Ratio

E_Grid: Energy injected into grid

E_Array: Effective energy at the output of the array

AP_Results: Actual Plant Results

CHAPTER 1

1.1 Overview

This chapter is made of introduction, literature review, objectives of the thesis and organization of the thesis. The subject matter is briefly introduced in the introduction and literature review is composed of scientific literature concerning solar energy and its performance evaluation.

1.2 Introduction

The demand for electricity has surged over the years; this is due to the rise in consumption of both developed and developing nation. This demand is expected to grow by 37% by 2040[15]. Though electricity is useful in driving industrial developments, health and agricultural developments, real estates and transportation, the cost and effects of electricity generation using fossil fuels is of concern because of the harmful effects of these fuels. Renewable energy sources (solar, wind, hydro bio-gas etc) of producing electricity are safe, cheap, clean and environmentally friendly.

Solar energy is the energy derived from the sun, when the sun's radiation reaches the earth's atmosphere; it is converted into other forms for the production of electricity. Enormous amount of solar energy is by the earth from the sun every day. 4.2kWh/m/day of solar energy is received by the earth. Part of this is reflected back into the atmosphere, others are used by biological lives and the rest goes to waste. The prospect of renewable for the future is undoubtedly growing fast with solar energy leading the growth. It's a matter of national security for countries which rely on fossil foil.

The four main solar energy technologies for producing electricity from the sun are solar photovoltaic systems, concentrated solar power, concentrated photovoltaic and solar thermal energy. The advantages of solar energy is vast, aside providing electricity at cheaper rates compared to fossil fuel, the biggest advantage of solar energy is environmentally friendly; does not produce any by-products which are harmful to the environment. The major setback for solar energy is the unavailability of sun light at night, winter and cloudy and stormy days. Photovoltaic system use silicon solar cells to produce electricity when exposed to light. The amount of electricity produced depends on several factors including the amount of irradiation and the size of the cell [16].

Serhatkoy PV power plant is located in North Cyprus. The plant has a nominal power of 1275.5kWp. The plant is made up 6192 Photovoltaic panels occupying an area of 8124m^2. The panels are manufactures by KIOTO Photovoltaic and 205Wp panel type is used for the solar park. From the manufacturer's manual, the panels have 90% efficiency for 10 year and 80% efficiency for 25year [3] 86 group of Aurora inverters are used to convert the CD power into AC, it has an efficiency of 98% and it is manufactured Power-one [17].

1.3 Literature review

This part of the thesis is a review of published articles and research papers relating to performance evaluation of stand-alone or grid connected photovoltaic systems. The authors in [18] finds calculative accuracy of PVsyst, TRNSYS ,PVGIS, Archelios, Polysun and PV*SOL (software) with to 19.8kWp grid connected PV system. System losses of 7% is used and to analyze the collected data from the software and plant, the following parameters were used; RMSE, MAD, MAPE and EF. The authors discovered the main source of error to be the model of PV cell and proposed further research into PV simulation against real-world results to improve the accuracy for each software.

Performance evaluation of PV systems using MPPT algorithm with backup battery is proposed by [19]. The proposed system is made up of 280Vdc PV module with 34kW to supply DC and AC load, 10kWdc series RL load and 100Var(at 220Vdc), 16kW$_{AC}$ parallel RL load and 800Var (at 400V$_{ph\text{-}ph}$ AC). 150 (800mAh) Li-Ion batteries are used as backup when the PV cell fails. The authors concluded that MPPT with charge controller is a better way to maximize the power of photovoltaic systems using backup batteries. Power output can be maintained even with varying irradiation and the V – I harmonics of Ac load is than 5%. Also the authors in [20] propose a system consisting of DC/DC buck converter with MPPT, PV model, BESS to interface DC bus to DC/DC boost converter and VSC used for grid interfacing. This is used to evaluate grid connected PV performance with battery energy storage. PSCAD/EMTDC is used for simulation, the simulations results show that BESS (for DC bus voltage regulation) is affected by power converter characteristics and chemistries of lead-acid battery start-up transient.

The aim of this research work was to evaluate the performance of subsystems operating under solar powered water pump [21]. The system is made up of 900Wp modules (72V nominal DC bus), DC/DC converter. VFD and 3phase induction motor. MPPT algorithm to maximize power of the model is used; the system was tested in Chennai, India. Two different topologies are used, one; 24 array PV modules, 3phase bridge made of 6IGBTs functions as a bridge. The second topology consists of 900Wp PV array, DC/DC converter, VFD, induction motor. Maximum peak overshoot is the 1100V of the cable rating used (3phase motor). Due to subsystems inefficiencies, water delivery and solar radiation are not proportional.

Comparison between NREL SAM and PVsyst on PV performance/yield comparison to determine the best software for analyzing PV systems [22]. The plant used for the analyses is 1MW Suniva (250 OPTIMUS mono-crystalline) system composed of 4004 modules with 14 string size (286 strings). The location of the plant is Atlanta Hartsfield Airport TMY3; tilt angle is 30^0 with azimuth angle of 180^0 for SAM system and 0^0 for PVsyst. The results of simulation shows 1586.206 MWH/yr and 1560 MWH/yr energy yield output for SAM and PVsyst respectively. The specific yield output for SAM is 1586MWH/yr and 1558MWH/yr for PVsyst. The PR recorded was 88% for SAM and 84.30% for PVsyst. From the results, SAM system performed better than PVsyst by 2%. SAM 2012.5.11 and PVsyst 5.56 software versions were used.

NREL explains the different methodology required in analyzing the performance of photovoltaic systems, explanations of predicted energy, expected energy and measured energy is made [23]. The test boundaries are also defined. Two case scenarios are made for test boundaries, the difference is in the first scenario ambient temperature, wind speed and global horizontal irradiance are measured and in the second scenario module temperature and plane of array irradiance is measured. In the conclusion, the results of using the two scenarios are presented.

This research is of two parts; calculation and simulation. The field data will be used to calculate the CF and PR. Simulation is done using PVsyst and the results are compared with plant energy output. This is to assess the efficiency and performance ratio of the plant. The energy yield, specific energy yield and grid injected energy is compared with energy injected into the grid. The losses are also analyzed.

1.4 Thesis Objectives

The main objective of this thesis is to evaluate the performance of Serhatkoy PV power plant. Since it's the first grid connected PV system in North Cyprus, the results of this research will be useful in solar energy policy planning, analysis of solar investments, future solar park or expansion of the existing one, plan maintenance and for educational and research purposes.

1.5 Thesis organization

The these is composed of five chapters

Chapter one

This chapter is made of introduction, literature review, objectives of the research/thesis and organization of the thesis.

Chapter two

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 three

In this chapter, we look at the recommend PV performance evaluation methods by industry players, purpose of evaluation and factors that affect the performance of PV systems

Chapter four

This chapter is made of performance evaluation calculations and PVsyst simulation. The energy output from the plant will be used to calculate the capacity factor, Performance ratio and payback period of the plant. Simulation of Serhatkoy PV power plant is done using PVsyst to determine the Performance of the plant.

Chapter five

This chapter is made up of conclusion and recommendation for future works.

CHAPTER 2

SOLAR ENERGY

2.1 Overview

In this chapter, we take a look at the following topics; radiation of the sun, Photovoltaic systems types, PV cell characteristics, and current/voltage characteristics, types of photovoltaic system, Cells/modules/Array and application of PV system.

2.2 Radiation of the sun

The sun radiates gargantuan amount of energy into solar system or universe, this energy travels at 3.0 x 10^8m/s^2; thus being able to reach the earth's surface within eight minutes. By the process of nuclear fusion the sun is able to produce this energy in its core which is made of Hydrogen and Helium gases [11]. The amount or percentage of energy produced by the sun which reaches the earth surface is small but an hour of this amount (4.3×10^{20} J) is enough to supply the required energy of the earth for a year (4.1×10^{20} J). Solar energy is considered renewable because it is constantly available (in the absence of weather conditions like winter, clouds, night, rainfall etc.) and it is replenished naturally [2].

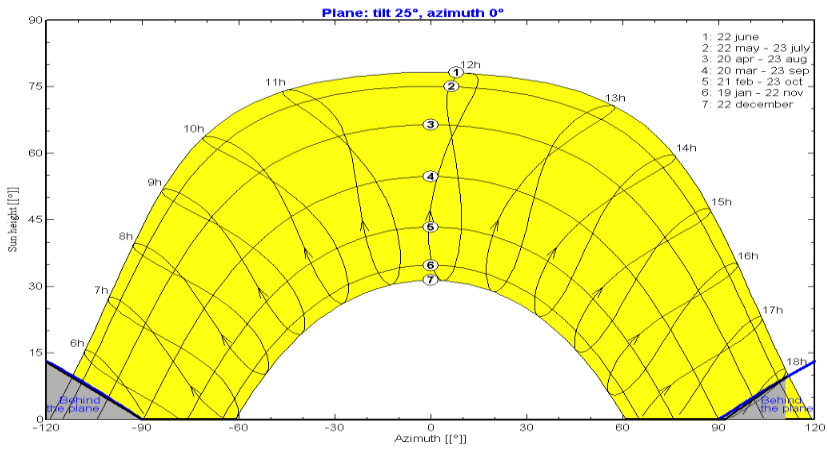


Figure 2.1 the sun's position over Serhatkoy

It takes 365 days for the earth to orbit the sun. Due to the rotation of the earth, only half of the earth is lit by sunlight at a time. Solar radiation comes in the form of electromagnetic wave which has wide spectrum. The longer the wavelength of the spectrum, the less energy it has and the shorter the wavelength the more energy it possess. Of all the spectrum of wavelengths of the sun, only wavelength ranging between 0.29µm and 2.3µm reaches the earth's surface [4]. Most of the solar energy which hits the surface of earth is reflected back into space, others are used for the evaporation of water resulting in rainfall, plants absorb part of the solar energy for photosynthesis and also the earth (land) and water bodies also absorb part, the rest goes unused. The amount of solar radiation that is absorbed or scattered in the atmosphere depends on the path length of the sun's rays through the atmosphere; this quantity is called the air mass (AM) ratio. It is the ratio between the length of the actual path taken by the rays and the minimum path length, i.e., the path length when the sun is at the zenith. Zenith is the point in the sky directly overhead the location, by definition, AM =1 when Zenith = 0 at sea level while AM=0 outside the atmosphere [6]. AM=1.5 is considered to represent the average terrestrial radiations in US.

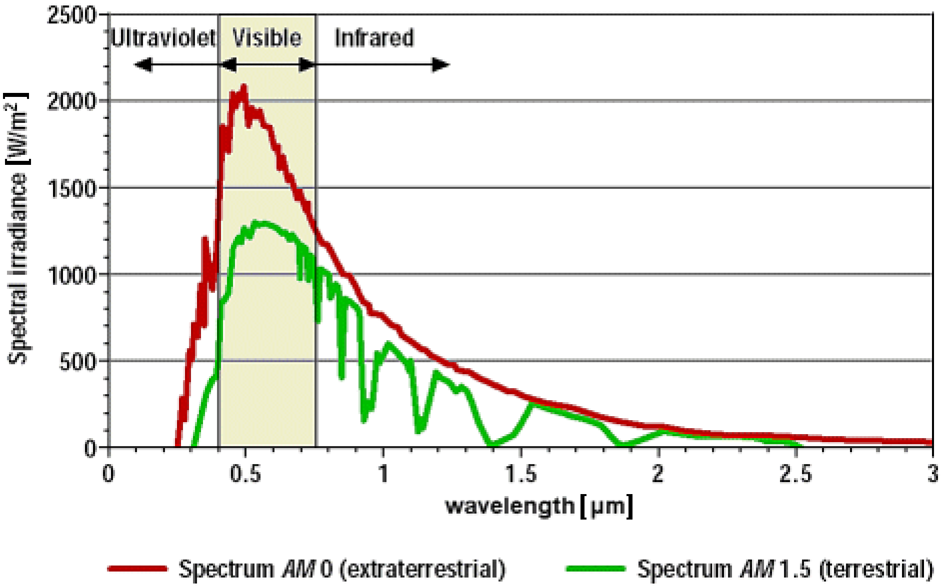


Figure 2.2 Extraterrestrial and Terrestrial Spectrum of Sunlight [5]

Irradiance or isolation is the solar radiation intensity which falls on a surface. This quantity is measured or expressed in watts per meter square (W/m^2).The *global irradiance*, *Gg*, is the solar radiation that reaches horizontal surface on the earth through the atmosphere. The following factors account for global irradiance.

- *Beam radiation (Ib):* is the radiation that passes straight through the atmosphere and hits the earth's surface, hits the plane. It is also known as Direct radiation.(very directional)

- *Diffuse radiation (Id):* in diffuse radiation, the solar radiation is scattered in all direction in the atmosphere and part of it arrives at the earth's surface.
- *Total radiation (It):* is the sum of the beam and diffuse radiation, sometimes known as *global radiation*.

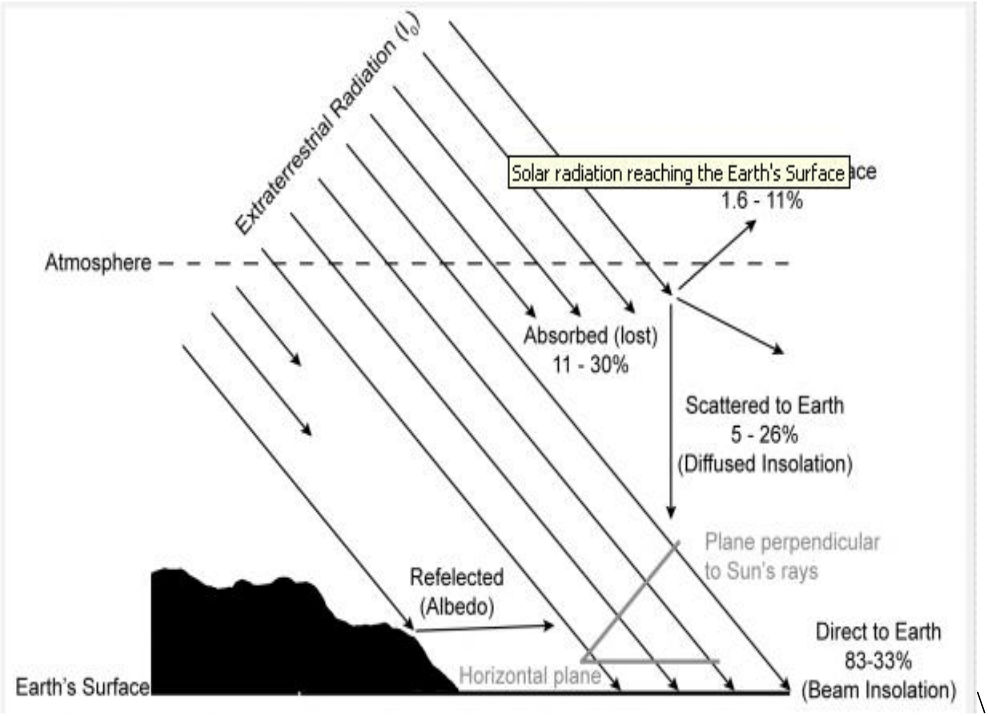


Figure 2.3 Types of insolation on the earth surface [5]

2.3 History of Solar Energy

The history of solar energy is as old as mankind. Solar energy has been used in various form until the last two centuries when solar energy was purposefully harnessed for electricity production, in the 7th century BC magnifying glass was used to converge light from the sun onto surfaces which resulted in fire [11]. Alexandre Edmond Becquerel in 1839 discovered that small amounts of electricity could be produced in certain materials when exposed to the sun [12]. Ever since there have been various breakthroughs in the development of solar energy industry, notably was the invention of solar powered steam engines by French scientist, solar boiler invented in 1936 by Charles Greeley Abbott, an American astrophysicist. The solar energy industry has since then made great strides, Homes, cars, boats/ships, airplane, satellites etc are now powered by means solar energy [13].

2.4 Solar Collectors

A perfect example of a solar collector is the car. When a car is parked under the sun with all windows closed, the wind screen (glass) absorbs the sun's radiation and converts it to heat in the car, because there's no way for the heat to escape, the temperature keeps rising and this usually results in breaking or cracking of the windscreen. Solar collectors use this technology to transfer heat energy into other mediums (useful mediums) such water, air, or solar fluid which is basically used for heating [13].

2.5 Photovoltaic Systems

Photovoltaic (PV) is the combination of two words, photo and voltaic. Photo means light and Voltaic means voltage. Photovoltaic systems are also called *Photovoltaic power systems*, *Solar PV systems*, *PV system* or *solar array* [11]. Photovoltaic systems consist of number components which is able convert energy from the sun into electricity. Photovoltaic cell is the primary component of a PV system, it converts solar energy into electricity other components such as Battery Bank, DC – AC inverter, DC and AC isolators, Metering systems etc. These components makes it possible for generation, transmission and distribution of solar energy i.e. electricity [9]. There are various ways of using solar energy. The main use of solar energy is converting sun light directly into electricity by the *Photovoltaic effect.* Also there two other ways of using solar energy, namely concentrating solar power (CSP) and solar thermal collectors (SHC).

2.5.1 Photovoltaic Effect

When irradiance occurs on the surface of a PV cell, electric field is generated in the cell, this leads to the separation of positive and negative charge carriers (p-type and n-type). *Photons* which are particles of sunlight bounces into negatively charged electrons of the Silicon atom, this leads to the breakaway of electrons from the Si atoms. The photon transfers its energy to the electron, several electrons are freed in this process and this leads to the flow of electrons. The flow of electrons in the internal field of the PV cells is what is called electric current. The greater the irradiance, the higher the amount of electric current generated.

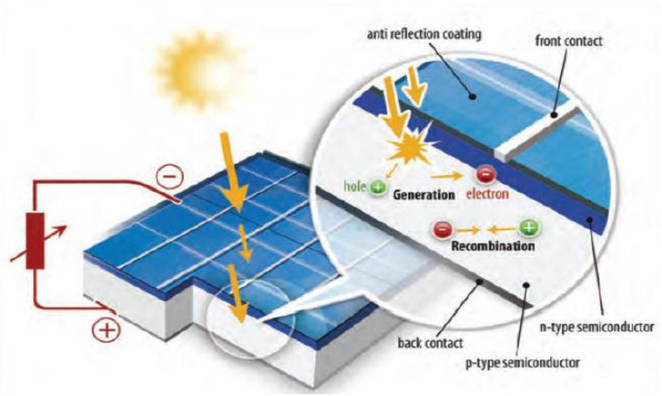


Figure 2.4 Cross-section of a solar cell [3]

2.5.2 Types of Photovoltaic Cells

PV cells can be defined as the basic photovoltaic device which is the building block for PV modules. Silicon is the most basic material for producing solar cells. The following manufacturing technologies are used for solar cell production:

- Monocrystalline
- Polycrystalline
- Bar-crystalline silicon
- Thin-film technology [11]

2.5.2.1 Monocrystalline Silicon Cell

The conversion efficiency for the silicon solar cell ranges between 13% to 17%, this makes it very common for most commercial use. Under very good light conditions, it is the best type of photovoltaic cell. The silicon solar cell can convert solar radiation of 1,000W/m^2 to 140W of electricity with a surface area of 1m^2. Absolute pure semiconducting material is required for the production of mono-crystalline silicon cell. Mono-crystalline rods are extracted from the molten silicon and sliced into thin chips (wafer). The lifespan of mono-crystalline silicon cell is between 25 to 30 years.

Some properties of mono-crystalline PV module

- Form: round, semi round or square shape.
- Thickness: 0.2mm to 0.3mm.

- Color: dark blue to black (with ARC), grey (Without ARC).[14]

2.5.2.2 Polycrystalline Silicon Cell

Polycrystalline also known as multicrystalline cell, Polysilicon or poly –Si, is high purity polycrystalline form of silicon and it is the raw material used by electronics and photovoltaic industry. Multicrystalline Si cell converts solar radiation of 1000W/m^2 to 130W of electricity with a total surface area of 1m^2. It is more economical to produce multicrystalline Si cell compared to monocrystalline Si cells. Polysilicon is produced from metallurgical grade silicon by a chemical purification process. This process involves distillation of volatile silicon compounds, decomposition at high temperatures, or refinement in fluid phase. Its life span is between 20 and 25 years. Properties of polycrystalline PV modules are:

- Efficiency: 13% to 16 %.
- Form: Square.
- Thickness: 0.24mm to 0.3mm.
- Color: blue (with ARC), silver, grey, brown, gold and green (without ARC).[14]

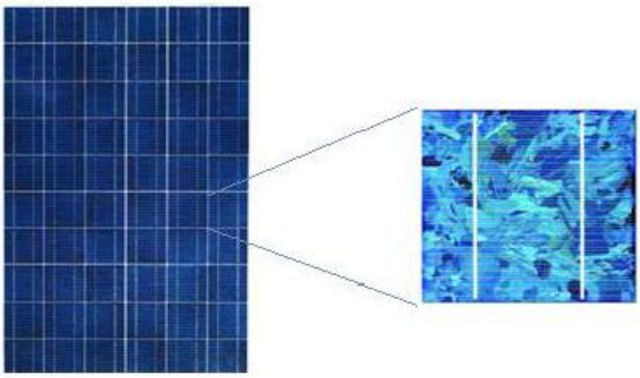


Figure 2.5 Polycrystalline cell and module [14]

2.5.2.3 Bar-crystalline silicon

Ribbon silicon has the advantage in its production process in not needing a wafer cutting (which results in loss of up to 50% of the material in the process of cutting). However, the quality and the possibility of production of this technology will not make it a leader in the near future. The efficiency of these cells is around 11%.

2.5.2.3 Thin film Technology

Thin film technology is the second generation of PV technologies. Fewer materials are used for its production and also its energy consumption is low. When compared to crystalline technology it is cheaper. Copper Indium Selenium (CIS), amorphous silicon and cadmium Telluride (CdTe) are used as semiconductor materials. These materials have high light absorption properties therefore when layer thickness of 0.001mm is used, it is sufficient to convert incident irradiation theoretically. Because of the high light absorption of these materials, layer thicknesses of less than 0.001mm are theoretically sufficient for converting incident irradiation [14]. Analyzing thin film and crystalline technologies shows that thin film technology has the following properties:

- Lower cell thickness,
- Lower semiconductor consumption
- Lower primary energy consumption

2.6 PV Cell Characteristics

There are certain important parameters which must be considered when modeling any PV system, these electrical characteristics determines the relation between the cell voltage and current and cell voltage and power. These parameters are the cell voltage under open circuit conditions, V_{OC}, the cell current under short circuit conditions, I_{SC}, and the cell voltage, current and power at the maximum power point, V_{MPP}, I_{MPP}, and, P_{MPP}, respectively.

2.6.1 Current-Voltage (I-V) Characteristics

I-V characteristics or parameter curve represents all the possible operating points that can be obtained by the current and voltage for PV cell. Experimentally, the curve can be generated by changing the electrical load value. From figure 2.6, if the voltage is increased, the current begins from the maximum value and gradually reduces to the zero point. Electrical load determines the operating point on the I-V curve. The standard for measuring or evaluating I-V curve points is determined at standard test condition (STC) with the following characteristics:

- ❖ Irradiance (G) = 1000 w/m^2

- Temperature (T) = 25°C
- Air Mass (AM) =1.5

The knee points, in I-V and P-V is the maximum power point which is at 0.5V and 2.75A in figure 2.6.The optimum electrical load is the load that operates the PV at its maximum power point (MPP), if the PV generator is able to deliver maximum power.

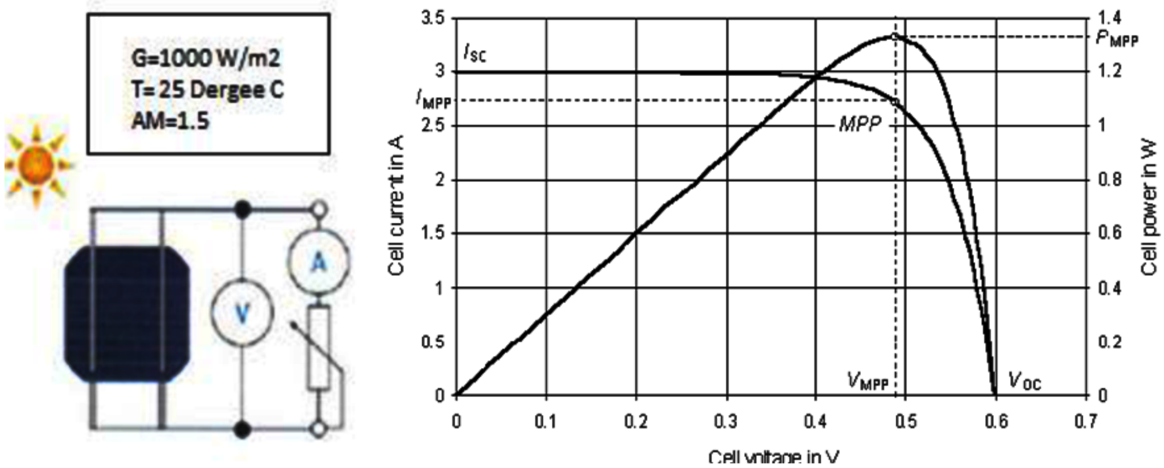
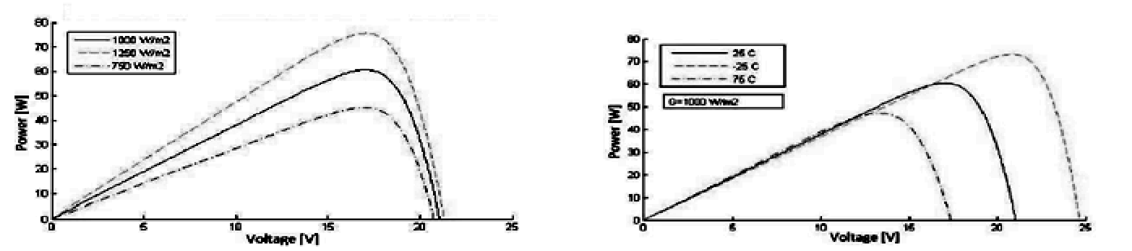
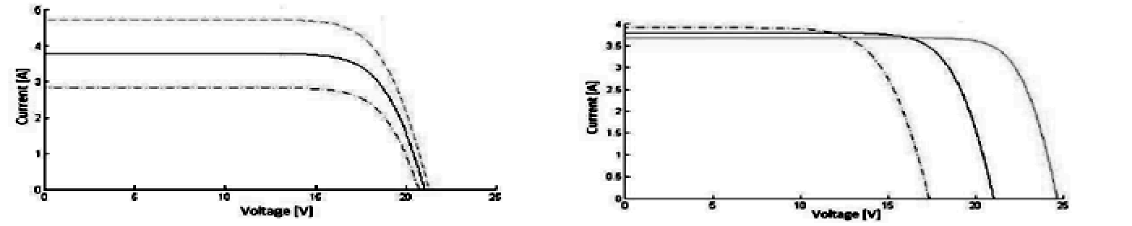


Figure 2.6 Current–voltage and power–voltage solar cell characteristics [5, 7]

Irradiance and cell temperature determines the electrical characteristics of a PV cell. In figure 2.6, there is a proportional relation between irradiance and current at different stages of constant temperature and irradiance. In figure 2.7 (a) and (b), the slightest change in irradiance has a strong effect on the short-circuit current and the solar cell's output power. But the effect on the open-circuit voltage is negligible. Also figure 2.7 (c) and (d) shows that at constant irradiance, any change in temperature affects the output power and open-circuit voltage of the cell, but the effect on the open-circuit current is negligible.



(a) Variable Irradiances and constant Temperature **(c) Variable Temperature and constant Irradiances**



(b) Variable Irradiances and constant Temperature **(d) Variable Temperature and constant Irradiances**

Figure 2.7 the effect of temperature and irradiance on the power output and open-circuit voltage of a cell [5].

2.6.2 Short Circuit Current (I_{SC})

The short circuit current of a PV system is dependent on the amount of sunlight available. Short circuit current at STC is the maximum possible current that can be delivered into a circuit by photovoltaic system [8].

2.6.3 Open circuit voltage (V_{OC})

Open circuit voltage is the maximum voltage which occurs at zero current, i.e. open circuit voltage represents the maximum possible voltage in a PV system under STC which does not allow the flow of current between the terminals of photovoltaic module under conditions of zero current and therefore no power [8].

2.6.4 Maximum Power Point (P_{MPP})

No power is generated for short circuit and open circuit systems; therefore the operating point falls into the range of PV cell's maximum power output. Its value is specified by a pair of voltage and current values, ranging between 0 and I_{SC} and between 0 and V_{OC}. Maximum power output is defined as the product of the voltage and the current at the MPP

$$\text{Maximum power point} = V_{MPP} \times I_{MPP} \tag{2.0}$$

Where:

V_{MPP} is the voltage at maximum operating point

I_{MPP} is the current at maximum operating point

MPP has a unit of Wp (watt peak) [8, 4]

2.6.5 Current at maximum power

Current delivered to the device at maximum power under standard conditions. It is used as nominal current of the photovoltaic module.

2.6.6 Voltage at maximum power

Voltage delivered by the device when the power reaches its maximum value under standard conditions. It used as a nominal voltage of the device.

2.6.7 Fill Factor (FF)

The fill factor (FF) indicates the quality of a PV cell. One is the maximum value of the fill factor i.e. it's a unity factor. A good I-V curve should have a fill factor close to one. It is defined as the ratio of the practical maximum power point and theoretical maximum power point. Practical maximum power point is the product voltage and current at maximum power point and Theoretical maximum power point is the product of open circuit voltage and short circuit current. 0.88 is the practical maximum value for silicon [4].

$$FF = \frac{Pmax.\ practical}{Pmax.\ theoretical} = \frac{Vmp\ X\ Imp}{Voc\ X\ Isc} \tag{2.1}$$

2.6.8 Efficiency of Solar Cell

PV system are able to convert only part of the incident radiation into electricity, this ability is defined as the ratio of electrical power produced to the amount of solar energy incident in a second. [10]

Efficiency of a solar cell is given by:

$$\eta = \frac{Pmax}{Pin} = \frac{Imax \quad X \quad Vmax}{Incident\ solar\ radiation\ X\ Area\ of\ solar\ Cell} \tag{2.2}$$

$$\eta = \frac{Voc \quad X \quad Isc \quad X \quad FF}{It \quad X \quad Ac} \tag{2.3}$$

Where $I_{max}$is the current at maximum power

V_{max} is the voltage at maximum power,

This is the solar intensity, which shows the relationship between fill effect and cell efficiency. [9]

2.7 Types of PV Systems

PV system can vary from simple PV modules to complex one. An example of a simple form of PV system can be solar water pump where the motor of the water pump is powered directly by the solar i.e. usually there's no storage unit for such a system. Whereas a more complex form is the PV system designed to power a home. Basically there are three main types of PV Systems:

- Stand alone
- Grid connected
- Hybrid[15]

The principle, elements and function remain the same for the types of PV systems. The systems are designed to meet specific energy requirements; this is done by varying the quantity and type of basic elements.

2.7.1 Stand-alone Systems

The stand-alone system is made up PV modules, load, batteries, sometimes and an inverter. Charge regulators or controllers are used systems where batteries are incorporated, its function is to switch of the PV modules when the batteries are fully charged. This system is usually suitable for places which are not connected to national grid system or where power is erratic.

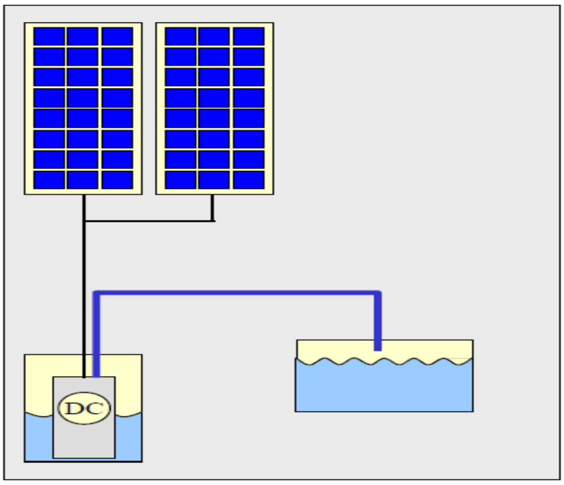


Figure 2.8 Simple PV system(DC) used to power a water pump [15]

2.7.2 Grid-connected Systems

The Grid-connected PV system is the stand-alone PV system which connected to the national grid via inverters. Most grid connected systems do not use battery or have storage units since all the power generated can easily absorbed by the grid. There is a metering system integrated into the setup which helps in calculating the amount of electricity generated.

2.7.3 Hybrid System

The hybrid system is composed of PV Modules in combination with a complementary means of power generation such as wind, gas or diesel generator. A common problem which is associated with the hybrid PV/diesel generator is the inadequate control of the diesel generator. If the batteries are maintained at too high a state-of-charge by the diesel generator, then energy, which could be produced by the PV generator, is wasted. Conversely, if the batteries are inadequately charged, then their operational life will be reduced [15].

2.8 Cells/ modules/ Array

PV cells can be described as semiconductor with p-n intersection which is able to directly convert sunlight into electrical power. PV modules are formed when a set of cells are connected in series or in parallel. Likewise PV arrays are formed when modules are connected in series or parallel.

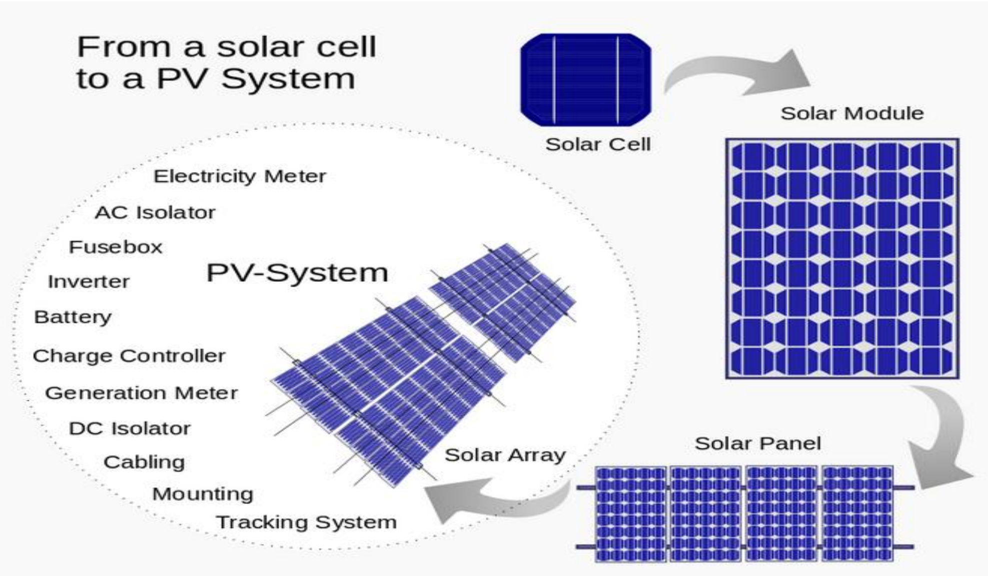


Figure 2.9 Diagram showing the building blocks of a PV system from a cell.

2.9 The Equivalent Circuit of PV Cell

A PV cell is usually embodied by an electrical equivalent of one-diode, resistance series Rs and resistance parallel Rp. When the p-n junction is formed in the semiconductor material a diode is formed as a result of this junction. Thus the equivalent resistance of a PV cell is made up of a diode and series and parallel resistances as shown in figure 2.10.

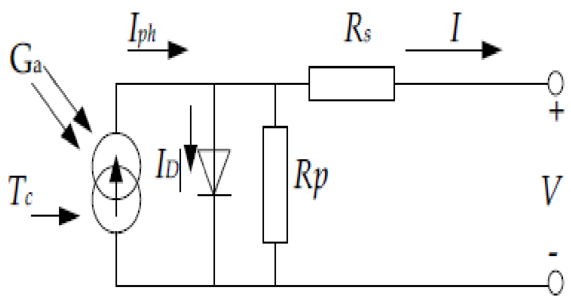


Figure 2.10 PV Cell one diode equivalent circuit [4]

From figure 2.10, the different parameters or characteristics of the PV cells are:

I_{ph}: currents generated by the solar cells (A)

I: output current of the PV (A)

V: output voltage of the PV (V)

R_s: resistance series (Ω)

R_p: resistance parallel (Ω)

T: cell temperature (K)

G_a: irradiance from the sunlight (W/m^2)

I_d: diode current (A)

2.9.1 Series and Parallel Connections of PV Modules.

The connection of cells usually depends on the expected voltage or current output. Mostly PV cells are connected in series from manufacturing to a module. Also power condition units are taken into consideration when arranging PV cells. There are basically two ways of connecting PV cells; series and parallel

2.9.2 Parallel Connection

Parallel connections of photovoltaic panels can be seen in figure 2.11. Parallel connection is obtained when all negative terminals are connected together and also when all positive terminals are connected together. Parallel connections of PV panels are needed when higher voltage is required. The sum of currents of each PV module constitutes the total current of the system. Whilst the total voltage of the system is the voltage across any of the PV modules [4, 7].

$V_{out} = V_1 = V_2 \ldots\ldots = V_n$ and $I_{out} = \sum_{i=1}^{n} Ii$ (2.4)

The output power of the solar array is given by:

$P_{out} = I_{out}$ X $V_{out} = V_{out}$ X $\sum_{i=1}^{n} Ii$ (2.5)

2.9.3 Series Connection

Photovoltaic modules are connected in series for higher voltage output of a system or an array. It can be seen from figure 2.11 that the positive terminal of one module is connected to the negative terminal of the next module. This method of connection forms a sting with positive and negative terminals. The output voltage at the end of each string is the sum of voltages of the modules which makes up the string [4, 7]. Equations 2.6 and 2.7 give the current, voltage and power of the system:

$I_{out} = I_1 = I_2 \ldots\ldots\ldots\ldots = I_n$ and $V_{out} = \sum_{i=1}^{n} Vi$ (2.6)

Power of the each string:

$P_{out} = I_{out}$ X $V_{out} = I_{out}$ X $\sum_{i=1}^{n} Vi$ (2.7)

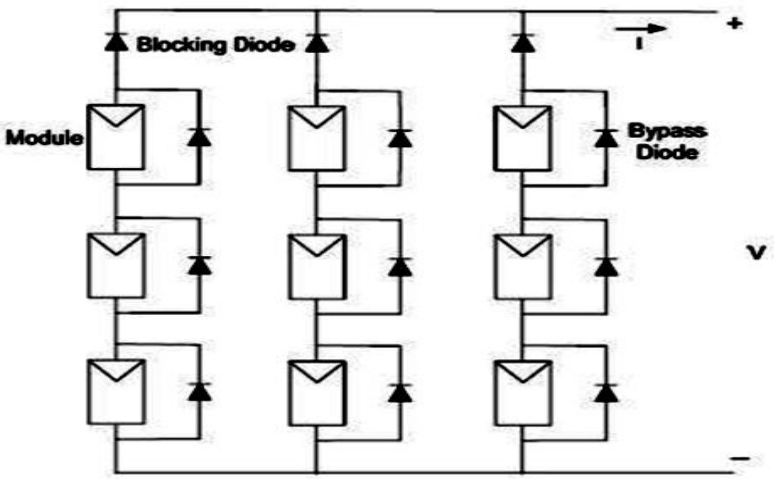


Figure 2.11Layout of a PV array [8]

To minimize electrical losses, similarity of voltages for modules connected in series should be taken into consideration [6, 8]. Fully or partially shaded modules affect current output of series connected modules. This effect is as though the whole module has been shaded if even it’s only one cell which is shaded. This also affects the power output and increases the module temperature which damages the shaded cell, to correct this problem, bypass diodes are connected in series with the modules for each string as shown in figure 2.11[4].

2.10 Applications of Photovoltaic systems

Solar Photovoltaic system produce cheap,reliable and clean (without out CO_2 emmissions) electric power, there are countless advantages for using Solar PV systems, examples [25, 9]

2.10.1 Applications in space

Photovoltaic systems are used in space by satellites; they are the source of power for most orbiting space craft. Due to the versatility of PV technology, it can be used in wide range of sun intensity and temperature. Solar cells are able to withstand radiation properties of the sun in space.

2.10.2 The application of PV in the communications

The most familiar application of solar photovoltaic power system is communications in the industrial field. Solar power used in unmanned microwave relay station, cable maintenance station, electricity /radio / communications / paging power systems, rural telephone carrier photovoltaic systems, small communication equipment, and soldier GPS-powered, etc.

2.10.3 Solar light

Solar light is the system of producing light using solar energy. Solar cells, batteries, power conditioning units etc. are all incorporated to supply light to areas which lack electricity via grid system. Examples are street lights, traffic lights, village and communities not connected national grid, farm lands and houses, security posts etc.

2.10.4 The application of PV in the highway

Because of their unique characteristics of the highway, it is one of the solar photovoltaic places. Power supply system of highway plays a crucial role in the safety of the highway. In the urban areas of less electricity, if you use mains as power supply, the cost of pull-based power grid is very expensive. I fusing solar energy photovoltaic power generation on the highway to supply power to necessary electrical facilities, it is energy saving, environmental protection and economic security. It’s applications is in the following areas: First, the service area on the highway which is away from the city power can build photovoltaic power station or photovoltaic-diesel hybrid systems, to supply are alighting, catering and other power needs to the service; The second is the emergency telephone system.

2.10.5 Residential

Providing electric power to homes without power, reducing the cost and reliance on grid power. Avoiding power cuts in countries with unreliable power supply. This technology is very suitable for developing countries.

2.10.6 Health

PV systems are used in developing countries to power refrigerators to store vaccines, blood and other drugs which require specific temperatures.

2.10.7 Agriculture

Water pump powered by PV systems to reduce labor and increase production all year round.

2.10.7 Remote observation Post

Remote weather and comunication installation use photovoltaic systems to provide electric power.

2.11 Concentrated solar power (CSP)

Concentrated solar power (CSP) also known as Thermal power is a method of producing electricity by the use of solar energy. Unlike Photovoltaic which uses cells to directly convert solar energy into electricity, CSP uses mirror, lens or glass to concentrate or focus the sun's rays onto heat-transfer mediums(like boiler tube) to heat water to steam which is used to power turbines to produce electricity. This method of electricity generation is clean i.e. without CO_2 emission, renewable and free. [24]

2.12 CSP Requirements

Concentrated Solar Power requires certain factors to make it suitable for a specific location; CSP uses beam radiation or DNI (Direct Normal Radiation) of sunlight. Beam radiation is not deviated by fumes, dust or clouds before reaching the earth surface. Regions which are able to receive a minimum of 2000KWh/m^2 (kilowatt hours per square meter) of sunlight radiation annually are good locations for citing CSP systems. 2800KWh/m^2 is the amount received by very good sites.[25].

Australia, south-western United States, Former Soviet Union, South and North Africa, Mediterranean countries of Europe, China, Pakistan, Deserts regions of India, Near and Middle East, and Iran are very good regions for CSP systems because they are without large percentages of fumes and dust, atmospheric humidity and they lie less than 40^0 of attitude North or South.[25]

Concentrated Solar Power requires cooling at the steam turbine cycle. Evaporating (wet) cooling is used in place where water is readily available or Cooling with air (Dry Cooling) is used. But dry cooling builds the cost of operation by 5 to 10%. To reduce this cost, a system of Hybrid cooling is employed.

2.13 Types of CSP systems

Concentrated solar power system is made up mainly of four systems/types.

- Parabolic Trough(PT)
- Linear Fresnel Reflector (LFR)
- Solar Tower (ST)
- Solar Dish(SD)

2.13.1 Parabolic Trough (PT)

Parabolic Trough use very high reflectors (mirror) to concentrate solar radiation onto fluid-carrying thermally efficient tube located in the parabolic's focal line. The suns radiation heats the fluid (e.g. synthetic thermal oil) in the tube to a temperature of about 400^oC, this produces steam which is used to generate electricity by convectional steam turbine generator or a combined cycle of steam and gas generator. PT are the best developed CSP technology and able to generate more power [24, 25].

California's Solar Electric Generating Systems I-IX use PT and have generated 12 million MW and earned more than $2 billion since 1984.[26]

Collector field is a group of troughs placed in parallel rows. They are aligned along the north-south path axis of the sun so as to be able to track the sun when it is moving from east to west. This makes it possible for a continuous radiation of the sun onto the receiver pipe all day. Most individual trough system can generate close to 80MW of power. Thermal storage can be incorporated into parabolic troughs this makes it possible for power generation during evening hours. Parabolic troughs are hybrid systems which makes them more efficient. Most are combined with natural gas fired or gas steam boiler/heater. Coal can also be incorporated with PT. [24]

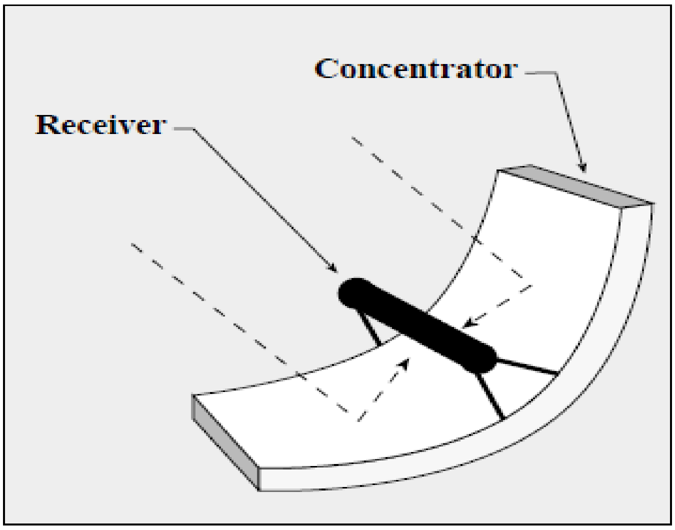


Figure 2.12 Parabolic Trough [24]

2.13.2 Linear Fresnel Reflector (LFR)

The principle of operation of the Linear Fresnel reflector is the same as the Parabolic Trough, But the Fresnel uses flat mirror instead of curved mirrors. These flat mirrors are used to concentrate solar energy onto elevated inverted linear receivers. Water moving in the receivers is converted to steam to generate electricity. This technology is relatively new compared to the parabolic trough, and has the advantages of low cost and small area (land) required [27].

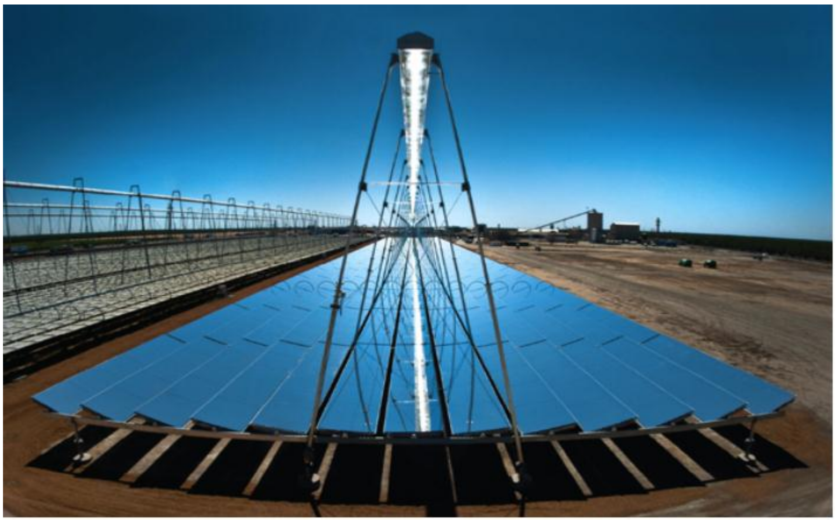


Figure 2.13 Kimberling liner Fresnel power plant (California) [Areva Solar][28]

2.13.3 Solar Tower (ST) /Central Receiver

An array of mirrors called Heliostats with sun tracking mirrors concentrates the reflected solar radiation onto a central receiver on top a tower of considerable height. The central receiver is a heat transfer medium which converts the heat into thermal energy used to produce steam for power generation. Water/steam, air or molten salt is used as the heat transfer medium, molten salt is used in most cases. Central receivers are able to concentrate heat energy at very high temperatures, thus making them very efficient for conversion rates. If air or pressurized gas is used at high temperatures of say 1000^{o}C, this can replace natural gas producing an excellent combined cycle of steam and modern gas. The central receiver is made up five main parts:

- Heliostats,
- Receiver
- Heat transport and exchange
- Thermal storage
- Controls[24, 25, 27]

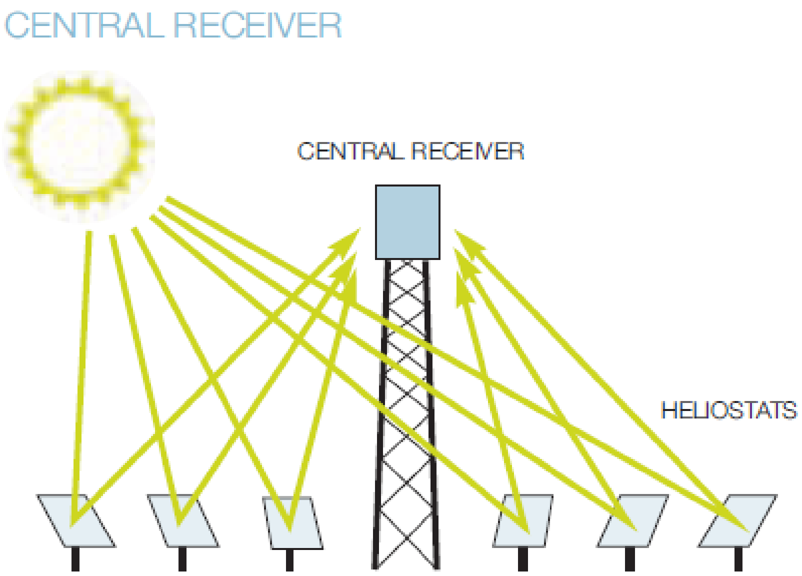


Figure 2.14 Central Receiver [24].

2.13.4 Solar Dish (SD)/Dish System

The Solar dish system looks exactly like a satellite receiver. Mirrors shaped into dish form are used to focus and concentrate solar radiation onto a receiver mounted in the middle or center of the dish. This system is a stand-alone system composed of:

- A collector
- Receiver
- Engine

The receiver transfers the absorbed energy to the engine(which similar to car engines), then the energy is converted to heat by the engine, by means of mechanical power, is compressed and expanded through a piston or turbine to produce mechanical power. Electric generator is used to convert the mechanical power into electricity, also an alternator can be used to achieve the same purpose as the generator. Dual axis collectors are used by Dish systems to track the sun, north to south movements. Parabolic is the ideal shape of the concentrator, and it's made by multiple reflectors or single reflecting surface. Concentrating photovoltaic modules, micro-turbine, Stirling cycle are types of engines used for Dish system.

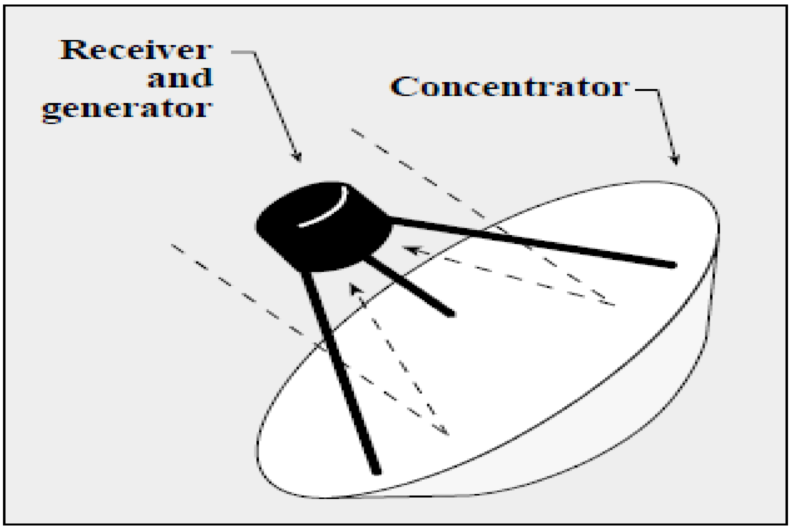


Figure 2.15 solar dish (dish system) [25]

Table 2.1 Applications of CSP type technologies [24]

PARABOLIC TROUGH	CENTRAL RECEIVER	PARABOLIC DISH	FRESNEL LINEAR REFLECTOR
Grid-connected plants, mid to high-process heat (Highest single unit solar capacity to date: 80MWe. Total capacity built: over 500 MW and more than 10 GW under construction or proposed)	Grid-connected plants, high temperature process heat (Highest single unit solar capacity to date: 20 MWe under construction, Total capacity~50MW with atleast 100MW under development)	Stand-alone, small off-grid power systems or clustered to larger grid connected dish parks (Highest single unit solar capacity to date: 100 kWe, Proposals for 100MW and 500 MW in Australia and US)	Grid connected plants, or steam generation to be used in conventional thermal power plants. (Highest single unit solar capacity to date is 5MW in US, with 177 MW installation under development)

Table 2.2 Advantages of CSP type technologies [24]

PARABOLIC TROUGH	CENTRAL RECEIVER	PARABOLIC DISH	FRESNEL LINEAR REFLECTOR
•Commercially available – over 16 billion kWh of operational experience; operating temperature potential up to 500°C (400°C commercially proven) • Commercially proven annual net plant efficiency of 14% (solar radiation to net electric output) • Commercially proven investment and operating costs • Modularity • Good land-use factor	•Good mid-term prospects for high conversion efficiencies, operating temperature potential beyond 1,000°C (565°C proven at 10 MW scale) • Storage at high Temperatures • Hybrid operation Possible • Better suited for dry cooling concepts than	•Very high conversion efficiencies – peak solar to net electric conversion over 30% • Modularity • Most effectively integrate thermal storage a large plant • Operational experience of first demonstration Projects • Easily manufactured and mass-produced from available parts	•Readily available • Flat mirrors can be purchased and bent on site, lower manufacturing costs • Hybrid operation Possible • Very high space efficiency around solar noon.

• Lowest materials demand • Hybrid concept proven • Storage capability	troughs and Fresnel • Better options to use non-flat sites	•No water requirements for cooling the cycle	

Table 2.3 Disadvantages of CSP types technologies [24]

PARABOLIC TROUGH	CENTRAL RECEIVER	PARABOLIC DISH	FRESNEL LINEAR REFLECTOR
• The use of oil-based heat transfer media restricts operating temperatures today to 400°C, resulting in only moderate steam qualities	• Projected annual performance values, investment and operating costs need wider scale proof in commercial operation	• No large-scale commercial examples • Projected cost goals of mass production still to be proven • Lower dispatch ability potential for grid integration • Hybrid receivers still an R&D goal	• Recent market entrant, only small projects operating

CHAPTER 3

METHODOLOGIES OF EVALUATING PV PERFORMANCE

3.1 Overview

In this chapter, we look at the recommended PV performance evaluation methods by industry players, purpose of evaluation and factors that affect the performance of PV systems.

3.2 PV performance evaluation methods

An increase in the use of PV systems over the years has led to questions of performance assessment by industry players. The ability to assess the performance of stand-alone or grid connected PV system will help in evaluating investments, plan maintenance and also choose the best system for a specific application and location. There are several methods proposed by industry players to assess the performance of PV system either for short–power (kW) or long-term energy (kWh).

3.3 Purpose of Performance evaluation

The purpose of evaluating PV systems is usually owner driven. This is to satisfy certain questions which the owner seeks answers to. The owner in this case can be the manufacturer, consumer, an engineer, or installer/businessman/company. Some of the questions usually asked by the owner are:

How is my system, or portion of my system, performing currently in comparison to how I expect it to perform at this point in its life?

How is my system performing for both the short-term and long-term in comparison to how it is capable of performing with its given design and site location?

How is my system performing over an assessment period in comparison to other, similar systems in similar climates to help make operating and maintenance decisions?

Did I get what I paid for in terms of cost of energy? [29]

So many industry player like IEA, NREL, IEC 61724, SMA, SolarPro, Taylor&Williams, CEC commissioning, SRP, STC etc have provided different guidelines for evaluating the performance of PV system, these guidelines have become the industry standards or benchmark for PV performance assessments.

3.4 Methods of Evaluating PV Performance

3.4.1 Yield

The Yield metric is the 'baseline' indicator which is able to tell the performance of PV system in relation to the amount of energy produced in a given time; usually it is an annual assessment. However, yield calculations do not take into weather conditions. The following factors produces good yield; years of operation, good insolation and lower PV temperature. Equation 3.1 shows the basic yield equation:

$$\text{Yield} = \frac{\sum_{start}^{end} kWh \quad AC}{kW \quad DC\ STC} \tag{3.1}$$

Where:

kWh AC is the energy of the PV system

kW DC STC is the dc energy at standard test conditions [29]

3.4.2 Performance Ratio (PR)

International energy commission and national renewable energy laboratory USA have set the performance ratio as the common metric for PV performance evaluation, the shortcoming of the PR as a standard metric for measuring PV performance is that temperature is not taken into consideration during calculations and this affects the results of PV performance calculations during winter, spring and summer. According to IEC61724, the equation for performance ratio PR is:

$$PR = (kWh/kW_{DC\ STC}) / (H/G_{STC}) \tag{3.2}$$

Where:

kWh is the energy measured in kilowatts hour produced after a period of time(A year) $kW_{DC\ STC}$ is the dc energy in kilowatts produced under standard test conditions

H is the measured irradiance in plane of array (W/m^2)

According to the national renewable energy laboratory of USA (NREL/TP-550-38603), performance ratio can be calculated using the equation:

PR = (100 x Net production / total incident solar radiation) / rated PV module eff.

Some other Performance Ratio proposed by industry players

According to SolarPro, Taylor & Williams,

$$PR = (E_{Actual} / E_{Ideal}) \times 100\% \quad (3.3)$$

Where E_{Ideal} is temperature and irradiance compensated

By SMA standards:

PR = Actual reading of plant output in kWh p.a./ Calculated, nominal plant output in kWh p.a. (3.4)

$$PR = kWh / (sunhours \times area \times efficiency) \quad (3.5)$$

Where efficiency is provided the module manufacturer

Specific production formula proposed by SolarPro, Taylor & Williams is given as:

Specific Production = MWhAC / MWDC STC (3.6)

Performance Index (PI) evaluation of PV plants as proposed by SolarPro, Sun Light & Power and Towsend is given as respectively:

$$\text{Performance Index} = kW_{measured} / kW_{expected} \quad (3.7)$$

Performance Index = Actual Power / (Rated power * irrad adj.* temp adj * degradation adj * soiling adj* BOS adj) (3.8)

Output power Ratio proposed by SolarPro, Sun Light & Power is given by the equation :

$$\text{Output Power Ratio} = kW_{measured} / kW_{predicted} \quad (3.9)$$

3.5 Factors that affect the Performance Ratio of PV Systems

Standard test conditions (STC) provides the bases for which all PV systems can be assessed; the STC condition for PV modules to be assessed is $1000W/m^2$ of solar irradiation and module temperature of 25^0C. Performance Ratio of PV plants can be affected by certain factors, thus making the modules less efficient, some of these factors are:

3.5.1 PV Module Temperature

Temperature of the PV module affects the efficiency and performance of the solar cell. PV modules operate best under cool/cold temperatures. Changes in weather conditions affect the PR of PV modules; lower temperature of PV modules produces better PR values whilst higher PV module temperature produces less PR values.

3.5.2 Solar Radiation

PR values tend to lower in certain seasons of the year and also at certain times of the day. In winter, late summer, morning and evenings, the sun is low thus the amount of incident solar irradiation almost equals power dissipation (input power minus output power).

3.5.3 Shading and Soiling of PV Modules

Shading of PV modules by buildings and plants i.e. casting of shadows onto the modules or blocking the suns radiation from reaching the modules by buildings and plants and also soiling of the modules surface by dust, weeds, snow can affect the ability of the module to absorb irradiation thus rendering the module inefficient. This also affects the PR value of the plant.

3.5.4 Conduction losses and Efficiency factors

The type of cabling materials used in constructing the plant will affects the amount or energy that will be delivered to grid, transmission of energy from the inverter to the grid will produces some loses, this lose will hardly be dependent on the type of material and cable used. PR values will be affected by these losses. The efficiency values of the PV module and inverter used in the plant build will affect the PR values considerably. Higher efficiency factor of inverter and modules will produce higher PR values. [30]

3.5.5 Degradation of Solar cells

All solar cells tend to degrade with age, and this result in a reduction of PR values of modules or plants. Most solar cells have useful life span of 20 to 30years.

Calculating the performance ratio of a PV power plant can be done by two methods;

- Manual calculation
- Automatic calculation

3.6 Manual Calculation of PR

Manual calculation can easily be done by anyone when the correct data for calculation is obtained. For example using the SMA formula proposed by NREL, USA, PR is obtained by dividing the actual plant output by the nominal plant output (calculated).

The following procedures are needed when PR calculation is done manually:

The period of analysis must be determined, usually it's a year

The plant area i.e. generating part of the plant

Efficiency of the modules used, provided by the manufacturer

Measured PV plant output

Incident solar radiation for the period of analysis

Nominal plant output (which is calculated) [30].

3.7 Automatic Calculation of PR

Automatic calculation of PV plant's PR is done by the help of software designed purposely for this task. Also there are online platforms which are able to accomplish same task for free or for a fee. Examples of solar plant evaluation software's and online platforms are :

1. ACRGIS 2. SuperGeo 3. pvPlanner
4. Solargis 5. SAM

CHAPTER 4
CALCULATION AND SIMULATION RESULTS

4.1 Overview

This chapter is made of performance evaluation calculations and PVsyst simulation. The energy output from the plant will be used to calculate the capacity factor, Performance ratio and payback period of the plant. Simulation of Serhatkoy PV power plant is done using PVsyst to determine the Performance of the plant.

4.2 Capacity Factor (CF)

Capacity is the maximum generation output of a power plant, mostly measured in kW, MW or GW ratings. Capacity Factor of any plant shows the efficiency of that plant. It is the relation between of the nominal power of the plant and the yearly power generated i.e. the ratio of energy produced during a period of time (usually a year) to nameplate capacity. CF of PV plants can either calculated from PV array DC output values or inverter AC output values. PV panels produce DC voltage; this DC voltage is then converted into AC voltage by inverters. It is best to use AC voltage values for calculating CF. The capacity factor of solar PV plants falls in the range of 15% to 25%, but PV cells with 45% efficiency have been developed. The formula for calculating capacity factor is:

Capacity factor (CF) = Real power generated / Yearly power generated

CF = Average power / Nominal power

Yearly power generated (KWh/YEAR) = Nominal power (kW) x 8760(hour/year)

Capacity Factor for the following operational years of Serhatkoy is calculated as:

In 2011 Capacity factor was:

$$\text{CF} = \frac{Real\ Power\ generated}{Nominal\ Power}\ x\ 100\%$$

$$\text{CF} = \frac{909955.73}{365\ x\ 24\ x\ 1275.5}\ x\ 100\%$$

CF = 8.144 %(January to April power production result is absent)

In 2012, Capacity factor was:

$$CF = \frac{1985214.9}{365 \ x \ 24 \ x \ 1275.5} \ x \ 100\%$$

CF = 17.76%

In 2013, Capacity factor was:

$$CF = \frac{2152368.97}{365 \ x \ 24 \ x \ 1275.5} \ x \ 100\%$$

CF = 19.26%

In 2014, Capacity factor was:

$$CF = \frac{1012469.44}{365 \ x \ 24 \ x \ 1275.5} \ x \ 100\%$$

CF= 9.06% (October to December power production result is absent)

4.3 PVsyst Simulation

The software used for the simulation is called PVsyst. PVsyst was designed by university of Geneva in Switzerland and it is used for the study of PV systems. One of the features of PVsyst is ‘PROJECT DESIGN’ which allows you to design new PV system using the meteorological data provided by NASA or Meteonom 7.1 satellite. Grid-connected or stand-alone system can be designed using the program. Figure 4.1 shows the flowchart for simulation of Serhatkoy PV power plant (grid connected). The output of the simulation represents the plant energy output and performance ratio.

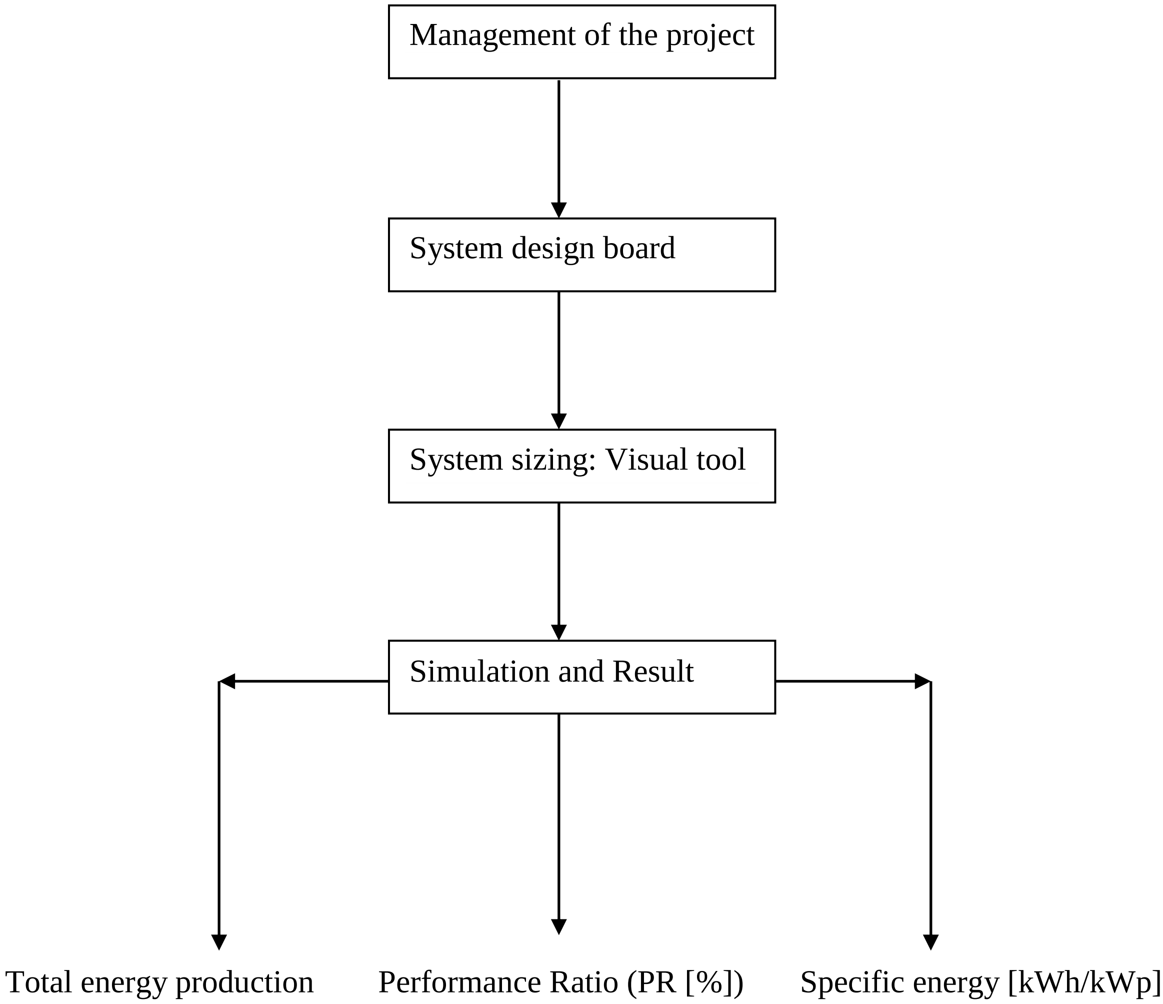


Figure 4.1 Flow chart flowing for determining PR using PVsyst.

4.3.1 Site Location

Serhatkoy is located in Guzelyurt in the northern part of Cyprus with geographical coordinates; latitude and longitude of 35.2^0N and 33.1^0E respectively, altitude of 110m and albedo 0.20. Cyprus is an island located south of Turkey and north-eastern part of Mediterranean Sea. Cyprus is a member of EU as *de facto* divided island [32] but the whole of Cyprus is EU territory.

4.3.2 Orientation

The orientation of PV panels must be done in other to optimize its absorption/collection efficiency. This is done with respect to the direction, position and angle of the sun. The tilt angle for Serhatkoy PV power plant is 24.84^0 and an azimuth angle of 0^0 is used for simulation purposes.

4.3.3 System

This feature allows you to model your project according to the parameters of the plant being evaluated or under investigation i.e. in this case; SERHATKOY PV POWER PLANT. Serhatkoy PV power plant consists of 6134 panels, made up of Polycrystalline solar cells and 86 group inverters. KIOTO photovoltaic is the manufacturers of the panels. KPV 205 PE model type is used. It has the following ratings; Power - 205Wp (Pmpp), $U_{mpp\ [V]}$ = 25.98V, $I_{mpp[A]}$ = 7.93V, $U_{oc[v]}$ = 32.57V, $I_{sc[A]}$ = 8.44A. The efficiency of the panel is 13.71% with 5 years guaranty and 90% and 80% efficiency guaranty for 10 and 20 years respectively. The inverter used is manufactured by Powerone with nominal DC power of 13kW and operating MPPT input voltage range of 200 – 850Vdc (580V nominal). The nominal power output of the plant is 1275.5kWp.

4.3.4 Detailed losses

Standard test condition (STC) parameters are used. These parameters are set under the following ratings; IAM 1.5 / 1000 W per m^2 / 25° C with normaised deatied losses provided by PVsyst.

4.3.5 System sizing : Visual tools

For simulation purposes, 1275.5kWp nominal power composed 6134 modules with an area of $8412m^2$ and 86 group of inverters is used. The panels and inverters used for constructing Serhatkoy plant model type is selected for simulation. Visual tools give a graph of I/V with MPPT range and the inverter limits for voltage, power and current.

4.3.6 Horizon

Figure 4.2 shows the daily-hour horizon line drawing for Serhatkoy. This also shows the sun’s height at specific hour of the day and month with respect to azimuth angle. The geographical site details of Serhatkoy are: latitude and longitude of 35.2^{0}N and 33.1^{0}E respectively, altitude 110m and albedo 0.20.

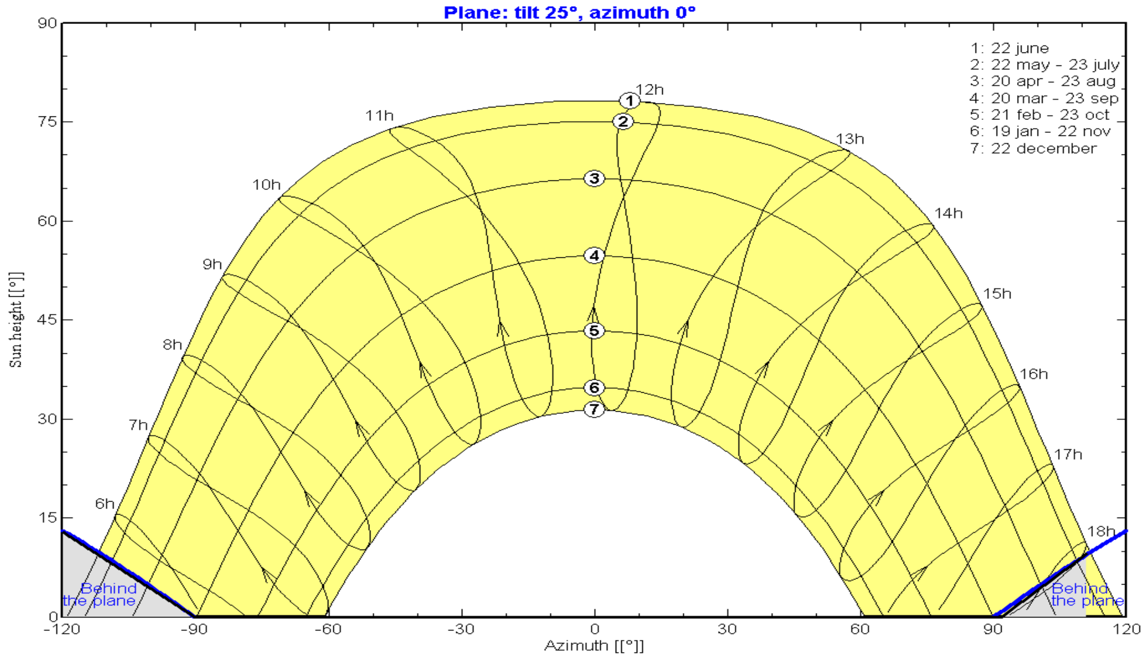


Figure 4.2 Horizon line drawings for Serhatkoy

4.3.7 Near Shading

Serhatkoy 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 4.3 shows the satellite imagery for Serhatkoy.

Figure 4.3 Satellite imagery of the landscape of Guzelyurt showing the PV power plant

4.4 Simulation and Results

Three main result parameters are presented by PVsyst after successful simulation, these result parameters are presented in a report form:

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

4.4.1 Normalized production (per installed kWp)

Figure 4.4 shows the normalized production (per installed kWp) with a nominal power of 1275.5kWp. It also shows the useful energy produced, collection losses and systems losses. June, July and August have the highest useful energy production and also have the highest collection and system losses; this can be attributed to the high temperature during these periods of the year (summer season). The temperature recorded at these periods exceeds the STC recommended levels by 20^{0}C in July and August. Collection looses is the difference in received irradiation and the amount of the received radiation converted into energy. Panels and modules are the primary cause of this loses. Collection losses determine the efficiency of PV panels. System loses can be attributed to the energy lost when converting DC energy into AC energy and this is mainly caused by inverter and cables. The higher the efficiency of inverters used, the less system losses will be produced.

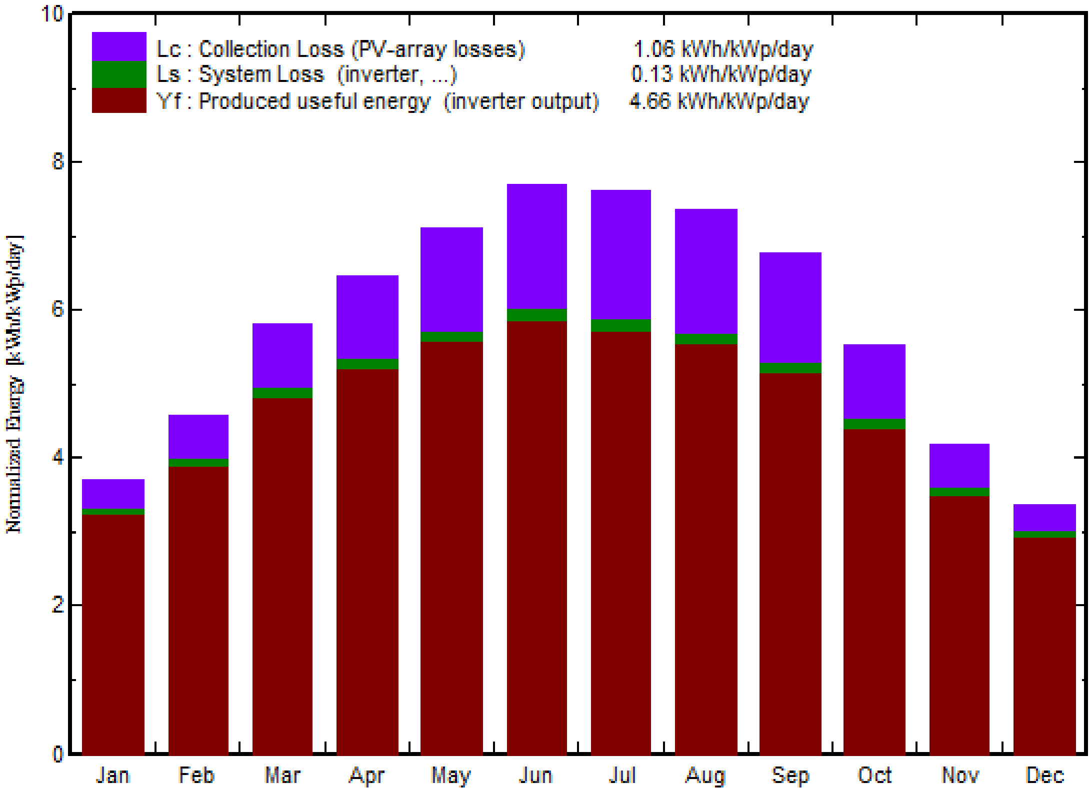


Figure 4.4 Normalized productions (per installed kWp)

From figure 4.4, spring and winter seasons are able to produce less losses (collection and system loses) as compared to summer season. The total loss experienced by the plant is the sum of collection and system losses which is 1.19kWh/kWp/day and the useful energy produced is 4.6kWh/kWp/day.

4.4.2 Performance Ratio

Performance ratio is a unity factor (ideally) i.e. it falls in the range of 0.1 to 0.99. The closer the PR value is to 1, the better. Multiplying the PR value by 100 gives the percentage of efficiency in terms of its performance. From figure 4.5, the PR for our simulation is 0.796 which is approximately 0.8(80%), January, February, March, October, November and December produces better PR values compared June, July and August. This is as a result of the high collection and system looses which occurred during periods.

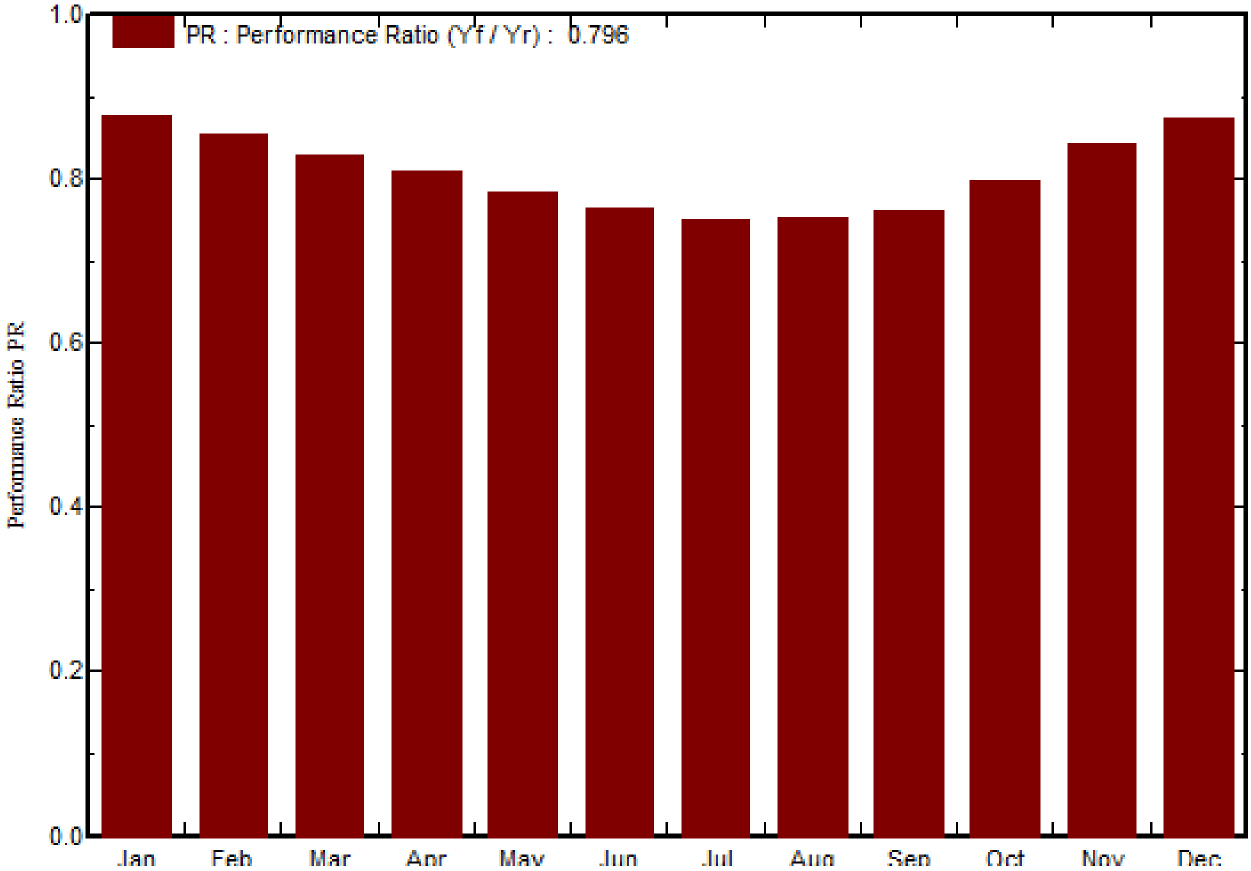


Figure 4.5 Monthly performance ratio values

4.4.3 PVsyst Simulation and Serhatkoy Power Plant output chart

Figure 4.6 show the graph of power produced by PVsyst simulation and the actual plant output by Serhatkoy PV plant. From the chart, the month of June recorded the highest energy output for all the variants, the difference in effective energy at the array output, energy injected into the grid and actual plant results is minimal except for May, June, July and August which is the result of high losses produced at these periods.

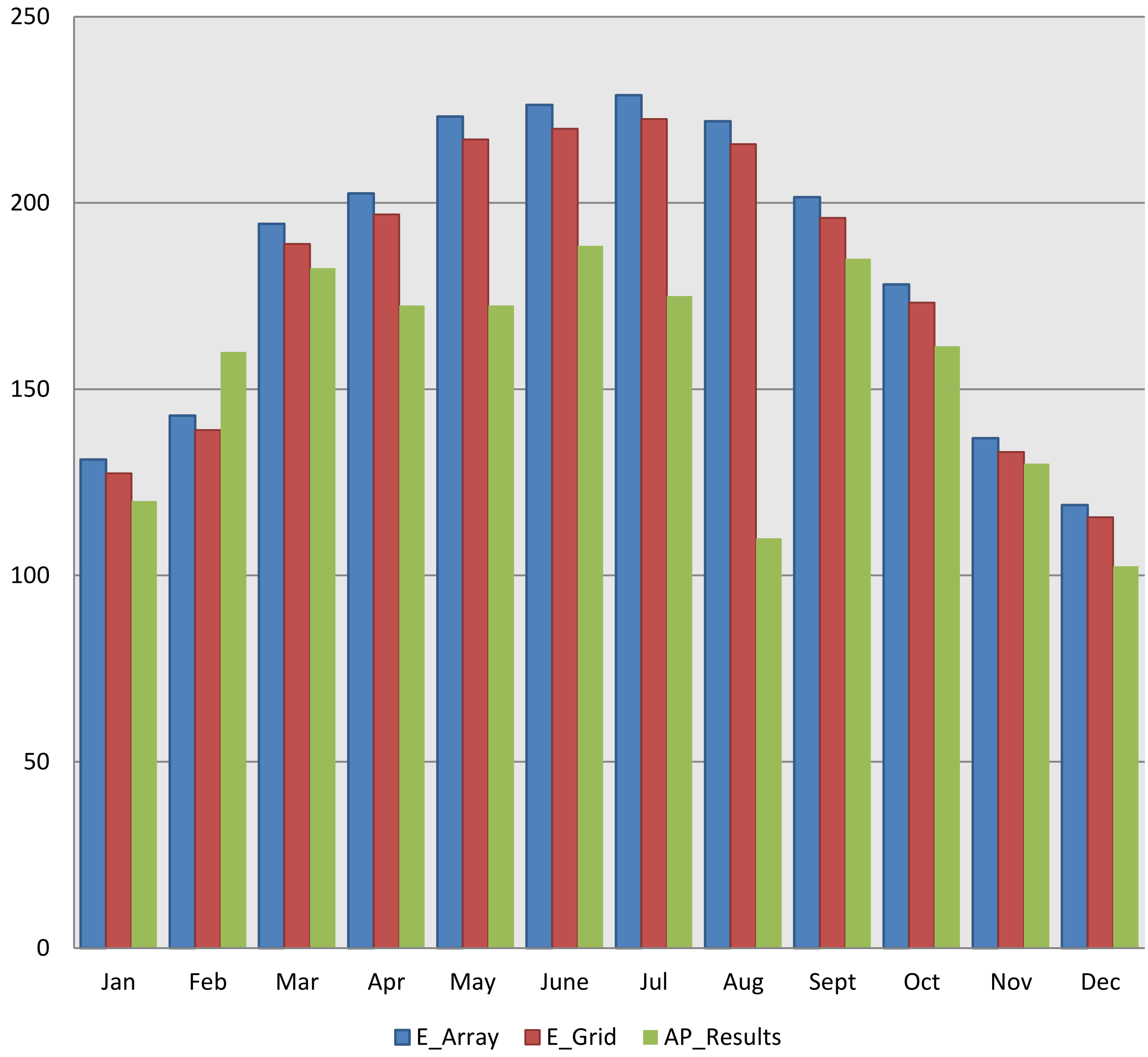


Figure 4.6 Comparisons between simulation and plant power output results.

E_Grid – Energy injected into grid

E_Array – Effective energy at the output of the array

AP_Results – Actual Plant Results

4.4.3.1 Daily energy output chart for PVsyst and Serhatkoy plant.

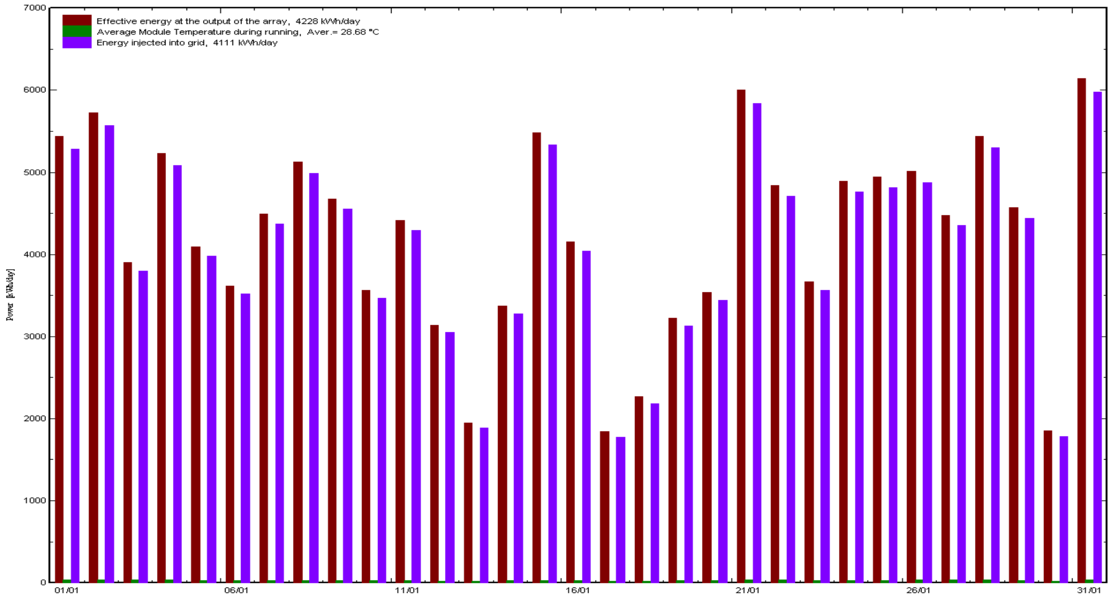


Figure 4.7 January energy output for PVsyst

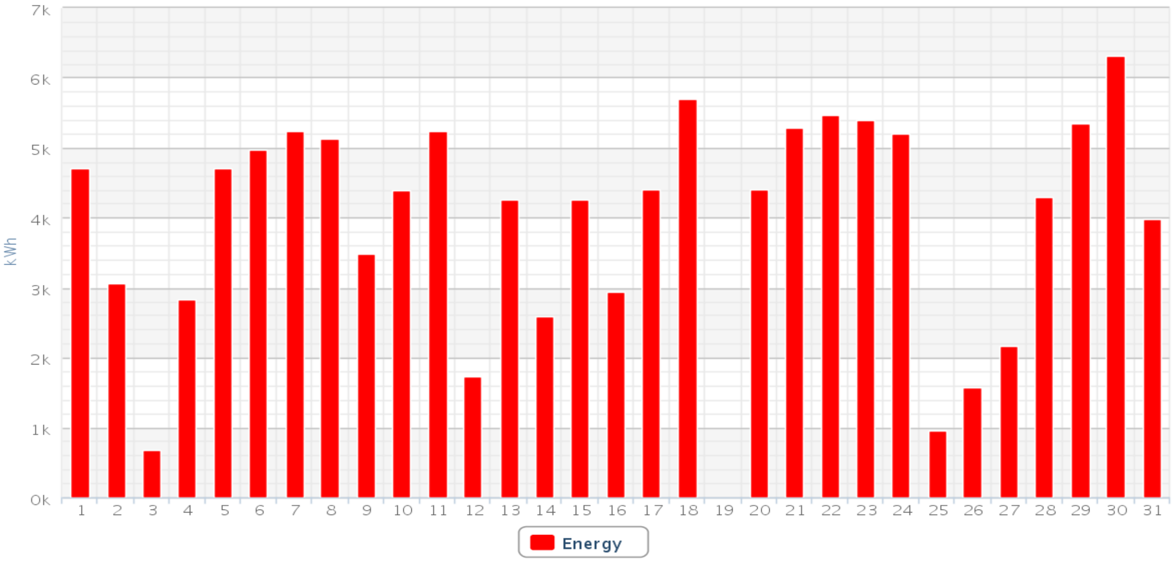


Figure 4.8 January energy output for Serhatkoy plant

Figure 4.7 shows the daily energy output for January using PVsyst simulation. The highest energy injected into the grid was about 6kWh/day. Figure 4.8 represents the daily energy output recorded from Serhatkoy PV power plant, the highest AC energy produced by the plant is 6.45kWh/day. 0.8kWh/day is the lowest energy produced by the plant. The plant was shut-down on the 19th for maintenance.

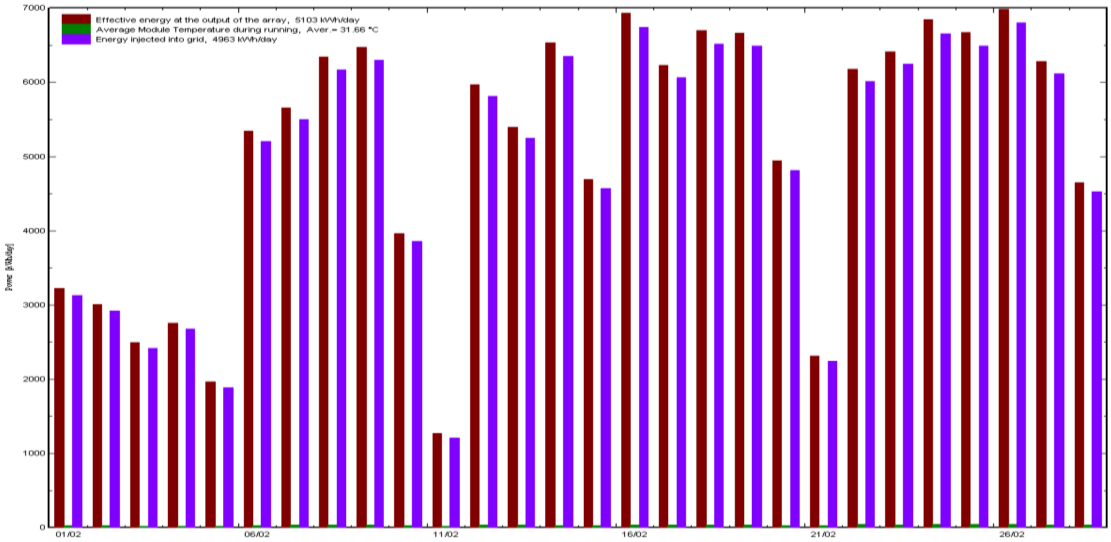


Figure 4.9 February energy output for PVsyst

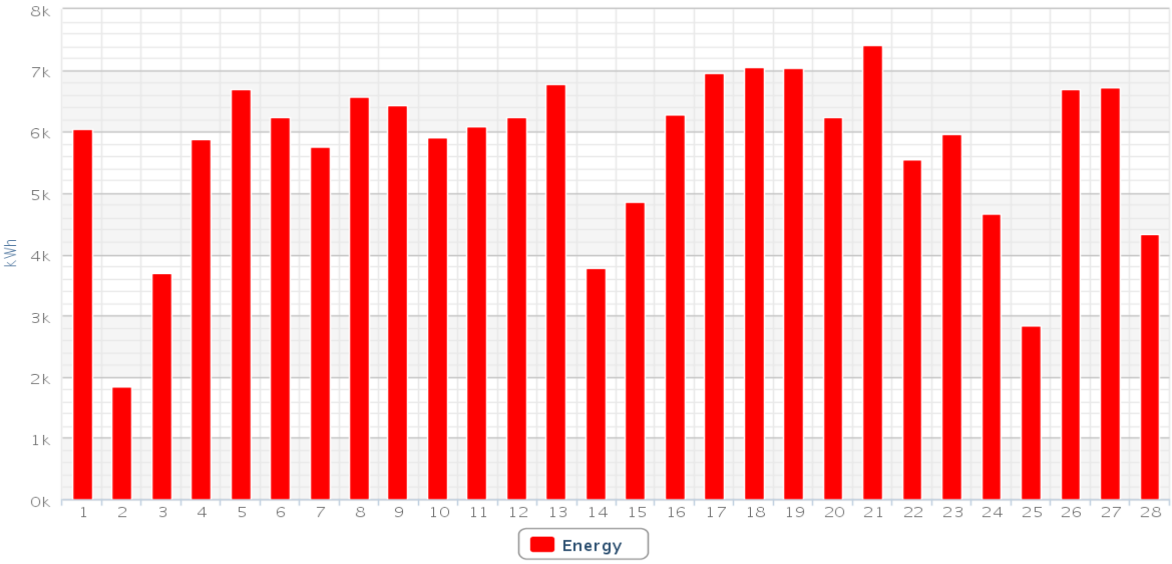


Figure 4.10 February energy output for Serhatkoy plant

Figure 4.9 shows the daily energy output for February using PVsyst simulation. 26th of February produced the highest energy; 6.525kWh/day, the least being 1.125kWh/day. Figure 4.10 represents the daily energy output recorded from Serhatkoy PV power plant for February; the highest AC energy produced by the plant is 7.4kWh/day, the least energy produced was on the 2nd of February.

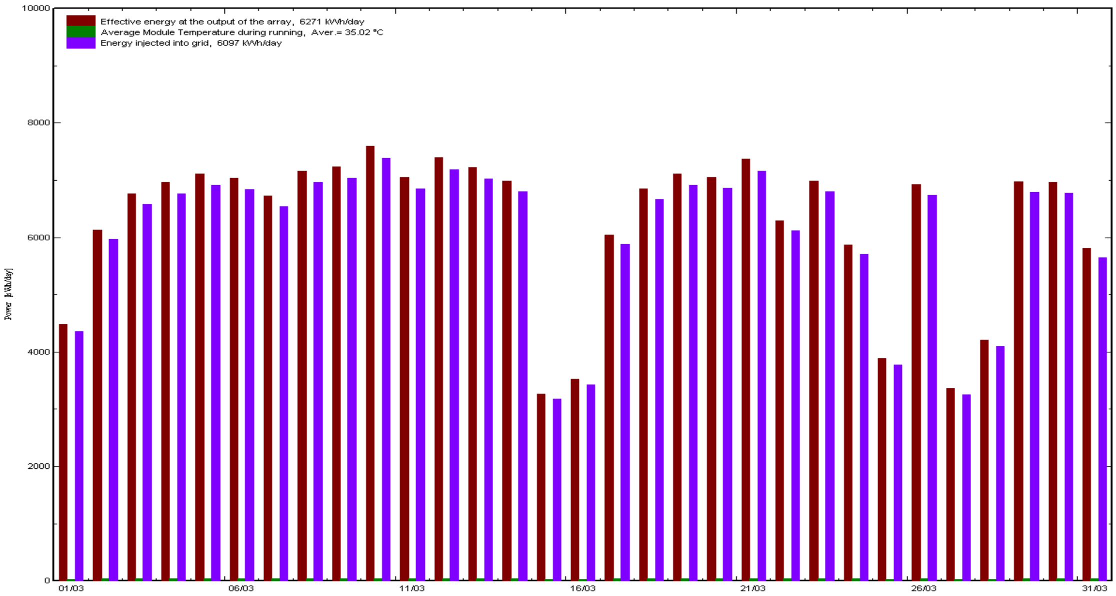


Figure 4.11 March energy output for PVsyst

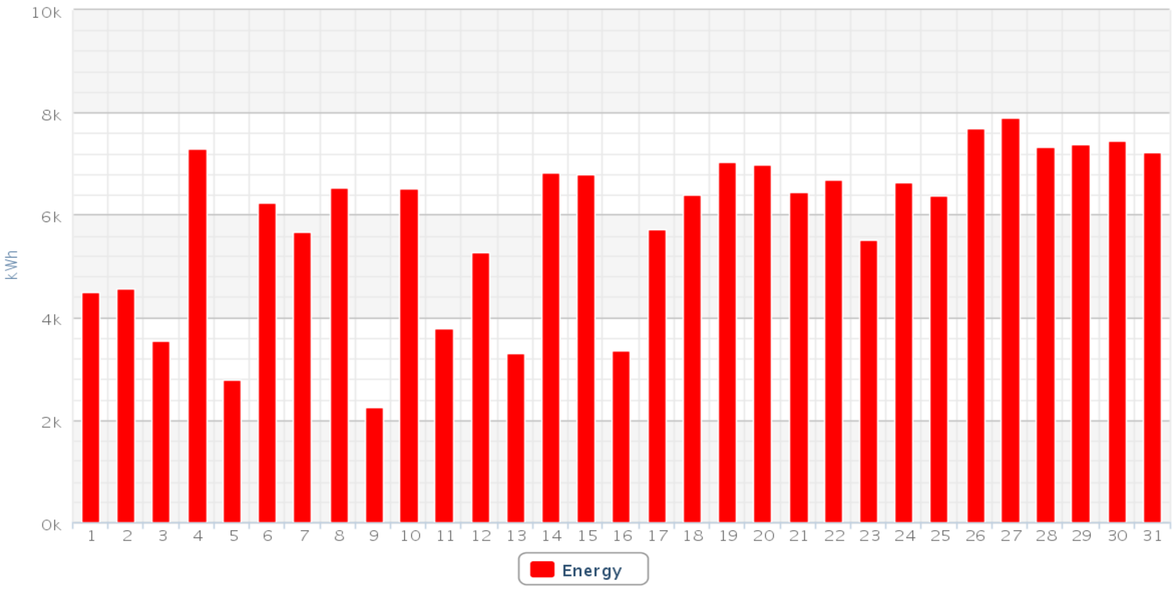


Figure 4.12 March energy output for Serhatkoy plant

Analyzing figure 4.11 and 4.12 shows consistent level of daily energy production for PVsyst from the 2nd to 15th of March, same cannot be said of the production from Serhatkoy Power plant. Instead consistent level of production for Serhatkoy Power plant start's from 19th to 31st March.

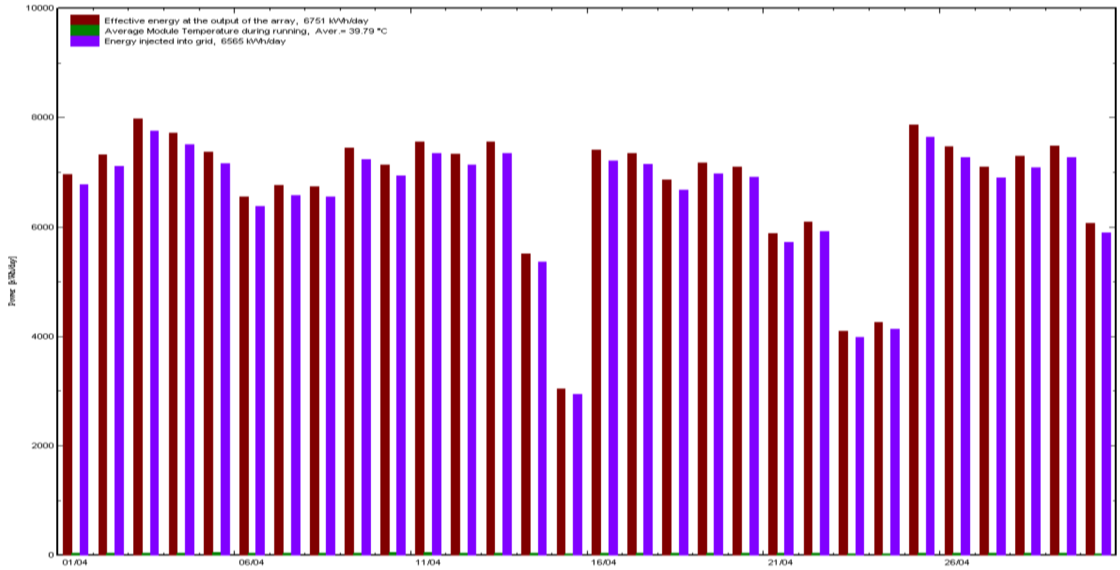


Figure 4.13 April energy output for PVsyst

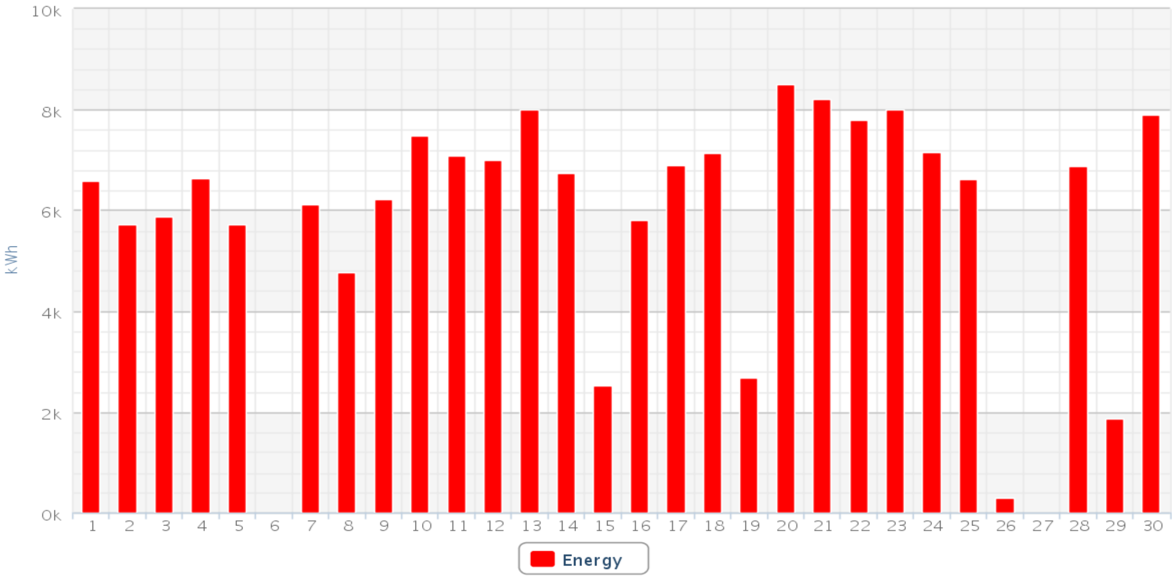


Figure 4.14 April energy output for Serhatkoy plant

Figure 4.13 shows the daily energy production for April from PVsyst. The brown color shows the effective energy at the output of the array whilst blue color shows the energy injected into the grid. Figure 4.14 shows April energy production from Serhatkoy PV power plant. There was maintenance on 6th and 27th.

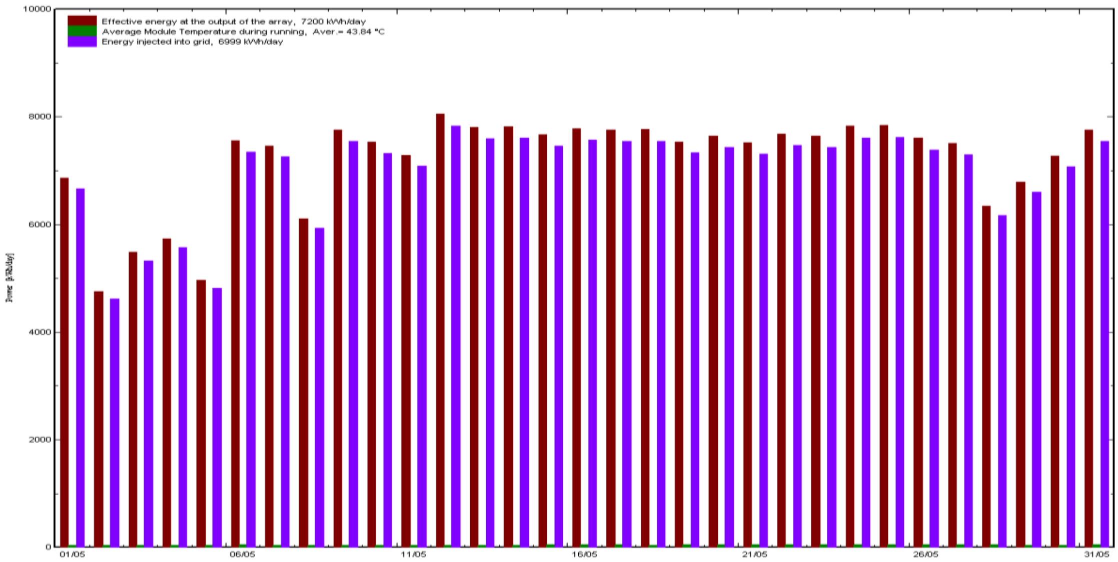


Figure 4.15 May energy output for PVsyst

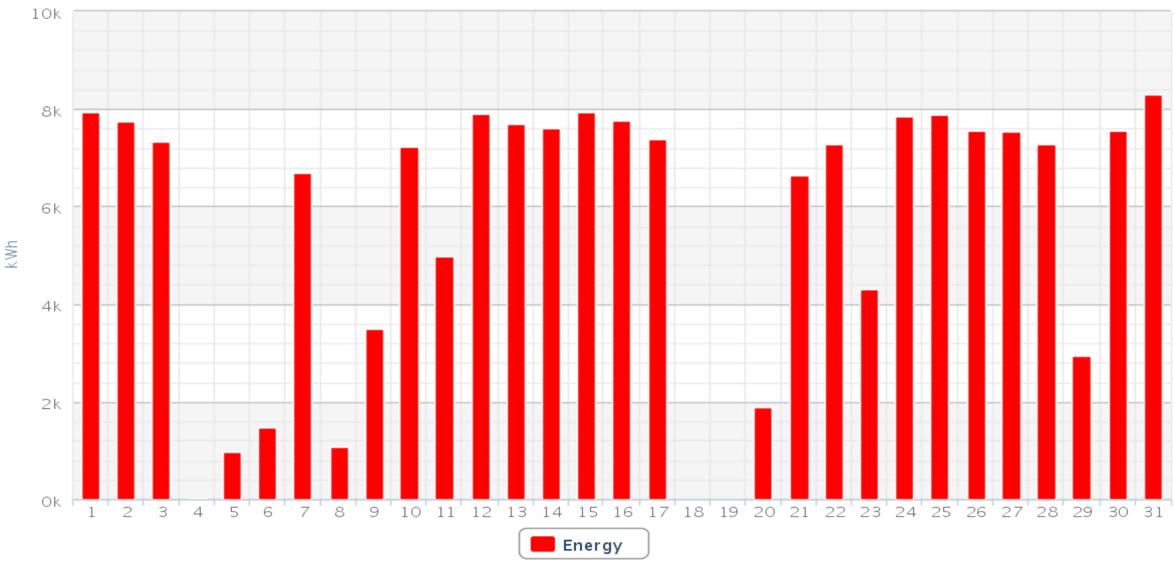


Figure 4.16 May energy output for Serhatkoy plant

The energy production result for May from PVsyst is shown in figure 4.15, the difference in effective energy at array output and energy injected into the grid is between 2% to 6% per day. As seen from figure 4.16, there was no production on the 4th, 18th, and 19th of May; due to faults. The highest daily energy produced was the 31st of May; which is 8.2kWh/day. This is about 0.4kWh/day more the energy produced from PVsyst on the same day.

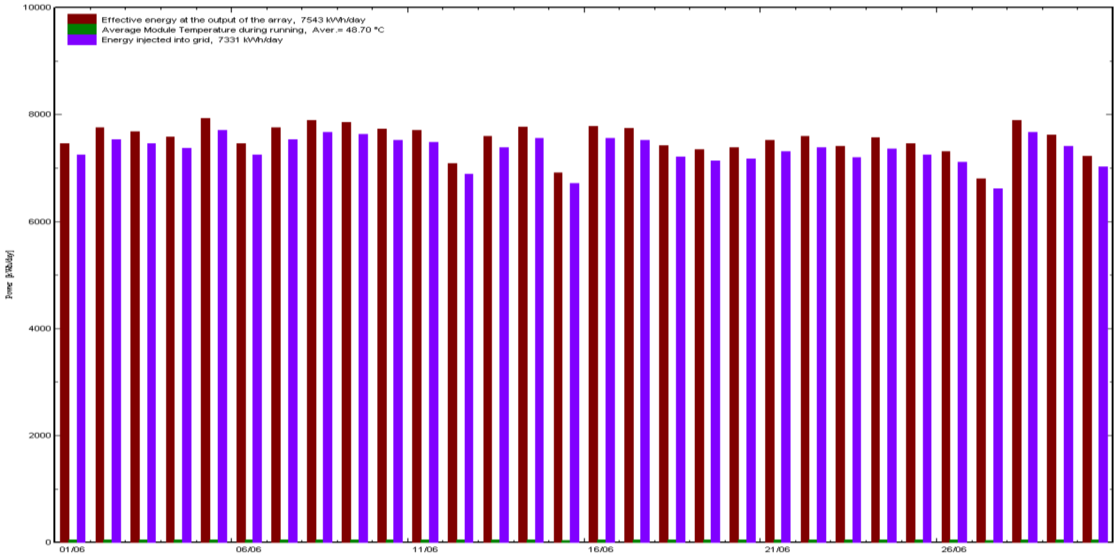


Figure 4.17 June energy output for PVsyst

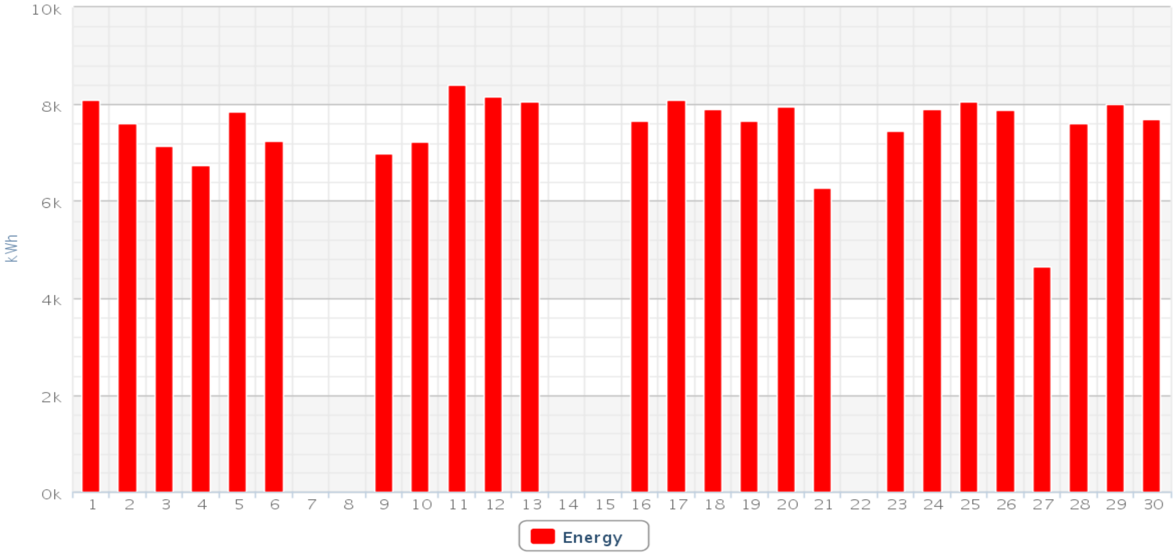


Figure 4.18 June energy output for Serhatkoy plant

Figure 4.18 shows almost consistent level of energy production for the month of June. The highest daily energy produced was the 29th. PVsyst software was used to simulate the results in figure 4.17. The results obtained from Serhatkoy PV power plant is shown in figure 4.18, there we periods of no productions due to faults and maintenance.

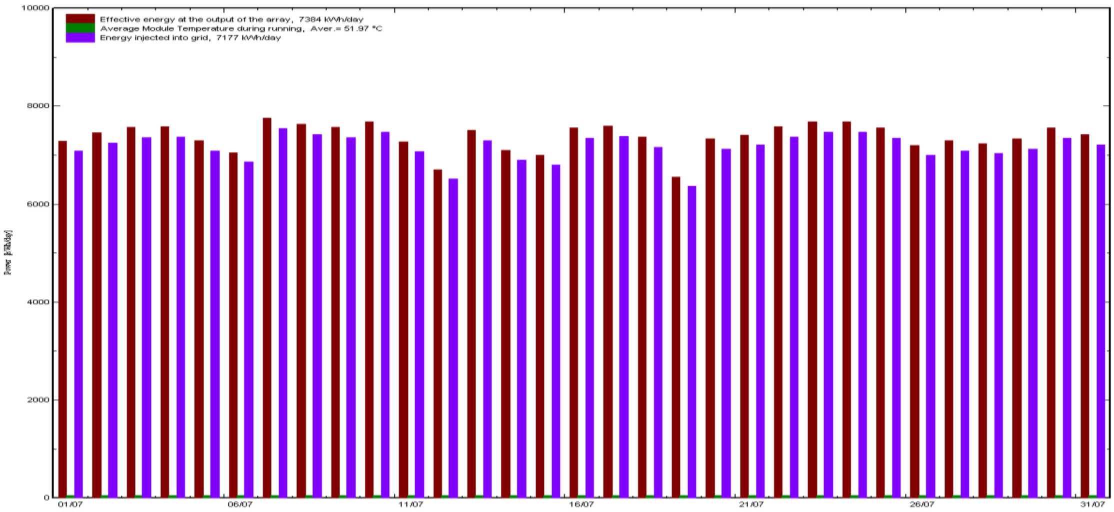


Figure 4.19 July energy output for PVsyst

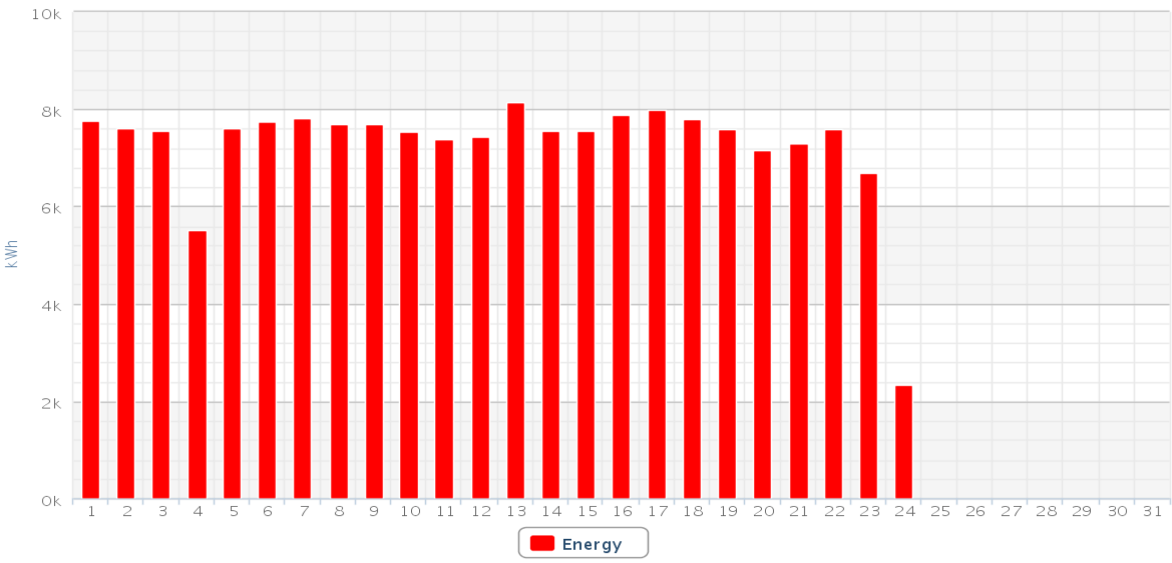


Figure 4.20 July energy output for Serhatkoy plant

Figure 4.19 and 4.20 shows the daily energy production for July obtained from PVsyst and Serhatkoy PV power plant respectively. The difference in highest and least energy produced from PVsyst is about 12.16%. The result from Serhatkoy PV power plant shows no production from 25th to 31st July.

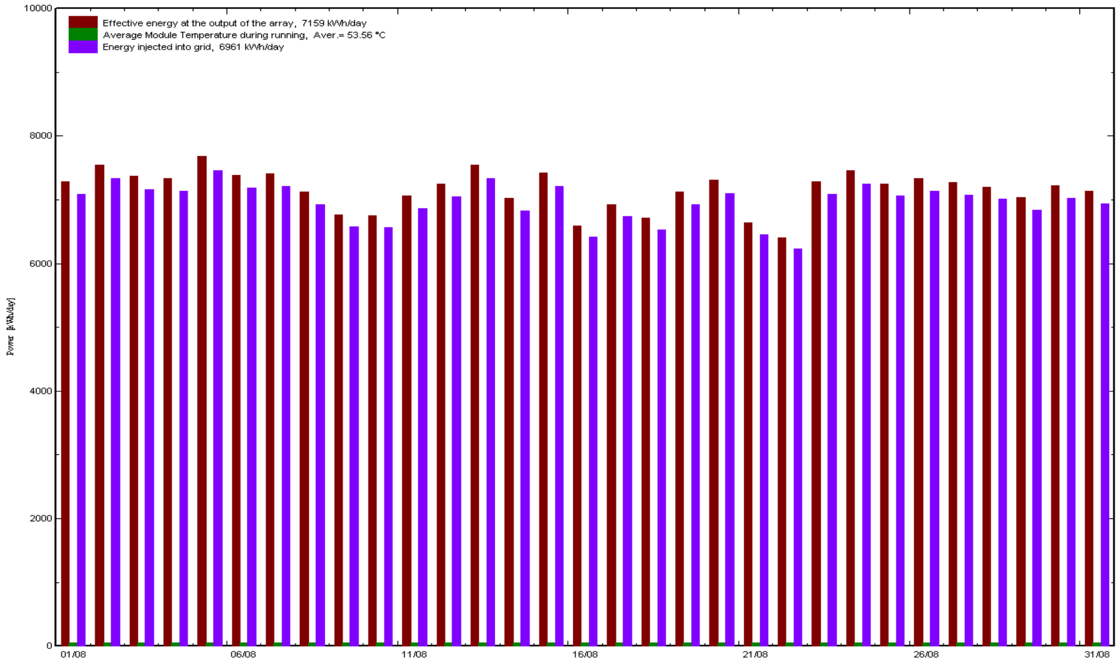


Figure 4.21 August energy output for PVsyst

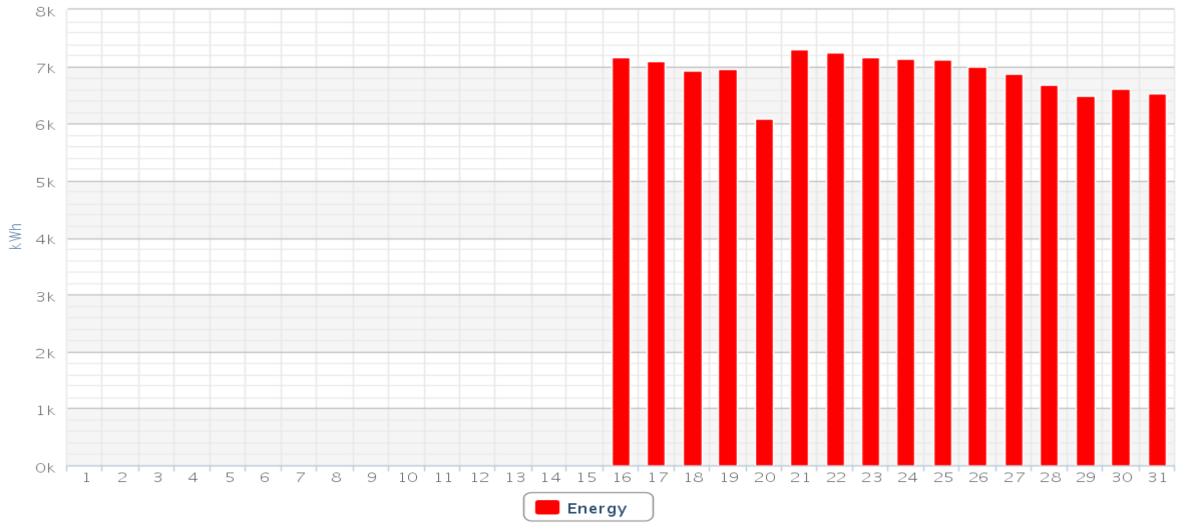


Figure 4.22 August energy output for Serhatkoy plant

Figure 4.21 shows the daily energy output for August using PVsyst simulation. The highest energy injected into the grid was on the 13th. Figure 4.22 represents the daily energy output recorded from Serhatkoy PV power plant, due to high temperature at this periods of the year, there is frequent shut-down for maintenance.

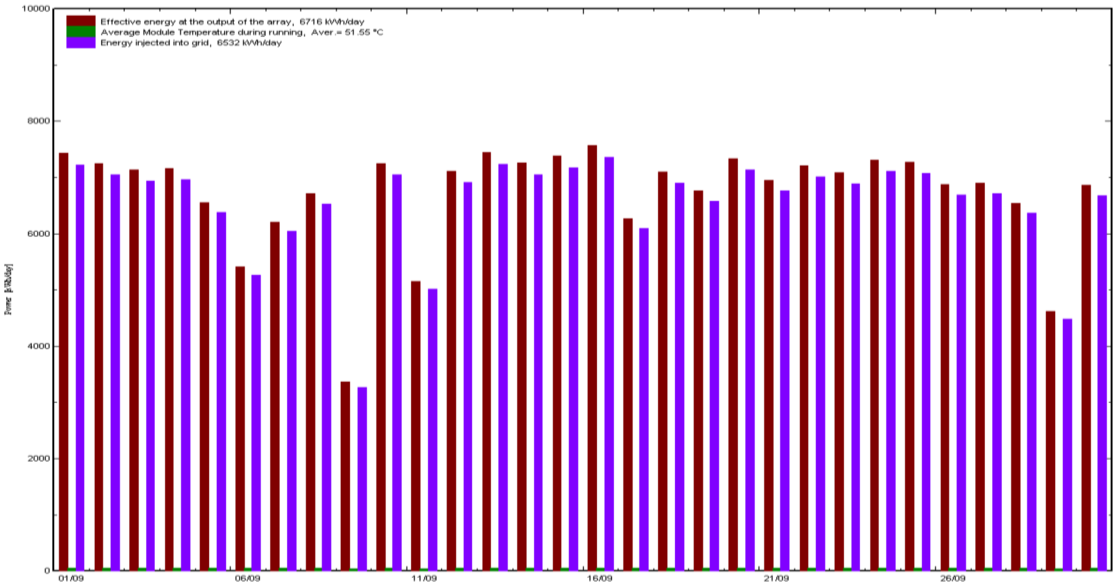


Figure 4.23 September energy output for PVsyst

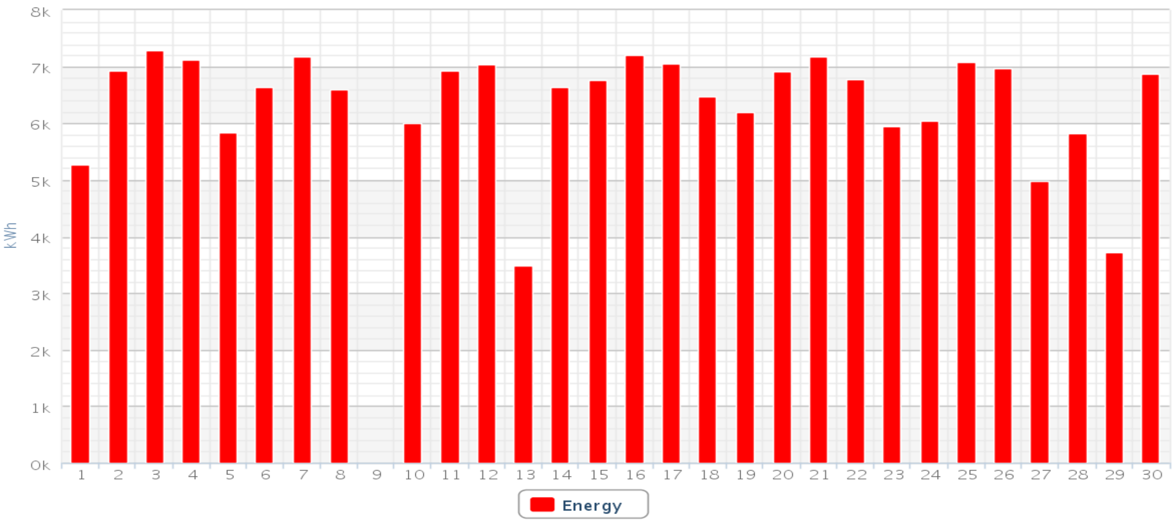


Figure 4.24 September energy output for Serhatkoy plant

Analyzing figure 4.23 and 4.24 shows a bit of consistent level of daily energy production for PVsyst from the 1st to 5th and 11th to 27th of September, same cannot be said of the production from Serhatkoy Power plant. Instead, there is no consistent level of production for Serhatkoy Power plant.

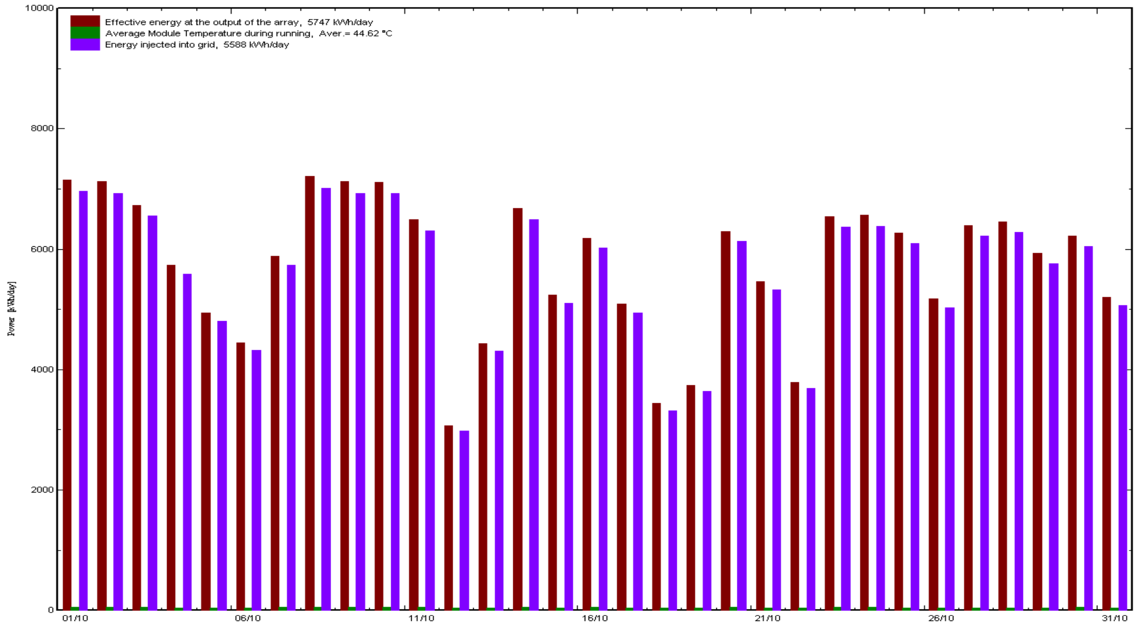


Figure 4.25 October energy output for PVsyst

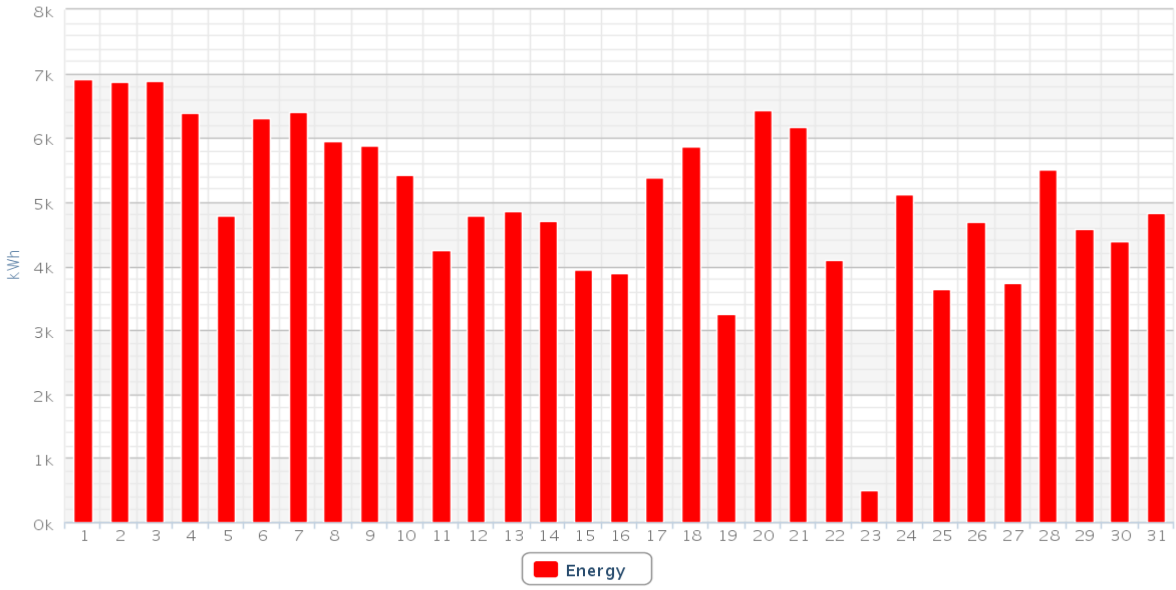


Figure 4.26 October energy output for Serhatkoy plant

Figure 4.25 shows the daily energy production for October from PVsyst. The brown color shows the effective energy at the output of the array whilst blue color shows the energy injected into the grid. Figure 4.26 shows October energy production from Serhatkoy PV power plant.

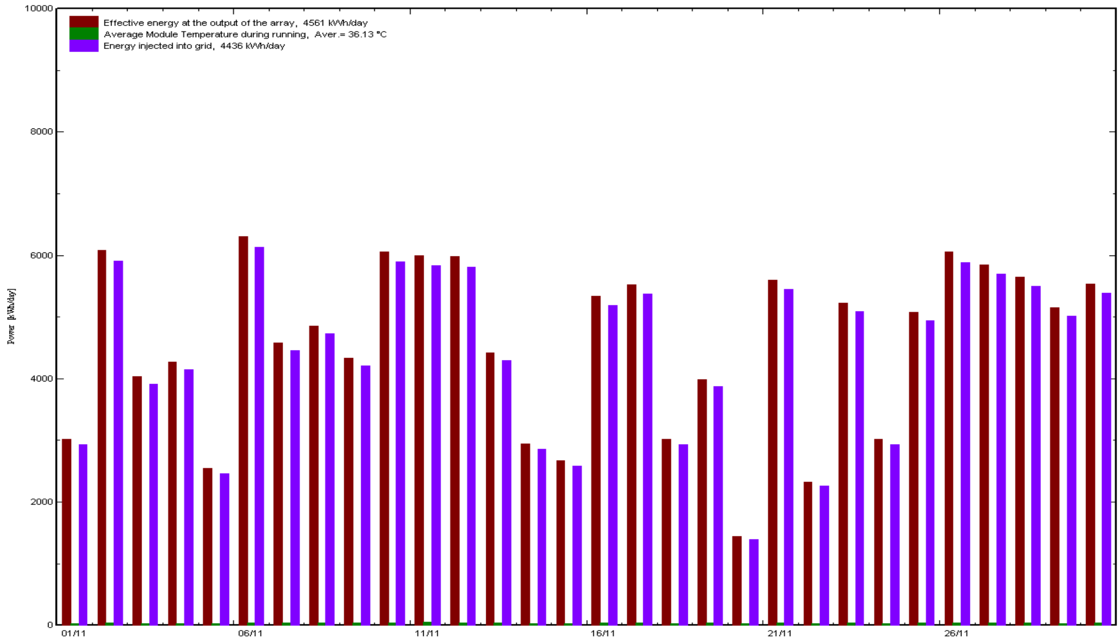


Figure 4.27 November energy output for PVsyst

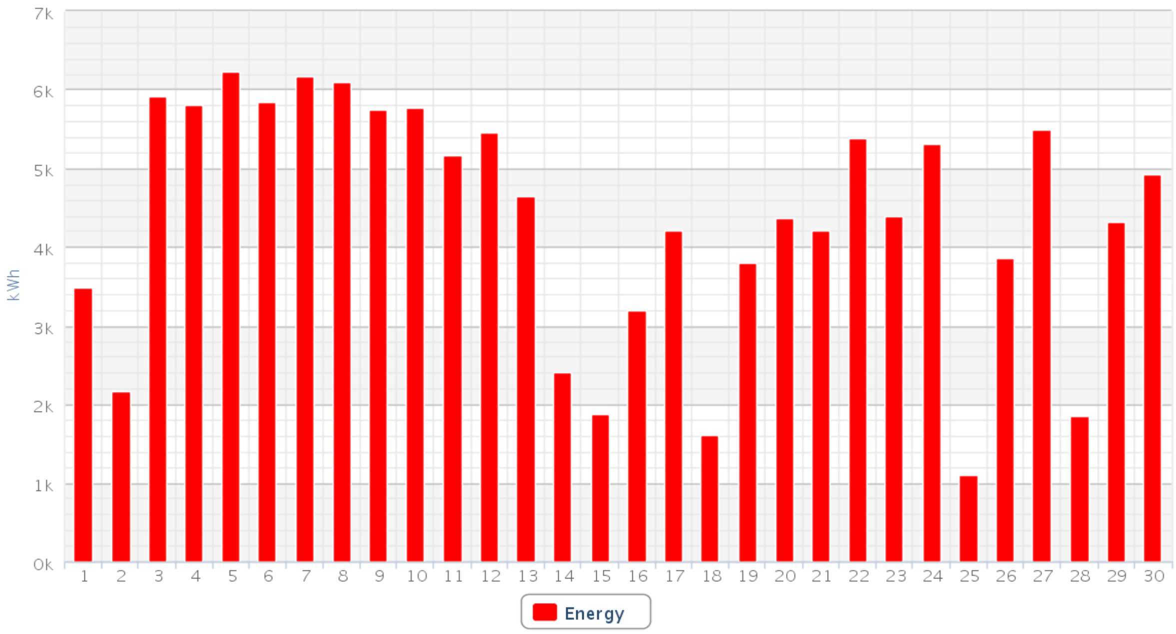


Figure 4.28 November energy output for Serhatkoy plant

Figure 4.27 and 4.28 shows the daily energy production for November obtained from PVsyst and Serhatkoy PV power plant respectively. Due to reduced hours of sunshine, the amount of energy produced is reducing when compared to other months.

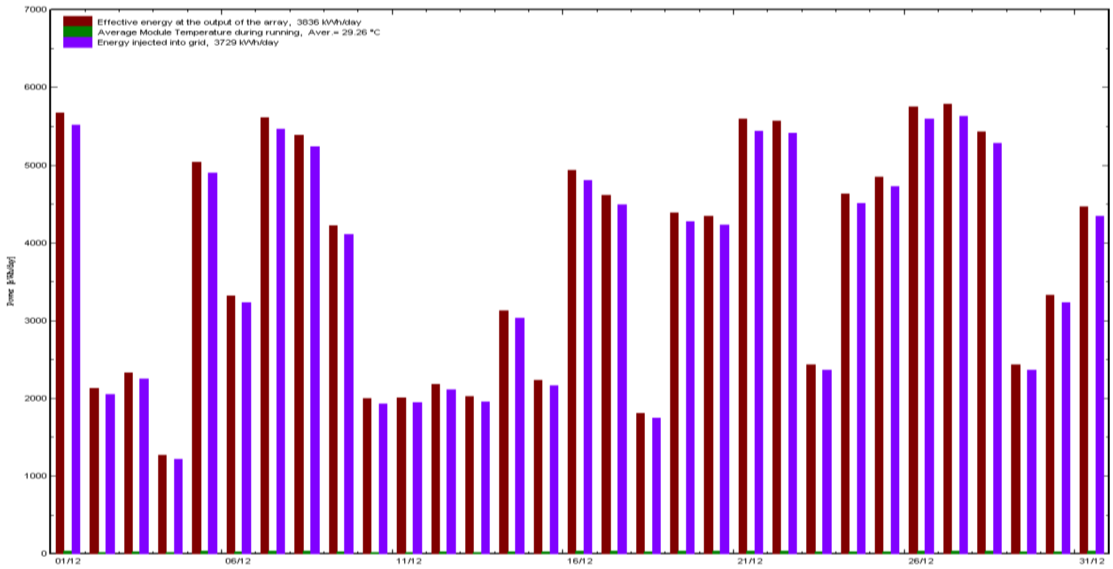


Figure 4.29 December energy output for PVsyst.

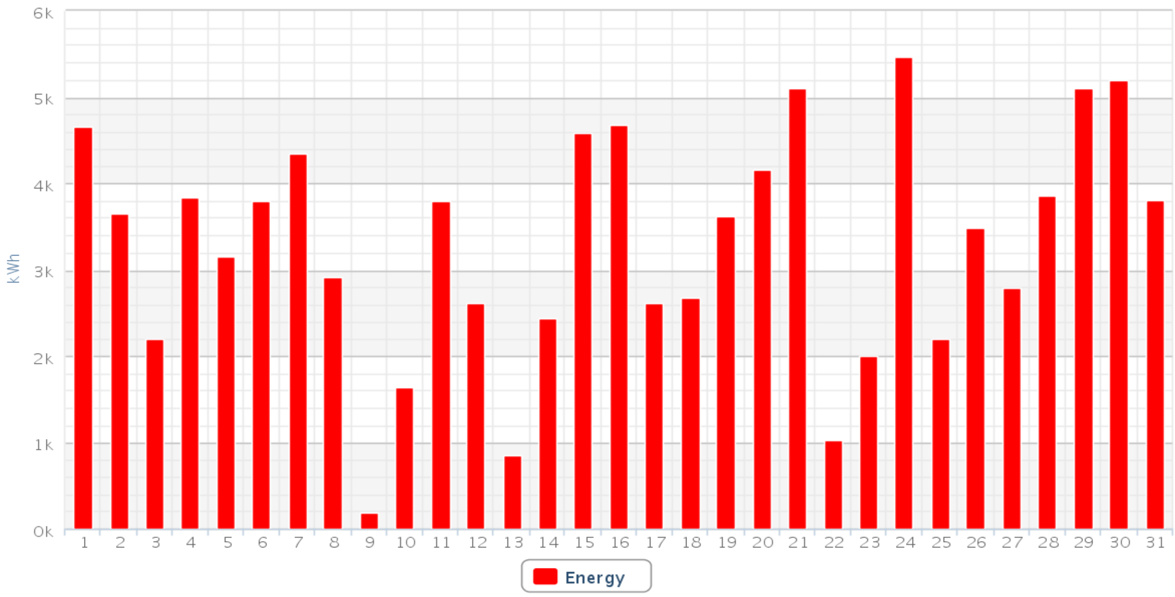


Figure 4.30 December energy output for Serhatkoy plant

The energy production result for December from PVsyst is shown in figure 4.29; the level of daily energy production is sparsely distributed. As seen from figure 4.30, the level of energy production is better than that of PVsyst. Figure 4.30 shows the results obtained from Serhatkoy PV power plant.

4.5 New simulation variant

Table 4.1 shows the balances and main results for Serhatkoy PV power plant. The total yearly global horizontal irradiation is 1898.7kW/m^2. The yearly effective energy produced at the PV array output and the energy injected into the grid is 2206.6MW and 2145.4MW respectively, the difference is the system losses which is 10.89% yearly.

Table 4.1 Balances and main results

	GlobHor kW/m^2	T Amb ^{o}C	GlobInc kW/m^2	GlobEff kW/m^2	EArray MWh	E_Grid MWh	EffArrA %	EffSysA %
January	77.2	12.15	115.7	112.4	131.1	127.4	12.34	12.00
February	96.3	11.93	129.4	125.9	142.9	139.0	12.04	11.71
March	149.7	13.89	181.9	177.3	194.4	189.0	11.65	11.32
April	179.4	17.53	194.2	188.8	202.5	196.9	11.36	11.05
May	224.4	21.57	220.4	214.1	223.2	217.0	11.04	10.73
June	243.6	25.89	229.8	223.3	226.3	219.9	10.73	10.43
July	245.8	29.28	236.3	229.7	228.9	222.5	10.56	10.26
august	219.5	29.40	228.8	222.6	221.9	215.8	10.57	10.28
September	176.4	26.82	205.1	199.9	201.5	196.0	10.70	10.41
October	132.1	22.70	173.5	169.1	178.1	173.2	11.19	10.88
November	86.1	17.70	125.9	122.4	136.8	133.1	11.84	11.51
December	68.2	13.73	105.3	102.1	118.9	115.6	12.31	11.97
Year (total)	1898.7	20.26	2146.2	2087.6	2206.6	2145.4	11.20	10.89

Legends:

GlobHor - Horizontal global irradiation T Amb- Ambient Temperature

GlobInc - Global incident in coll. Plane EArray- Effective energy at array output

E_Grid - Energy injected into grid EffArrA- Effic. Eout array/rough area

EffSysA - Effic. Eout system/rough area

GlobEff- Effective global corr. For IAM and shading

4.6 Loss diagram

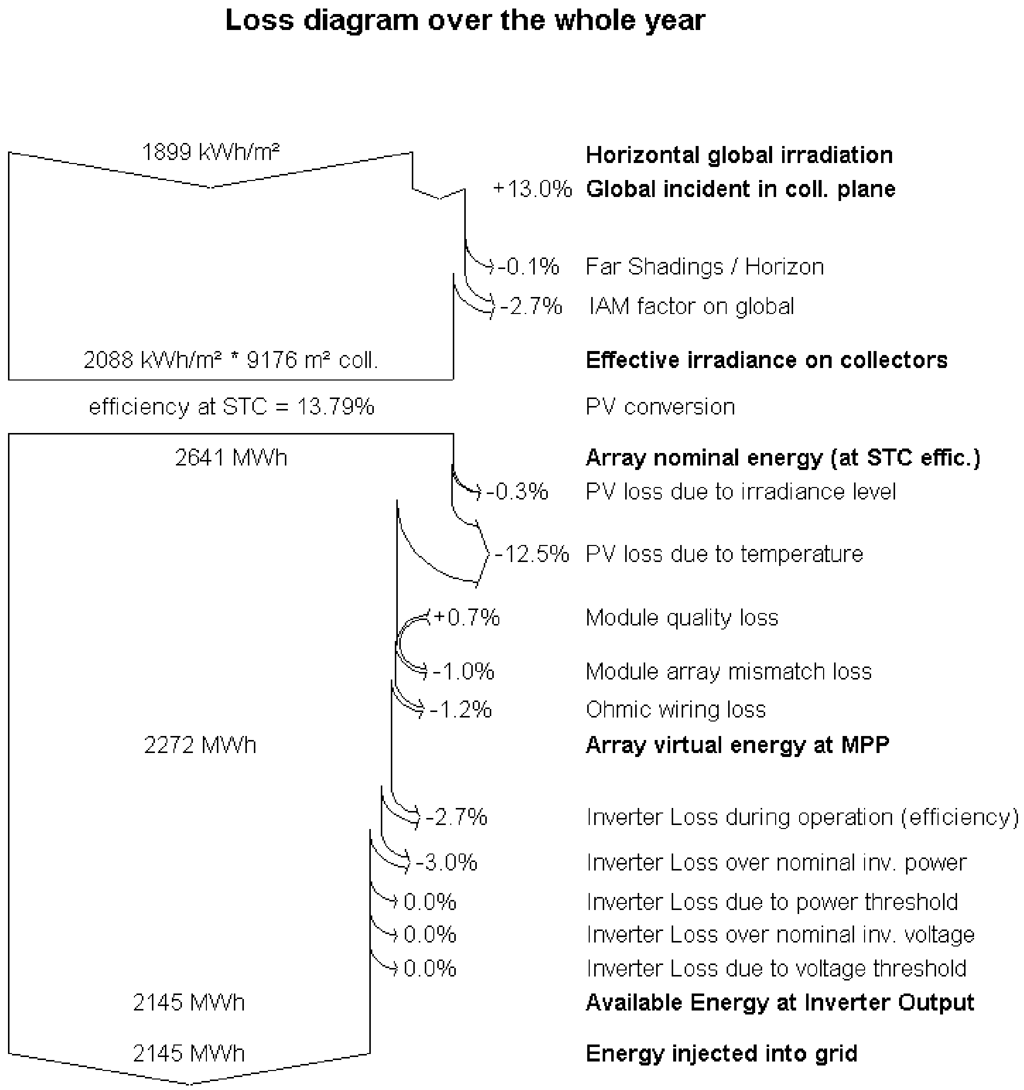


Figure 4.31 Loss diagram

Figure 4.31 represents the loss diagram for our PVsyst grid-connected system design; the loss diagram identifies the main source of loss which affects the output of our design. Meteorological and optical losses, energy losses, PV array losses and system losses are the events which affects the output energy of PV array as against the nominal power ratings described by the manufacturer at STC.

Table 4.2 Detailed Monthly System Losses

	ModQual kWh	MisLoss kWh	OhmLoss kWh	EArrMPP kWh	InvLoss kWh
January	1006	1351	119	132613	5167
February	1113	1495	1457	146533	7563
March	1534	2060	2298	201649	12655
April	1596	2144	2498	209795	12851
May	1762	2366	2945	231322	14366
June	1786	2400	3164	234397	14461
July	1802	2420	3257	236353	13869
August	1746	2345	3161	229031	13232
September	1588	2134	2840	208403	12449
October	1393	1871	2188	183046	9805
November	1056	1418	1342	139045	5976
December	911	1223	973	120150	4558
Year	17291	23228	27242	2272339	126950

Legends:

ModQual- Module quality losses MisLoss- Module mismatch loss

OhmLoss- Ohmic wiring loss InvLoss- Inverter Loss

EArrMPP- Array energy at maximum power point

Table 4.2 shows the detailed monthly system losses, from figure 4.4 the daily system losses was .13kWh/kWp/day. The effective array energy at maximum power point is 2272339 kWh per year. The module quality loss for a year is 17291 kWh. The ohmic wiring losses, module mismatch losses and inverter losses are 27242 kWh/year, 23228kWh/year and 126950 kWh/year respectively.

4.7 Performance Ratio (PR) Calculations

As stated in chapter three, there are various methods of calculating the Performance Ratio (PR) of power plants. For example, using the SAM method proposed by NREL of USA, the PR of Serhatkoy power can be calculated by the method:

Period of Analysis = 1 year

Average solar irradiation in a year =2000kWh/m^2

PV Plant area (generating) = 8412m^2

PV module efficiency = 13.71%

4.7.1 Solution

Extrapolated = 2000 x 8412= 16824000kWh

Nominal plant output = 16824000kWh x 0.1371 = 2306570.4kWh

Performance Ratio for 2011 = $\frac{909955.73kWh}{2306570.4kWh}$ x 100%

PR = 0.394505 x 100

PR = 39.45% (January to April power production result is absent)

The performance ratio for 2012 is:

$$PR = \frac{1985214.9kWh}{2306570.4kWh} \text{ x } 100\%$$

PR = 0.8606 x 100

PR = 86.067%

For 2013, the performance ratio is:

$$\text{PR} = \frac{2152368.97kWh}{2306570.4kWh} \text{ x } 100\%$$

PR = 0.93314 x 100

PR = 93.314%

The performance ratio for 2014 is:

$$\text{PR} = \frac{101269.44kWh}{2306570.4kWh} \text{ x } 100\%$$

PR = 0.4389 x 100

PR = 43.895%

(October to December power production result is absent)

4.8 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. From KIBTEK, managers of the Serhatkoy PV Plant, the cost of installation is 3.7million Euros. The cost of 1kWh of power produced by the plant is sold to customers at 0.45TL (Turkish Lira). Table 4.3 shows the yearly produced power since the inception of operation and the revenue generated.

Table 4.3 Revenue generation for Serhatkoy PV Plant

Year	Energy Produced (kWh)	Generated Revenue (0.45/kWh)TL
2011	909955,72	409480.074
2012	1985214,9	893346.705
2013	2152368,97	968566.0365
2014	1012469,44	455611.248
Total	6060009.03	2727004.064

From Table4.3 the total revenue generated for Serhatkoy PV Plant for four years of operation is 22727004.064TL. From january 2011 to december 2014, the exchange rate of

1euro to the turkish lira has flatuated from a low of 2.00tl to 1euro and a high of 3.11tl to 1euro between 2011 and 2014, using 2.55tl to 1euro as the average exchange rate for this period, the total revenue generated will be 1069413.358euro, the average of this is 267353.34euro (1069413.358euro /4). At this rate of revenue geration, the payback period of the plant will be 11years, this excludes maintenance cost and other cost incured during operation.

4.9. Discussions

For the four years of operation of Serhatkoy PV power plant, 2013 produced the highest energy output and this can be attributed to good weather conditions; long hours of sunshine and lower temperature and the continuous operation of the plant with little shutdown's for maintenance. This impacted well on the capacity factor 19.26% (2013) and 17.66% (2012) which translate into high efficiency of the plant; the industry standard of CF for photovoltaic is 15% - 25%. The performance ratio according SAM method for 2013 was 93.134% and 86.06% for 2012. These results are better when compared to the results obtained from simulation which was 80%. This proves the plant is in good working condition except for the high collection and system losses produced during summer season.

Comparing the monthly power output results from the plant and simulation (figure 4.8), it's evident that, the efficiency of the panels were affected by excessive heat. Solar panels are tested at 25^{0}C about 77^{0}F (STC). An increase in the temperature of solar panels reduces the output voltage linearly whilst the current is increased exponentially; this in turn affects the power output of the plant. Depending on results obtained for grid injected energy from simulation and actual plant energy output, the efficiency of the panels was affected by 18.66% (May, June, July figure 4.8). The temperature coefficient for KIOTO KPV 205 PE is Pmpp= -0.46 %K (Uoc= -116.1 mV/K Isc = +4.40 mA/K) which means that for every 1^{0}C of temperaure beyound the STC value, the power of the panel is reduced by -0.46%K and for every 1^{0}C of temperature below STC value, the power is improved by 0.46%K.

From our simulation results, the percentage difference between effective energy at array output and energy injected into the grid is 2.77%. Aurora inverter was used for constructing Serhatkoy PV plant; it has efficiency of 98%. This means the system losses produced by simulation is 0.77% higher than plant system losses. Comparing the energy injected into the grid from simulation (2145.5MWh) and energy produced by Serhatkoy plant yields the results in table 4.4:

Table 4.4 Serhatkoy PV plant performance

Year	Plant Energy Output MWh	Production Performance
2011	909	42.36%
2012	1985.21	92.53%
2013	2152.36	100.32%
2014	1012.47	47.19%

From table 4.4, the percentage production for 2011 and 2014 is less than 50% because, in 20011, production started from from May, ie between January and April the plant was on test production phase. The energy production results for October to December 2014 was not avaible during my research period. In 2013, the energy injected into the grid by the plant was 0.32% more than the simulation results. The yearly performace of Serhatkoy PV power is impresive when compared to simulation results. The difference in monthly energy output between the pant and simulation results is between 5% to 10% except for where the plant produced 15% energy more than the simulation.

The payback period of the plant is a little high and this is becuase of the increase depreciation of the Turkish lira against most international currencies. As at the start of production of the plant May 2011, the exchange rate between the turkish lira and Euro was 2.1TL using this rate and revenue generated in 2013, the payback will be 9years.

The number factor mitigating against the succesful operation of the plant is high tempearture normally recorded in June, July and August of each year.

CHAPTER 5

CONCLUSION

Solar energy continues to play pivotal role in the delivery of clean and affordable source of generating electricity. Photovoltaic is the most promising technology amongst the types/methods of producing electricity from solar energy currently; it's easy to install and cheap when compared to other solar energy technologies. Serhatkoy PV power plant is the first and only grid connected PV systems in North Cyprus.

The goal of this thesis is to evaluate the performance of Serhatkoy PV power plant and make recommendations from the findings. The research was divided into two parts. In the first part, calculations were done using the real power output from the plant to verify the efficiency of the plant. Secondly, PVsyst software was used to simulate the plant model using meteorological data from NASA. The report/results of the simulation contains the following, PR, Produced energy at array output and energy injected into the grid and detailed losses.

Comparing the production results of Serhatkoy PV power plant with simulation, Serhatkoy PV power plant is under near perfect working condition. As stated in the abstract, the results of this research will be useful data for recommendation, as such due to near perfect working condition of the plant, it is advisable to either expand the solar park to increase the energy output thereby reducing production from fossil fuel or replicate a bigger facility to a location with similar meteorological data but with lower temperature records for summer season.

FUTURE WORK

Further research can be done to verify if the output energy will increase when rotating or solar tracking systems are incorporated into the design. There are several tracking systems; maximum power point tracking, tracking tilted horizontal N-S or E-W, two axes tracking etc. To solve the high losses incurred during high temperatures, cooling systems can be developed or new panels can be designed to with high temperature with minimal losses.

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