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Presented by

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STUDY AND DESIGN OF 20kW$_p$ GRID-CONNECTED SOLAR PHOTOVOLTAIC SYSTEM. CASE STUDY: AMBATOLAMPY, MADAGASCAR

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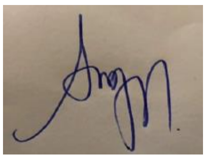
DECLARATION OF INDEPENDENT WORK

I, ANDRIAMANALINA Max Brown Cohen, National Identity number: 201091008711 and student registration number PAUWES/2017/MEE09, do hereby declare that this design project submitted to the Pan African University Institute of Water and Energy Sciences (Inc. Climate Change), for the Master of Science Degree in Energy Engineering, is my own independent work; and complies with the code of Academic Integrity, as well as other relevant policies, procedures, rules and regulations of the Pan African University, and has not been submitted before to any institution by myself or any other person in fulfillment of the requirements for the attainment of any qualification. I also declare that all information, material and results from other works presented here, have been fully cited and referenced in accordance with the academic rules and ethics.

Student Signature:  Date: July 30th 2019

SUPERVISOR'S CERTIFICATION

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

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ABSTRACT

The demand for electrical energy in Madagascar has been on the increase since the country got its independence. This increase in power consumption has been due to population increase and national economic growth. The increase in demand without a matching increase in generation has resulted in perennial electrical power shortfall necessitating the JIRAMA, the National Electricity and Water Utility to resort to expensive fossil fuels for electrical power generation. This electricity shortfall has affected the industrial growth. If the problem is not addressed, future national growth projections may not be met. This research therefore, sought to explore available methods so as to develop a renewable method to mitigate electrical power generation shortage in the country using grid-connected SPV electricity generation.

First of all, the main components in a grid connected SPV system are described. After that, climatic data at the site and several parameters such as available area, topography, environmental and social considerations, accessibility, grid connection, module soiling, water availability are assessed in order to identify the favourable location for the installation of the PV system. The site selected is in the location of Ambodiriana - Ambatolampy which meets all the requirements for the installation of a grid connected SPV system. Next, the design parameters such as mounting structure, module orientation, inter-row spacing are also evaluated. PVsyst is used as the simulation software to design, evaluate and to carry out a financial analysis of the designed photovoltaic system. Then, the system wiring, sizing of cables as well as the selection of fuses and circuit breakers suitable for installation are outlined. And finally, the maintenance and troubleshooting for the grid connected photovoltaic system are presented.

The main results obtained for the design of 20kWp grid connected SPV system are: for optimum production, 92 PV modules (Suntech STP 240-20/Wd) and one central inverter (SMA, Sunny tripower 20000TLEE-JP) is needed. The annual energy produced by the SPV system is equal to 34,20 MWh/year with a LCOE of 486Ariary/kWh and payback time of 11.02 years which is less than the SPV system lifetime that makes the project profitable. The evaluation parameters for the designed SPV system are 79,73% of PR, 20.29% of CF and annual $Yield_{sp}$ of 1549 kWh/kWp/year.

Keywords: Grid-connected, Photovoltaic, PVsyst software, Annual energy production, Financial analysis, PV system maintenance.

RESUME

La demande en énergie électrique à Madagascar est en augmentation depuis l'indépendance du pay. Cette augmentation de la consommation d'énergie est due à l'augmentation de la population et à la croissance économique nationale. L’augmentation de la demande, sans augmentation correspondante de la production, a entraîné un manque persistant d’énergie électrique, obligeant la JIRAMA, le service national de l’électricité et de l’eau, à recourir à des combustibles fossiles coûteux pour la production d’électricité. Ce manque d'électricité a affecté la croissance industrielle. Si le problème n'est pas résolu, les futures projections de la croissance nationale risquent de ne pas être atteintes. Cette recherche visait donc à explorer les méthodes disponibles afin de développer une méthode renouvelable à but d’atténuer la pénurie de production d'électricité dans le pays en utilisant la production d'électricité par le système solaire photovoltaique connectée au réseau.

Tout d'abord, les principaux composants d'un système solaire photovoltaique connecté au réseau sont décrits. Ensuite, les données climatiques du site et plusieurs paramètres tels que la surface disponible, la topographie, les considérations environnementales et sociales, l’accessibilité, la connexion au réseau, la salissure des modules, la disponibilité de l’eau sont évalués afin d’identifier l’emplacement favorable pour l’installation du système photovoltaique. Le site sélectionné se trouve à Ambodiriana - Ambatolampy, qui répond à toutes les exigences pour l'installation d'un système solaire photovoltaique connecté au réseau. Ensuite, les paramètres de conception tels que la structure de montage, l'orientation du module, l'espacement entre les rangées sont également évalués. PVsyst est utilisé comme logiciel de simulation pour concevoir, évaluer et effectuer une analyse financière du système solaire photovoltaique conçus. Ensuite, le câblage du système, le dimensionnement des câbles ainsi que la sélection des fusibles et des disjoncteurs adaptés à l'installation sont également décrits. Et enfin, la maintenance et le dépannage du système photovoltaïque connecté au réseau sont présentés.

Les principaux résultats obtenus pour la conception d'un système solaire photovoltaique connecté au réseau de 20 kWp sont les suivants : pour une production optimale, 92 modules photovoltaïques (Suntech STP 240-20 / Wd) et un onduleur central (SMA, Sunny tripower 20000TLEE-JP) sont nécessaires. L'énergie annuelle produite par le système photovoltaïque est égale à 34,20 MWh / an, avec un coût actualisé de l'électricité de 486 Ariary / kWh et un temps de retour sur investissement de 11,02 ans, ce qui est inférieur à la durée de vie du système rendant le projet rentable. Les paramètres d'évaluation du système photovoltaique conçu sont 79,73% pour le ratio de performance, 20,29% pour le facteur de capacité et un rendement specifique annuel de 1549 kWh / kWp / an.

Mots-clés : Connecté au réseau, Photovoltaïque, Logiciel PVsyst, Production d'énergie annuelle, Analyse financière, Maintenance du système photovoltaïque.

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LIST OF ABBREVIATIONS AND SYMBOLS

SPV	Solar Photovoltaic
LCOE	Levelized Cost of Electricity
JIRAMA	Jiro sy Rano Malagasy
CF	Capacity Factor
PR	Performance Ratio
GDP	Gross Domestic Product
UV	Ultra Violet
ISO	International Standards Organization
IEC	International Electrical Code
NOCT	Nominal Operating Cell Temperature
CSA	Cross-Sectional Area
EAF	Energy Availability Factor
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
AEP	Annual Energy Production
BOS	Balance of System
SPP	Simple Payback Period
GCR	Ground coverage ratio
SMA	System Mess und Anlagentechnik
STC	Standard Test Condition
NEC	National Electricity Code
IAM	Incidence Angle Modifier
VAT	Value Added Tax
NPV	Net Present Value
IEA	International Energy Agency
COE	Cost of Electricity
GHG	Green House Gases
NASA	National Aeronautics and Space Administration
SBR	Set Back Ratio

1. CHAPTER ONE: INTRODUCTION

Like most countries in the world, Madagascar uses electrical energy to meet domestic, commercial and industrial energy requirements. Electrical energy comprises 6 % of the total energy used in the country annually. Lately there has been increased demand for more electricity generation due to population growth and economic development. This chapter presents the current electricity generation position and introduces the methods that could be used to enhance electricity generation in the country.

1.1 BACKGROUND OF THE STUDY

The electricity generation mix of JIRAMA, the national electricity and water utility consists of: diesel, hydro, SPV, to the fewer extent of wind and biomass (a few hundreds of kWs installed). Most of this electrical energy is consumed by industries in the urban centers. A considerable amount of this energy is also consumed by the urban domestic consumers during the evening and the morning peak energy demands.

The country has three main interconnected networks with a total installed generation capacity of 588MW, comprising 20MW of SPV, 162MW of hydropower and 406MW of thermal energy generated from diesel [33]. JIRAMA relies on hydro power generation for up to 30% when the reservoirs are full of water, the largest installed capacity is Andekaleka and Mandraka plants which is account for 58MW of the total capacity of hydro power generation [33]. There are hundreds of mini and small-scale hydro plants throughout the island. However, 70% of the electricity consumed in the country is generated by diesel power plants. The country has several thermal power plants, the newly completed Mandroseza diesel plant now adds 40 MW into the national grid [33]. Some of these hydro and diesel power generation plants are shown in table 1.1.

Madagascar is endowed with hydro power, its potential has previously been estimated to 7800MW, with only 2% being utilized [33]. In spite of the fact that Madagascar has a great potential in hydro, the major generating plants is still diesel plants, meaning that the country still heavily depends on expensive fossil fuel for electricity generation. In addition, JIRAMA estimates that there are 799 outages due to power breakdowns on the medium voltage network every year, more than twice a day on average [33].

Table 1-1:Existing hydro and diesel power generation plants. Source [50]

Power plant	Type	Output MWh	CO_2/kg	Intensity Kg/MWh
Andekaleka	Hydro	357,617	0.0	0.0
Mandraka	Hydro	147,980	0.0	0.0
Antelomita	Thermal	95,665	18,688,900	195
Ambohimanambola	Thermal	82,953	39,926,100	481
Sahanivotry	Hydro	79,773	0.0	0.0
Ambohimanambola	Thermal	73,219	37,087,500	253
Tamatave	Thermal	64,379	31,666,200	492
Tulear	Thermal	59,277	29,363,800	495
Volobe	Hydro	43,839	0.0	0.0
Antsirabe	Thermal	39,709	15,707,900	396
Namorona	Thermal	38,885	4,734,600	122
Mahajanga	Thermal	30,728	15,565,500	253
Toamasina-3	Thermal	18,247	13,601,400	373
Manandrona	Hydro	14,717	0.0	0.0
Antsirabe Hydelec	Thermal	12,309	6,235,530	253
Mahajanga	Thermal	6,839	5,619,010	411
Nosy-be	Thermal	6,186	3,718,550	601
Taolagnaro	Thermal	5,998	4,007,400	334
Tsihombe	Thermal	5,998	4,007,400	334
Ambanja	Thermal	4,782	3,573,670	374
Ambatondrazaka	Thermal	3,849	3,084,070	787
Antsohihy	Thermal	3,905	3,051,390	391
Ankidona	Thermal	3,434	2,170,890	632
Maroantsetra	Thermal	2,815	1,810,740	643
Ampanefena	Thermal	2,781	1,789,880	644
Ambositra	Thermal	2,676	2,422,180	453
Antetezambato 1	Hydro	383	0.0	0.0
Mandritsara	Hydro	247	0.0	0.0
Manja	Thermal	213	120,529	283
Morafenobe	Thermal	201	111,293	277
Ampefy	Hydro	185	0.0	0.0
Firahaiana	Thermal	145	73,325	253
Masomeloka	Thermal	117	59,118	254
Midongy Sud	Thermal	113	57,240	253
Imerimandroso	Thermal	122	61,612	253
Beloha	Thermal	131	68,041	260
Beneitra	Thermal	91.6	46,403	253
Vondrozo	Thermal	131	67,090	256
Antsalova	Thermal	131	68,041	260
Iakora	Thermal	134	69,811	261
Ikongo	Thermal	134	69,811	261
Anahidrano	Thermal	62	55,338	892
Antsiafabositra	Thermal	43	21,847	253

Some parts of the capital experience load shedding of several hours each day, while anticipated power breakdowns are organized in secondary cities. Many residential and commercial establishments maintain diesel generators to compensate for load shedding.

Unlike the standard practice world over, where electricity supply industries use hydro generation for peak demand, Madagascar relies on hydro generation for its base load. Hence, electricity generation shortfall is worse during the dry seasons when the water reservoir levels are very low and the electricity supply industries is forced to rely more on the diesel plants to supply the base load, like the case of 2017 dry spell. During that period, the electricity supply industries totally relied on diesel plants to supplement the hydro plants to meet the demand.

With the current global climatic changes, the Madagascar electricity supply industries has to review its electrical generation mix with a view to develop and exploit other energy resources like solar photovoltaic, wind, biogas. The world-wide trend is to shift from over reliance on fossil fuels to renewable energy resources. Madagascar has to make the same shift if the electricity supply industries is to continue serving the consumer effectively. Furthermore, if Madagascar is to realize the objectives of vision 2030, the electricity supply industries must be enhanced to withstand the energy demand pressure that comes with rapid economic and population growth.

Renewable energy has been used in many countries. Countries like the United States of America (USA) have instituted a policy that in every state, 6% of the total electricity generation must come from renewable sources to cut down on pollution caused by fossil fuel plants [4]. In Germany, the introduction of the Renewable Sources Act of 2000, of granting priority to renewable energy sources, encouraged growth of the installed SPV capacity level from 113 MWp in 2000 to 794 MWp in 2004 and 7.5 GWp by 2011[39]. In Ghana, government support schemes, particularly the national electrification scheme backed by donor funding increased solar PV growth from 160 kWp in 2000 to 1MWp in 2004 and 1.8 MWp by 2009 [35]. And Kenya had 3.6 MWp installed solar PV by the end of 2009 that was mostly concentrated in the rural areas [22].

1.2 OBJECTIVES OF STUDY

1.2.1 Main objective

The main objective of this study is to design and size a grid connected solar photovoltaic system and investigate the impact of such systems on Madagascar electricity supply industry. The work is also an introduction of the Photovoltaic solar energy in the Madagascar national electrical network. It represents a study of the implementation of 20 kWp solar power station into Ambatolampy sub-station.

1.2.2 Specific objectives

The study has the following specific objectives:

-To identify the favorable site for the installation of the grid connected SPV system.
-To design and size a typical grid connected SPV electricity generation system for the case study.
-To assess the energy produced by the grid connected SPV power generation, to evaluate the performance of the system and its impact to the grid for the case study.
-To perform a financial analysis of the SPV electricity generation system and the environmental impact of such system.
-To outline system wiring, installation, maintenance and trouble shooting procedures for the system designed.

1.3 PROBLEM STATEMENT

From the overview done on the Madagascar electricity supply industries, it is evident that there is insufficient electricity supply and overreliance on fossil fuels in electricity generation. The installed effective electricity generation capacity in Madagascar stood at 588MW as of June 2018 while the peak power demand was 551MW [33]. The difference of 35MW or 6 % of generation comprised spinning reserve which was below recommended best practice of 12 to 15%. With a 6% spinning reserve capacity, the industry encountered difficulties in handling the sharp evening peak power demand. Furthermore, the effective electricity generation capacity which is account for 70% is made up of fossil fuel-based generation whose unit cost relied on the ever-increasing price of petroleum products. This amount of fuel-based generation contributed a large percentage to electrical energy price in the country. Thus, there is a need to reduce fuel base electricity generation by exploiting and increasing renewable methods of generation.

1.4 JUSTIFICATION OF THE STUDY

In view of the present electrical energy shortfall in the Madagascar electricity supply industries as highlighted, it is evident that the industry needs to take urgent measures to make supply more reliable. Grid connected SPV systems seems to be one of the alternative solutions to avoid customer inconvenience due to electrical power interruption and to satisfy peak demand.

2. CHAPTER TWO: LITERATURE REVIEW

It is important to state that the amount of literature on Madagascar's solar energy, Photovoltaic technology and SPV grid-connected system is enormous. This chapter will cover just a little portion of that enormous amount of literature.

2.1 THE GENERAL STATE OF MADAGASCAR

Madagascar is a large island in the Indian Ocean off the eastern coast of southern Africa, east of Mozambique. It is the fourth largest island in the world. The capital Antananarivo is in the hauts plateaux near the center of the island. Madagascar has a total area of 587,040 square kilometers [51]. The country overview is shown in the figure 2-1.

Figure 2.1:Country overview. Source [51]

The current population of Madagascar is 26,833,424; based on the latest United Nations estimates [51]. 37.8 % of the population is urban (10,183,611 people in 2019), 62.2 % of the population live in rural area [51]. According to the word bank, the Gross Domestic Product of Madagascar was estimated to $39,763,887,263 [51]. The agricultural sector is accounted for 34% of GDP and industry is accounted for 11% of GDP. Therefore, the availability of energy is vital for the economic and social development of the country [51].

2.2 THE STATE OF SOLAR ENERGY IN MADAGASCAR

Madagascar has a large solar energy potential. Almost all regions of Madagascar receive over 2,800 hours of sunshine per year, with the daily solar radiation ranging from 1,500 to 2,100 kWh/m^2[15]. The country's global horizontal irradiation is shown in the figure 2-2.

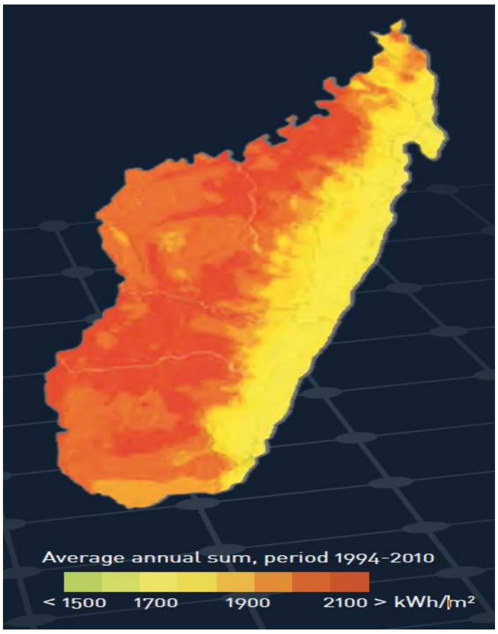


Figure 2.2:Madagascar's Global Horizontal Irradiation. Source [Solargis]

2.3 THE STATE OF SOLAR PHOTOVOLTAICS IN AFRICA

Africa has abundant solar resources but also has a desperate need for new capacity to improve existing supply quality and meet demand growth. The continent is increasingly turning to SPV as an economic means to bolster energy security, meet social and development goals and support rapid economic growth in a sustainable manner. In 2014, new capacity additions of SPV in Africa exceeded 800MW, more than doubling the continent's cumulative installed PV capacity [29]. This was followed by additions of 750MW in 2015 (refer to figure 2.3). There is also a fast-growing PV market to meet off-grid electricity needs. Technology improvements and lower costs have spurred local and social entrepreneurs in the solar home system (SHS) market and in developing stand-alone mini-grids.

As for Madagascar, PV systems are currently utilized for powering public buildings such as health clinics, as well as off-grid community electrification solutions. A few foreign companies are assisting with various electrification projects on a small-scale (i.e. solar-powered pumps for clean water) [16].

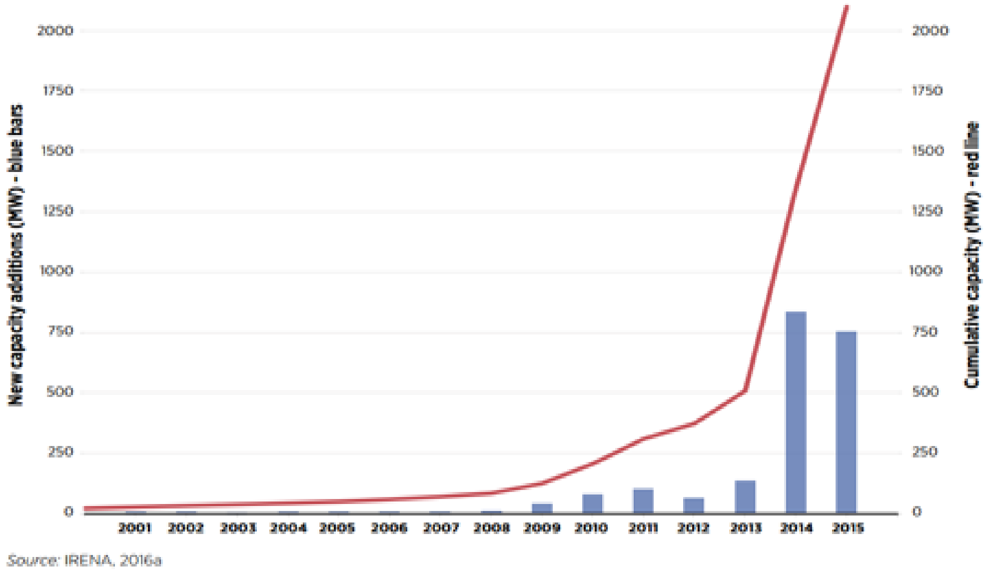


Figure 2.3:Africa's total installed cumulative solar PV capacity and annual new additions, 2001-2015. Source [29].

2.4 PHOTOVOLTAIC TECHNOLOGY

In the following section, the Photovoltaic technology will be described. It includes the elements of solar PV, the effect of some parameters on the performance of a PV module and the different types of solar PV system.

2.4.1 Photovoltaic cell

A photovoltaic cell converts solar energy to electricity due to the photoelectric effect. Most solar cells are made of semiconducting material, with crystalline silicon (c-Si) being the most commonly used in solar cells today. The solar cell can absorb a wide spectrum of photons from the incident solar radiation, depending on the optical and electrical features of the semiconductor material used in the solar cell.

Figure 2.4:PV cell

2.4.2 Photovoltaic modules

A solar cell typically has an open circuit voltage ranging from 0.55 - 0.72 V. To generate a usable voltage and current, several solar cells can be interconnected to form a PV module. PV modules often contain 36, 60 or 72 solar cells, usually connected in series to minimize resistive losses and enable high voltages. The efficiency of a module is lower than a solar cell due to the mismatch losses and resistive losses in the interconnections between the cells.

Figure 2.5:PV module

<u>Module structure and materials</u>

The typical components of a crystalline silicon PV module are illustrated in figure 2-6. The front surface is a low iron, tempered glass with a high transmissivity which provides mechanical stability. The solar cells are sandwiched between two layers of encapsulants to protect them against the environment. The encapsulant needs to be transparent, have low thermal resistance and withstand high temperature and UV radiation. A backsheet protects the cells from water, is electrically insulating and helps dissipate heat. The most common backsheet is a combination of Tedlar and polyester [3]. The surrounding frame enhances the mechanical stability and the junction box contains all the electrical connections to the solar cells.

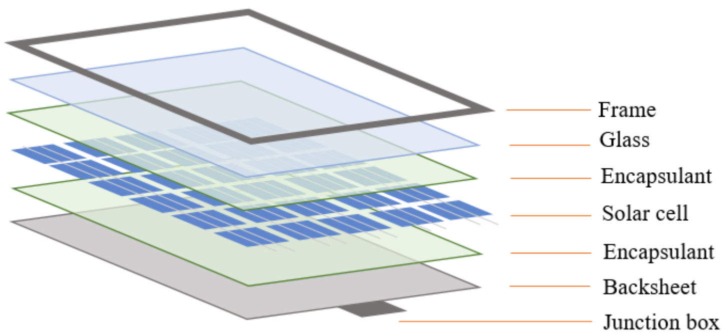
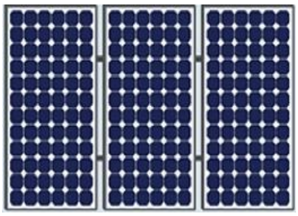
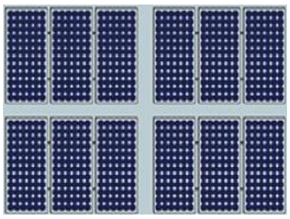


Figure 2.6:Structure of a crystalline silicon PV module. Source [3]

2.4.3 Photovoltaic array

Desired power, voltage, and current can be obtained by connecting individual PV modules in series and parallel combinations in much the same way as batteries. When modules are fixed together in a single mount, they are called a panel and when two or more panels are used together, they are called an array. Single panels are also called arrays. When circuits are wired in series, the voltage of each panel is added together but the amperage remains the same. When circuits are wired in parallel, the voltage of each panel remains the same and the amperage of each panel is added. This wiring principle is used to build photovoltaic (PV) modules. Photovoltaic modules can then be wired together to create PV arrays.





a) PV panel b) PV array

Figure 2-7:PV Panel & Array

2.4.4 Describing photovoltaic module performance

- EFFECT OF THE TEMPERATURE ON THE BAND GAP

The term "band gap" refers to the energy difference between the top of the valence (outer electron) band and the bottom of the conduction (free electron flow) band. In the valence band electrons are tightly held in their orbits by the nuclear forces of a single atom. In the conduction band, electrons have enough energy to move around freely and are not tied to any one atom. A material with a large almost insurmountable band gap, greater than 3 electron volts is called an insulator. In metal conductors, the valence and conduction bands overlap, so they do not have a band gap. Materials with a small band gap, which behave as insulators at absolute zero, but allow excitation of electrons into their conduction bands (at temperatures below their melting point) are called semiconductors. Electrons are able to jump from one band to another given an "energy lift" by some external force, such as a sunlight photon. In order for an electron to make the leap from the valence band to the conduction band, it requires a boost of "band gap" energy. Electrons can gain enough energy to jump to the conduction band by absorbing either a "phonon" (heat) or a "photon" (light) with at least band gap energy. Photons with energy less than the band gap will not separate electron pairs and simply pass through the solar cell. Photons, with more energy than necessary to separate an electron pair, do generate an electron and a hole with the balance of their enegy being dissipated in the form of heat. Band gap energy differs from one material to another.

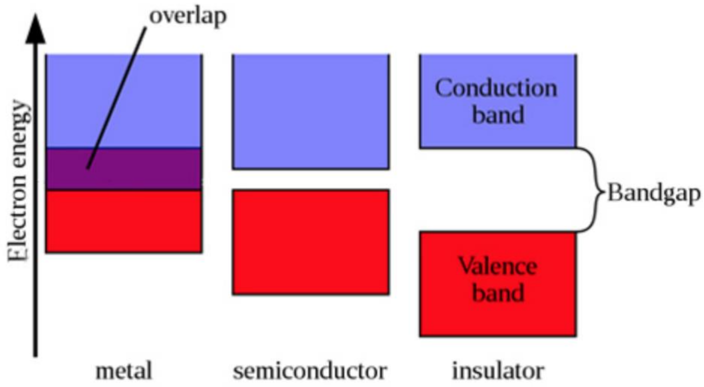


Figure 2.8:Band gap of different materials

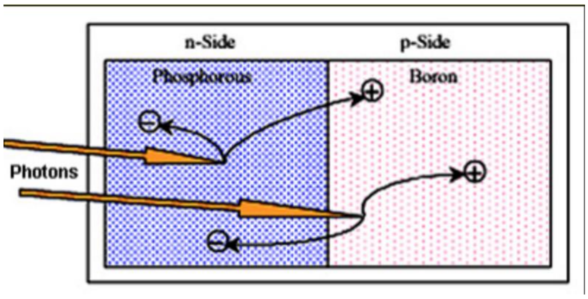


Figure 2.9:Photoelectric effect

Like all other semiconductor devices, solar cells are sensitive to temperature. Increases in temperature reduce the band gap of a semiconductor, thereby effecting most of the semiconductor material parameters. The decrease in the band gap of a semiconductor with increasing temperature can be viewed as increasing the energy of the electrons in the material. Lower energy is therefore needed to break the bond. In the bond model of a semiconductor band gap, reduction in the bond energy also reduces the band gap. Therefore increasing the temperature reduces the band gap. In a solar cell, the parameter most affected by an increase in temperature is the open-circuit voltage. The impact of increasing temperature on the output of a PV module is going to be described in the following paragraph.

- IMPACT OF SOLAR RADIATION ON V-I CHARACTERISTIC CURVE OF PHOTOVOLTAIC MODULE

Standard sunlight conditions on a clear day are assumed to be 1000 W/m^2 [17]. This is sometimes called "one sun," or a "peak sun." Less than one sun will reduce the current output of the module by a proportional amount. For example, if only one-half sun (500 W/m^2) is available, the amount of output current is roughly cut in half. For maximum output, PV modules should be pointed as straight toward the sun as possible.

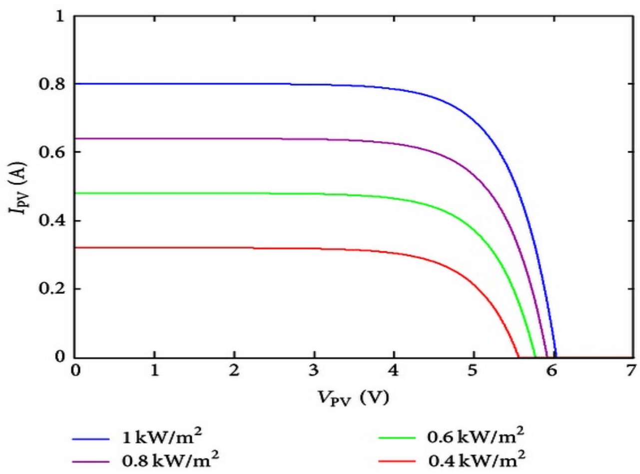


Figure 2.10:Effect of the solar radiation on the PV I-V curve. Source [17]

- IMPACT OF TEMPERATURE ON V-I CHARACTERISTIC CURVE OF PHOTOVOLTAIC MODULE

Module temperature affects the output voltage inversely. Higher module temperatures will reduce the voltage by 0.04V to 0.1V for every one Celsius degree rise in temperature (0.04V/°C to 0.1V/°C) [17]. That is why modules should not be installed flush against a surface. Air should be allowed to circulate behind the back of each module so its temperature does not rise and reducing its output. An air space of 4-6 inches is usually required to provide proper ventilation [17].

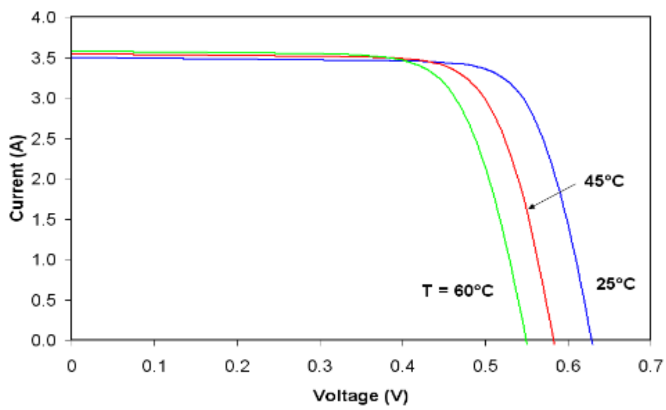


Figure 2.11:Effect of temperature on the PV I-V curve. Source [17]

- IMPACT OF SHADING EFFECT ON V-I CHARACTERISTIC CURVE OF PHOTOVOLTAIC MODULE

Because photovoltaic cells are electrical semiconductors, partial shading of the module will cause the shaded cells to heat up. They are now acting as inefficient conductors instead of electrical generators. Partial shading may ruin shaded cells. Partial module shading has a serious effect on module power output. For a typical module, completely shading only one cell can reduce the module output by as much as 80% [17]. One or more damaged cells in a module can have the same effect as shading. That is why modules should be completely unshaded during operation. Thin film modules are not as affected by this problem, nevertheless, they should still be unshaded.

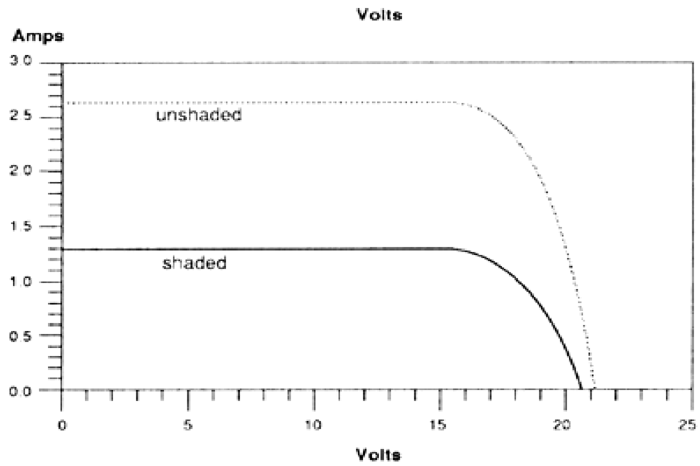


Figure 2.12:Effect of shading on the PV I-V curve. Source [17]

2.4.5 Types of photovoltaic system

PV technology was first applied in space, by providing electricity to satellites. Today, PV systems can be used to power just about anything on earth. On the basis, PV systems operate in three basic forms.

- Grid Connected PV Systems

These systems are connected to a broader electricity network. The PV system is connected to the utility grid using a high-quality inverter, which converts DC power from the solar array into AC power that conforms to the grid's electrical requirements. During the day, the solar electricity generated by the system is either used immediately or sold off to electricity supply companies. In the evening, when the system is unable to supply immediate power, electricity can be bought back from the network.

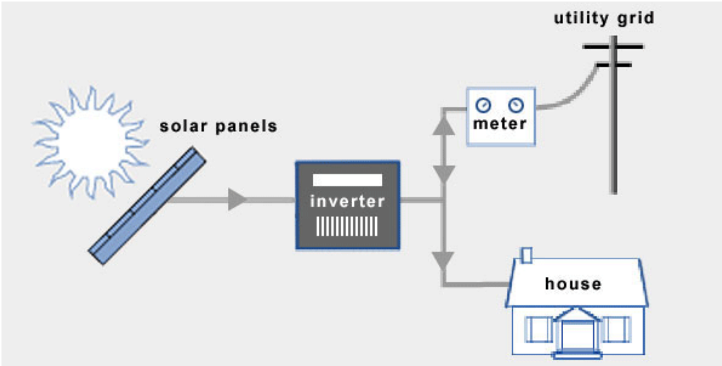


Figure 2.13:Grid Connected PV Systems. Source [55]

- Grid Tied with Battery Backup PV system

Solar energy stored in batteries can be used at nighttime. Using net metering, unused solar power can be sold back to the grid. With this system, you will have power even if your neighborhood has lost power.

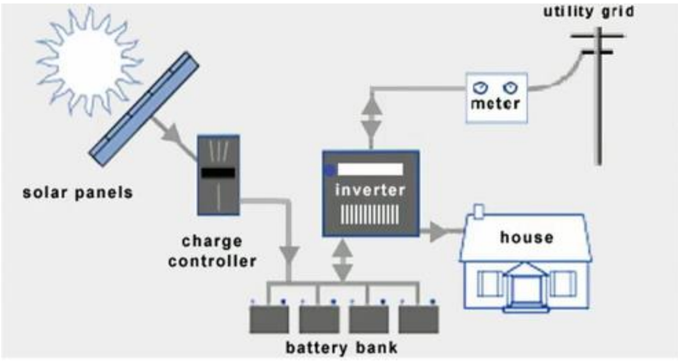


Figure 2.14:Grid Tied with Battery Backup PV system. Source [55]

- Standalone PV Systems

PV systems not connected to the electric utility grid are known as Off Grid PV Systems or "stand-alone systems". Direct systems use the PV power immediately as it is produced, while battery storage systems can store energy to be used at a later time, either at night or during cloudy weather. These systems are used in isolation of electricity grids, and may be used to power radios, telephone booths and street lighting. Standalone PV systems also provide valuable and affordable electricity in developing countries, where conventional electricity grids are unreliable or non-existent.

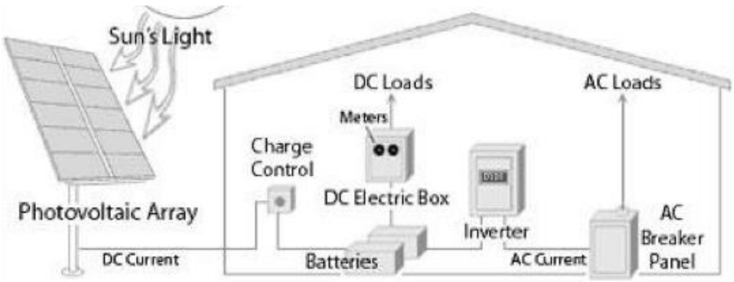


Figure 2.15:Standalone PV Systems. Source [55]

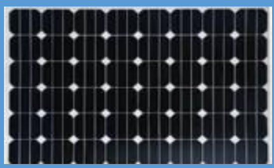
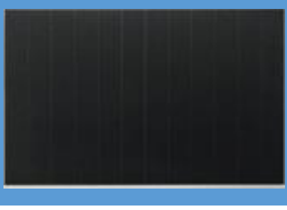
2.5 GRID-CONNECTED SPV SYSTEM COMPONENT

In this section, a description of the main components forming a grid-connected SPV system is presented. This section is also meant to assess technologies (evaluate and explore the different merits of various PV components and inverter based on their price, performance and technical feasibility) in order to select the final optimized components to be used in the detailed design section.

2.5.1 Photovoltaic solar modules

Solar photovoltaic modules, as the core of any SPV system, generate electrical energy from incident sun rays based on photoelectric effect. Currently, single-junction cells with either silicon crystalline or thin-film technology and multiple-junction solar cells are presented on the market. Despite of considerably higher theoretical efficiency of multiple-junction solar cells, about 87 % compared to 33 % of theoretical maximum of single-junction solar cells, they have very limited use due to complex manufacturing process and high price to performance ratio [7]. Various single-junction photovoltaic modules are currently available and used in all sorts of PV installations. The choice of a PV module technology depends on the complex of factors such as price, efficiency, availability, and site-specific indicators. The most commonly used photovoltaic technologies are silicon crystalline and thin-film sole cells. Summary of key advantages and disadvantages, potential issues of each photovoltaic technology can be found in the table 2-1.

Table 2-1:Strengths and weaknesses of different photovoltaic technologies. Source [30]

PV Technology	Strengths	Weaknesses
Monocrystalline Silicon (mono-Si) 36% of market share 	- Efficiency: 15-20% (21.5% as current maximum) - Durability up to 25 years - Space-efficient	- The Highest price - Sensitivity to ambient temperature (performance decrease significantly with an increase of ambient temperature - Sensitivity to shading issues, snow and dirt - Wasteful manufacturing process
Polycrystalline Silicon (P-Si or m-Si) 55% of market share 	- Simple, cost efficient and not wasteful manufacturing process - Insignificant intolerance to high ambient Temperature	- Impurity and efficiency of 13-16% - Not space efficient - Energy extensive manufacturing process
Thin-film (TFSC): **-Amorphous Silicon (a-Si)** **-Cadmium Telluride (CdTe)** **-Copper indium gallium selenide (CIS-CIGS)** 	- Cost-efficient and simple manufacturing process - Flexible configurations applicable different installation - High tolerance of shading issues and variation of ambient Temperature	- Low efficiency: 9-12% - Low space efficiency - High degradation rate

<u>PV module selection for the design of 20kWp SPV for the case study</u>

Selecting a module to use may be challenging as there are numerous modules available in sizes, power, types, prices and efficiency from multiple manufacturers. It is important to make sure that the module complies with IEC standards for module design and quality and investigate the module warranty. Another factor to consider is which modules are available in the country and which modules installers are familiar with. When choosing a module, site specific factors such as available area, local weather conditions, temperature and near shading objects should be taken into consideration, as well as price. For a limited available area, a module with high efficiency and power may be chosen to maximize the power production per area. If the available area is unlimited, cheaper, lower quality models may be chosen to reduce costs. Thin film modules have a greater tolerance for shading than crystalline modules [44] and are more flexible in terms of their geometric dimensions. Thin film modules have a lower efficiency than crystalline modules, but can absorb visible light with short and medium wavelengths more effectively. The power loss due to temperature is also lower for thin film modules. To decide whether to use polycrystalline or mono-crystalline modules is not easy. It requires consideration regarding weighing costs against efficiencies.

For the case study, a large area is available to install the modules. No harsh temperature has been recorded in the location, near and far shading are neglected since no shading object is present on the location and the topography of the site presents no hills nor mountains, it is considered as flat terrain (Refer to site identification in section 3.2). All those criteria lead to a conclusion that high-quality polycrystalline modules would be suitable for the project. After carefully reviewing costing information and reading module specification (type, power, cost and warranty) of a large variety of PV panels, the German Suntech STP 240-20/Wd Polycrystalline PV module was chosen and has been proven to be the most optimal module from a financial and performance perspective. This module is available in the country, and modules installers are familiar with it. Electrical Data for Solar Panel Suntech STP 240-20/Wd is shown in table 2-2.

Table 2-2:Selected PV module Specification

Suntech STP 240-20/Wd		
Type of technology	Polycrystalline solar cells (60 cells)	
Nominal capacity	240 Wp	
Power tolerance	0/+5%	
Dimensions	1640 x 992 x 35 mm	
Weight	18.2 kg	
MPP current	7.95 A	
MPP voltage	30.2 V	
Short circuit current	8.43 A	
Open circuit voltage	37.2 V	
Power Temp Coeff	-0.43%/°C	
Voltage Temp Coeff	-136mV/°C	
Maximum Array Voltage IEC	1000 V	
Module efficiency	14.76%	

The manufacturer’s specifications were based on original PVsyst database.

See technical datasheet in Appendix 1 for more information

2.5.2 Inverter

An inverter is a critical interface component that deploys feed-in function and converts direct current (DC) from the PV array into alternate current (AC) for the system output to be compatible with a local utility grid in terms of voltage and frequency values (mostly 50 Hz and 60 Hz in the USA). PV inverters can be classified in different topologies. The topology of the solar inverter will determine the connections between the PV modules and the inverter and their possible applications. Different topologies of PV inverters and their Strengths and weaknesses can be seen in table 2.3.

Inverter selection for the design of 20kWp SPV for the case study

When selecting the inverter, consideration should be made of the size of the system, cost, flexibility of the system, partial shading, number of sub-strings or strings and their orientation. Care should be taken to ensure that only modules with the same orientation, angle and shading conditions are connected together in strings. There are several configurations of inverters for grid-connected PV systems, for areas with large amounts of shading or continuous diurnal shading, module inverters or a string inverter with optimizers may be a good alternative to maximize the power output. For areas with less shading, one central inverter may be sufficient. A consideration should be made between maximum power output, price and availability in the country.

In addition, care needs to be taken in the integration of modules and inverters to ensure optimum performance and lifetime. Inverters have to be sized such that to handle the expected power level, and be compatible with the specifications on the grid side as shown in the table 2.4.

For this project of 20kW ground-mounted grid connected PV system, the shading effect are considered minimum. Moreover, all modules have the same specification, same tilt and same orientation. Hence, we consider that all modules are almost experiencing the same conditions in the same array (receiving the same irradiance….). As a result, a central inverter is selected for the design. Another aspect of choosing central inverters is that they have advantages over other inverter topology like: low initial investment, easy maintenance and simple to implement.

Table 2-3:Strengths and weaknesses of different inverter topologies [11]

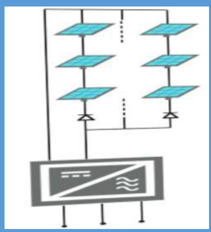
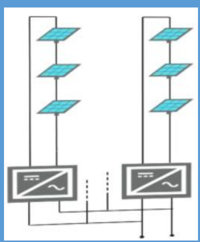
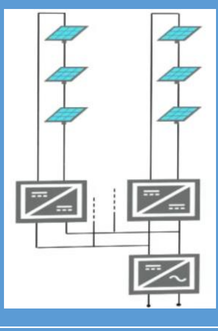
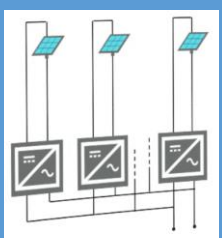
Topology	Strengths	Weaknesses
Central Inverter: **From several kW to hundred MW range** 	- Low investment cost - Easy maintenance - Simple Design and Implementation	- High DC wiring cost - High shading performance loss - Little scope for the scalability of the system (system designed for a fixed power)
String Inverter: **Typically rated from 500W to few kW range** 	- Performance loss mitigation (Resilient to partial shading) compare to the central inverter because each string is independently operating at each maximum power point tracking that guarantee a high energy yield	- Implementation more complex than the module inverter - High investment cost - Complex maintenance compares to central inverter
Optimizer or multi-string inverter**:** **Typically rated around 1kW to 10kW range** 	- Combine high energy yield of a string inverter and the lower cost of a central inverter, each string is prepower processed using low DC/DC converter, each string has its maximum power point Tracker implemented alongside the DC/DC converter	- More complex to implement - Complex maintenance - High investment cost
Module Integrated inverter or micro inverter: **Typically rated around 50 to 400W** 	- Performance loss mitigation (due to mismatch or partial shading) since each module is independently operateing at each MPPT. - High scope of scalability - Low DC wiring cost	- High investment cost - Complex maintenance

Table 2-4:Grid specifications

Grid Specification	
No. of Phases	Three phases
Voltage rating	400 Volts AC
Frequency	50 Hz

The selected central inverter was chosen based on recommendation from Clean Energy Reviews. The most used inverter brand for PV systems in the 11 - 99 kWp range is SMA. The SMA, Sunny tripower 20000TLEE-JP Transformless inverter was used in all ground mounted simulations [31]. Moreover, SMA, Sunny tripower 20000TLEE-JP Transformless inverter is available in the country. Selected Inverter Specification is shown in table 2-5.

Table 2-5:Selected Inverter Specification

SMA, Sunny tripower 20000TLEE-JP			
Type of inverter	Central inverter		
Input Values	MPP Voltage range	580V….800V	
	Maximum DC Voltage	1000V	
	Maximum DC Current	36A	
Output Values	Rated Output Power	20kW	
	Nominal Main Voltage	3 x 400V	
	Maximum AC Current	29A	
	Main Nominal frequency/Range	50Hz,60Hz	
	Power factor cos(f)	0.8	
	Grid connection	Three phases (without a neutral conductor)	
Efficiency	Maximum efficiency	98.5%	
Ambient Conditions	Ambient Temperature Range	-25°C….+60°C	
	Ambient Temperature Range at Rated Power	-25°C….+50°C	
Weight and dimensions	Weight	45kg	
	Dimensions (WxHxD)	665x680x265 mm	

The manufacturer’s specifications were based on original PVsyst database.
See technical datasheet in Appendix 1 for more information.

2.5.3 Transformers

A transformer is an electric device which transfer electric power applied in a primary winding to a secondary winding by electromagnetic induction. The transfer of power is done at the same frequency, but with different voltage and current. Transformers are used in a grid PV solar system to step-up the output voltage of the inverter in order to reach the AC grid voltage level. Selection criteria for transformers include technical and economic factors: efficiency, guarantee, vector group, system voltage, power rating, site conditions, sound power, voltage control capability and duty cycle among other factors. Furthermore, the selected transformer for any PV project should be accredited by ISO 9001.
For the 20kWp grid-connected SPV system for the case study Ambatolampy, the connection to the grid is done at the Low Voltage Level Network (3x400V) which is the already compatible with the output voltage of the chosen inverter, hence a step-up transformer is not required.

2.5.4 Switchgear

The switchgear is the set of switches, fuses or circuit breakers used to control, protect and isolate the electrical equipment included in the system. Switchgears installed in a PV system should meet the following requirements: accomplish IEC standards and national electrical codes; show the on and off position clearly; option to be secured by locks in off/earth positions; be rated for operational and short-circuit currents; rated for the correct operational voltage; and be provided with suitable earthing [21].

For the 20kWp grid connected SPV project, a disconnecting combiner box on the DC side and a dual pole circuit breaker on the AC side are selected. The circuit breakers used for the project is sized in the sub-section 4.4.

2.5.5 DC and AC cables

DC cables connect the PV modules between them and with the inverters while AC cables connect the rest of the electrical equipment inside the PV plant, unless the collection system of the PV plant is operating in DC, but nowadays it is not a common solution. The cables installed in a solar project should meet the international and local requirements of these type of installations. There are three main parameters defining the selection criteria for DC cables [21]:

- Cable voltage rating. The cable selected must withstand the voltage of the PV modules connected.
- Current carrying capacity of the cable. The cable must be sized in order to withstand the current for the worst case possible.
- Minimization of voltage drop. Reduce the energy losses is a key aspect which can determine the viability of a PV plant project; therefore, it is important to reduce the voltage drop in the cables.
- The cables installed in a specific PV solar plant should be adequately protected for the site conditions (sun, moist, heat…).

The cable used for the project is sized in the sub-section 4.3

2.6 PVsyst SOFTWARE BRIEF DESCRIPTION

Nowadays, a wide variety of design, simulation and optimization tools and software for SPV system are available on the market but the most common used are: pvPlanner, PVSOL, PVsyst. The choice of the best available option depends mainly on the desired output and which parameters are the most critical for the project. For example, some tools might be used for sizing, optimization, prefeasibility calculations, shading analysis and so on, while more comprehensive studying of solar PV system requires more complex software package that comprises a set of interacting tools. In addition to that, the choice of a software to be used is also based on its availability, solar input data and configuration of the system to be simulated.
Out of 3 tools mentioned above, PVsyst, which is a standard tool for PV installations, delivers the most comprehensive and detailed analysis of the performance of the PVsystem. PVsyst's uncertainty in the simulation process is low that makes the results more accurate compare to the other simulation tools. On the whole, PVsyst provides the most robust results as a simulation software tool.

PVsyst is a software package that allows the user to employ full-featured study and analysis of a PV project. PVsyst integrates simulation of a PV system with evaluation of its pre-feasibility, sizing and financial analysis, no matter whether it is a grid-connected, stand-alone, pumping or DC grid system. At the database level, PVsyst has radiation data from a large number of cities. The radiation data for the case study Ambatolampy, Madagascar, was imported from Meteonorm 7.1. It only requires entering in the geographical coordinates and it automatically imports the meteorological information required for the photovoltaic project. Similarly to

Meteonerm 7.1, various measured, interpolated or synthesized meteorological data from such sources as Satellight, SolarGIS, US TMY2/3 NASA-SSE, and others are available for simulation in PVsyst. It is also possible to import user defined data including set of parameters listed in the table 2-6.

Table 2-6:PVsyst meteorological data input. Source [30]

Mandatory data	
Header = GHI	Horizontal global irradiation (W/m^2)
Header = Tamb	Ambient (dry bulb) air temperature (deg°C)
Additional data	
Header = DHI	Diffuse horizontal irradiance (W/m^2)
Header = DNI	Direct normal irradiance (W/m^2)
Header = GPI	Plane of Array irradiance (W/m^2)
Header = WindVel	Wind velocity (at 10m altitude) (m/s)

Economic evaluation of the system can be employed by setting investment, financing and loan parameters. In other words, the user shall define the cost of the components, (i.e. PV modules, inverters, wiring, mounting system), taxes, subsidies and loan term and interest rate. Carbon balance, as a performance characteristic of the system, can be evaluated within financial analysis tool. Figure 2-15 shows the main interface of PVsyst.

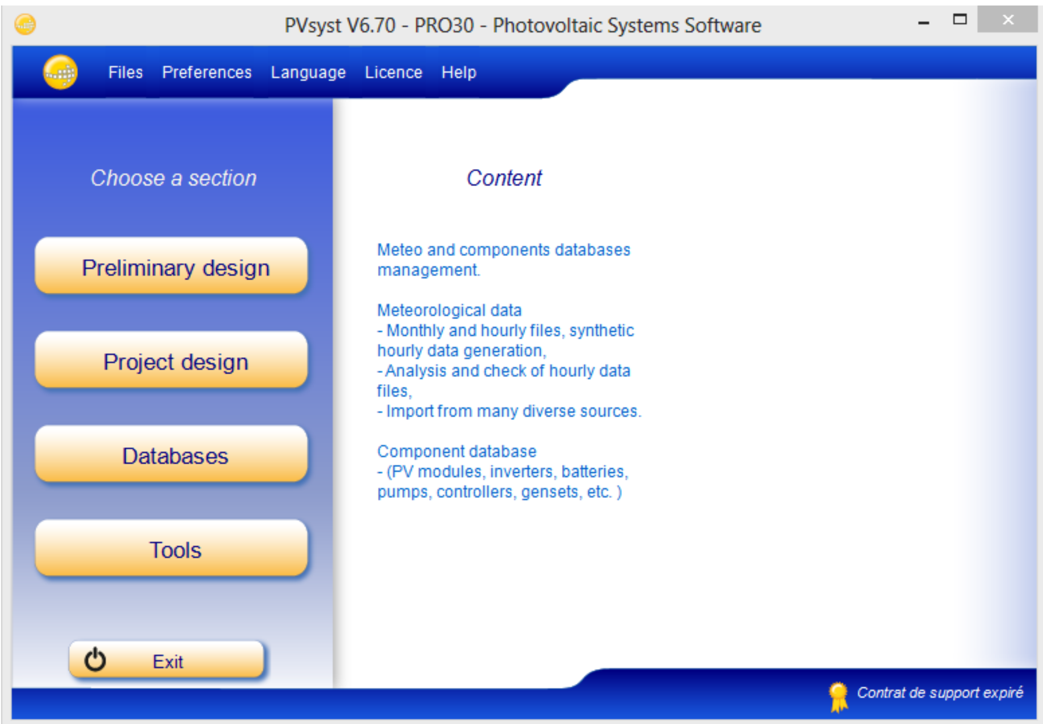


Figure 2.16:PVsyst software main interface

3 CHAPTER THREE: METHODOLOGY

The methodology of designing a grid connected PV system is divided in two sections: site assessment and technical assessment. The following section tries to elaborates the SPV desing method.

3.1 GRID-CONNECTED SPV SYSTEM DESIGN

This project is focused on prefeasibility and feasibility phases. The calculations and estimations of the following sections try to:

- Identify a favorable site for a PV system;
- Perform technical and financial evaluation of the PV project.

3.1.1 Site identification

Before doing the required calculations for the design of the PV power plant it is necessary to select the site where the PV plant is going to be installed. The selection of the site is a very important issue due to the meteorological conditions of the site selected will largely determine the energy production of the PV plant. In addition to the meteorological conditions of the site selected, some criteria should be analyzed in order to choose the final location. The main aspects taking into account for the site selection are: available area, solar resource, local climate, topography, environmental and social considerations, accessibility, grid connection, module soiling, water availability [21].

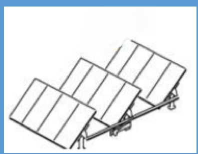
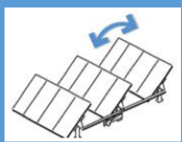
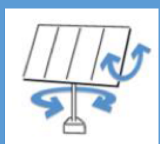
3.1.2 Mounting structures, orientation and tilt

Mounting structures are used to fix the PV modules to the ground and they determine the tilt angle and the orientation of the modules. A classification of the mounting structures can be done depending on their assembly to the ground [56]:

- Pole mounts: Mounting structures are directly installed into the ground or embedded in concrete.
- Foundation mounts: Structures are fixed into the ground by means of concrete slabs or poured footings.
- Ballasted footing mounts: Mounting structures do not penetrate into the ground and are fixed to it by means of the weight of concrete or steel bases.

The selection criteria of the mounting structures involve many factors such as: cost of manufacturing, cost of installation and difficulty of installation, lifespan of the structures, resistance to corrosion or protection against adverse climatic conditions.
Besides, mounting structures are the responsible to endow to the PV modules the required tilt angle and orientation. Regarding this aspect there are two main categories of mounting structures: fixed structures and tracking axis systems. Their strengths and weaknesses are depicted in table 3.1.

Table 3-1:Mounting structures strengths and weaknesses. Source [25]

Mounting Structure	Strengths	Weaknesses
Fixed tilt system 	- The least expensive - Easy maintenance	- Not capable to modify neither the orientation nor the tilt angle - The energy production not optimum
1-axis tracking system 	- Better energy capture compares to fixed tilt system - One degree of freedom	- Expensive compare to fixed tilted system - Difficult maintenance compares to fixed tilt system
2-axis tracking system 	- The best energy capture - Multiple degrees of freedom	- The most expensive - Complex maintenance - Requires huge area of installation

Orientation and tilt: to be applied in a fixed tilt system. Optimal orientation and tilt angle depend on the terrain, microclimate, surroundings and obstacles. As the rule of thumb, the system should face true north (for southern hemisphere) with a tilt angle equal to latitude [10].

3.1.3 System sizing

PVsyst software designs the PV grid connected system by determining different parameters using the following equations and steps. Those parameters are: number of modules, number of modules in series and parallel, area occupied by the PV modules, ... In addition, PVsyst makes the performance evaluation of the system by determining the system losses, hourly production, monthly normalized energy production, performance ratio and some more. The formulas used in this project are based on the paper published by Kerekes et *al.* [52]

- NUMBER OF PV MODULES ($\boldsymbol{N_{PV}}$)

Depending on the module technology selected for the PV plant, the total number of PV panels required in the system will vary as well as the area needed for the implementation of the PV plant will also differ depending on that parameter.

For calculating the required number of PV panels, $\boldsymbol{N_{PV}}$, the following equation is used:

$$N_{PV} = \frac{P_{desing}}{P_{M,STC}} \quad (3.1)$$

Where, P_{desing} is the power plant design capacity and, $P_{M,STC}$ [W] is the PV module power rating (maximum power under Standard Test Condition). The calculation of the number of PV modules is only an indicative calculation based on power plant design capacity, the final number of PV modules in the system will be recalculated afterwards.

- AREA OCCUPIED BY THE PV MODULES ($\boldsymbol{S_{array}}$)

Calculation of the surface area of each PV module:

$$S_{PV} = lenght\,.width \quad (3.2)$$

Where, S_{PV} [m^2] is the product of multiplying the length [m] by the width [m] of the PV module selected.

For calculating the total area occupied by the PV array, S_{array} [m^2], the following formula is used:

$$S_{array} = S_{PV}\,.N_{PV} \quad (3.3)$$

Again, this calculation is not considering the final value of the number of PV modules, therefore this parameter will also be recalculated afterwards.

- CALCULATION OF THE MAXIMUM NUMBER OF PV MODULES IN SERIES AND PARALLEL ($\boldsymbol{N_{s,max}}$,$\boldsymbol{N_{p,max}}$)

The calculation of the number of PV modules in series and parallel depends on the specifications of the inverter selected. The algorithm used for the calculation of the maximum number of PV modules in series per inverter is shown in figure 3.1:

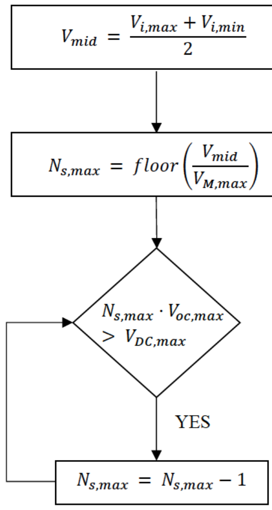


Figure 3.1:Maximum number of PV modules in series algorithm

Where, the specifications of the inverter are: $V_{i,max}$ [V] is the DC input maximum MPP voltage, $V_{i,min}$ [V] is the DC input minimum MPP voltage and $V_{DC,max}$ [V] is the maximum permissible DC input voltage; and the specifications of the PV module are: $V_{M,max}$[V] maximum MPP voltage and $V_{oc,max}$[V] maximum open-circuit voltage. The optimum number of modules connected in series is a number smaller than $N_{s,max}$, but to simplify the calculations the number of PV modules in series used for further calculations is $N_{s,max}$. By choosing the maximum number of PV modules in series, the number of necessary inverters is reduced, but in terms of energy capture this procedure is not always the best option, since the inverter is more efficient when is working closer to its rated power.

The number of PV modules connected in parallel is calculated using the values of current of the module and the current of the inverter:

$$N_{p,max} = floor(\frac{I_{DC,max}}{I_{M,max}}) \tag{3.4}$$

Where, the specification used of the inverter are: $I_{DC,max}$ [A] is maximum continuous current; and the specification of the PV module used in in this calculation: $I_{M,max}$ [A] is maximum MPP current.

- FINAL NUMBER OF PV MODULES ($\boldsymbol{N_{pv,final}}$) AND FINAL AREA OCCUPIED BY THE PV MODULES ($\boldsymbol{S_{array,final}}$)

With respect to the number of selected inverters, total number of PV modules previously calculated must be recalculated. Or, instead of recalculating the number of PV modules, could be that one inverter (or more than one) was not connected to the maximum number of modules in series and parallel. The final solution is to slightly oversize the system in order to make all the PV sets in the system of the same size (number of modules per inverter). The formula used to calculate the final number of PV modules in the PV plant is shown below:

$$N_{PV,final} = N_s . N_p . N_i \tag{3.5}$$

Where N_i is the number of inverters. As the number of PV modules is changed respect to the initial design conditions, the output power of the PV array is also modified:

$$P_{array} = N_{pv,final} \cdot P_{M,STC} \tag{3.6}$$

Also, the area occupied by the PV modules must be recalculated.

$$S_{array,final} = S_{PV} . N_{PV,final} \tag{3.7}$$

- SOLAR PANEL TEMPERATURE CALCULATION (T_M)

It is important to calculate the temperature of the PV module because this parameter is directly related with the performance of the module. The formula based on [20] used for calculating the temperature of the PV module is the following:

$$T_M = T_{amb} + \frac{G_t}{800} (N_{OCT} - 20) \tag{3.8}$$

Where, T_{amb} [ºC] is the ambient temperature, G_t [W/m^2] incident solar radiation and N_{OCT} [ºC] nominal operating cell temperature.

- MPP POWER OF EACH PV MODULE (PM)

The power output of each PV module is calculated considering meteorological conditions such as temperature of the PV panel and irradiance (both previously obtained). The formula describing the power output of the PV modules is the following:

$$P_M = P_{M,STC} \cdot \frac{G_t}{1000} . (1 - \gamma . (T_M - 25)) \tag{3.9}$$

Where, γ [%/ºC] is the temperature parameter of the PV module at MPP and it is specified in the technical specifications of the PV modules selected.

- ACTUAL POWER OUTPUT OF EACH PV MODULE ($\boldsymbol{P_{PV}}$)

Once the MPP power of each module is obtained the actual power output of each module can be calculated considering the losses of operation. The formula describing the actual power output is the following:

$$P_{PV} = (1 - \frac{df}{100})(1 - \frac{S_p}{100}) P_M \tag{3.10}$$

Where, P_M is the rated power of each module, df (%) is the PV module output power derating factor due to the dirt that is deposited on its surface. Sp [%] are the losses due to shading effect. Once the MPP power of each module (P_M) and actual power output power of each module (P_{PV}) are calculated, the power losses can be easily obtained:

$$P_{PV,losses} = P_M - P_{PV} \tag{3.11}$$

- OUTPUT POWER OF EACH PV SET (P_{IN})

The number of PV modules forming a PV set is formed by the number of modules in series multiplied by the number of modules in parallel. The number of PV sets in the PV power plant is equal to the number of inverters required.

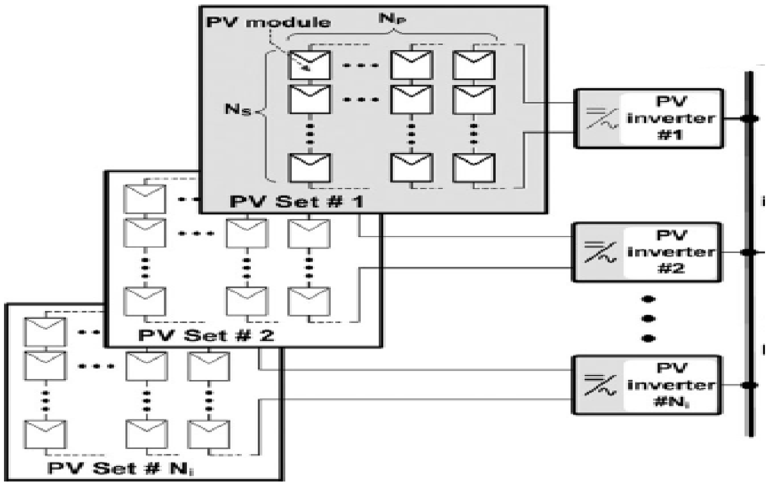


Figure 3.2:PV set configuration on PV plant. Source [52]

The calculation of the output power of each PV set depends on the actual power output of each module, MPP efficiency of the inverter, voltage drop of the dc cable and mismatch losses.

$$P_{in} = N_s N_p \frac{\eta_{mppt}}{100}\left(1 - \frac{\eta_{dc}}{100}\right)\left(1 - \frac{\eta_{mismatch}}{100}\right) P_{PV} \tag{3.12}$$

Where, η_{mppt} (%) is the MPP efficiency of the dc/ac inverter. η_{dc}(%) is the voltage drop of the dc cable. Another important factor affecting PV set power output are mismatch losses, $\eta_{mismatch}$. These losses appear due to slight difference in the manufacturing of PV modules interconnected, or also they can be caused due to PV modules experiencing different conditions in the same array.

- TOTAL OUTPUT POWER OF EACH DC/AC INVERTER (P_o)

Each PV set is connected to an inverter and depending on the specifications of this inverter, the final energy obtained will vary. The output power of each DC/AC inverter is calculated using the following equations:

1) If $P_{in} \leq P_{i,na}$,then $P_o = \frac{\eta_{inv}}{100} \cdot P_{in}$, Else $P_o = \frac{\eta_{inv}}{100} \cdot P_{i,na}$ *(3.13)*

2) If $P_{in} \leq P_{i,sc}$, then $P_o = 0$

Where, $P_{i,na}$[W] is the inverter maximum permissible power level, η_{inv} [%] is the inverter power conversion efficiency and $P_{i,sc}$ [W] is the self-power consumption of the inverter.

- LAND OCCUPIED BY THE PV SOLAR POWER PLANT

For further calculations it is important to know the area which the PV power plant is going to occupy. To make this calculation, some assumptions have been made: The total dimensions of the land occupied is assumed from literature and it is set at 0.036 km^2/MW_{ac} ($Land_{raelation}$) [41].

$$Land = \max(P_o) \,.\, N_i . Land_{raelation} \quad (3.14)$$

- POWER THAT PV PLANT CAN INJECT INTO THE GRID (P_{PLANT})

Power that can be injected into the grid is calculated considering losses in the AC side cable. The formula used for this calculation is the following:

$$P_{plant} = \frac{\eta_{cable}}{100} . P_o . N_i \quad (3.15)$$

Where, η_{cable} [%] is the efficiency of the AC cable connections.

- TOTAL ENERGY INJECTED INTO THE GRID FROM THE PV POWER PLANT ($E_{plant,tot}$)

The energy injected into the grid is calculated considering the time steps used along the previous calculations and adding an availability factor of the PV power plant due to maintenance reasons. The formula used in this step to calculate the energy injected for each time step is the following:

$$E_{plant} = \frac{EAF}{100} . P_{plant} . \Delta t \quad (3.16)$$

Where, EAF [%] is the Energy Availability Factor of the PV plant due to maintenance of the PV power plant components. Δt [h] is the time step. Total energy injected into the grid, or Annual Energy Production (AEP in MWh/year) is calculated using the following formula:

$$E_{plant,tot} = \frac{EAF}{100} . \sum_{t=1}^{n} P_{plant} . \Delta t \quad (3.17)$$

Where, t is the number of time steps considered during the calculations of the PV power plant. For one-year t is equal to 8760. The calculation methodology and the steps explained previously are summarized in the following Figure 3-3:

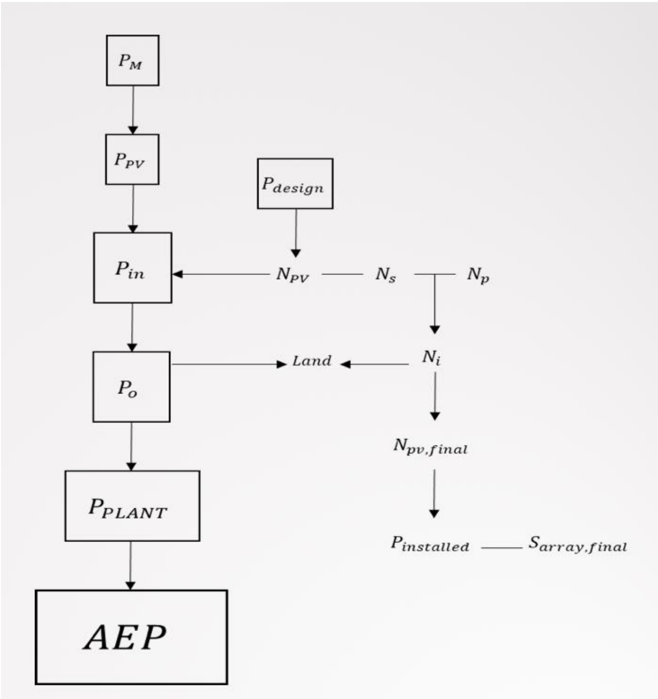


Figure 3.3:Calculation methodology scheme

3.1.4 Cables sizing

As much as the design/sizing of the grid connected PV system is important, the accurate selection of system wiring cables is very essential in order to keep the system safe. The wiring must not reduce the performance of any of the components of the system. The cables in a grid connected system must be sized correctly to reduce the voltage drops in the cable and to make sure that the safe current handling capacity of the cable is not exceeded.

- Sizing of DC cables:

Cables between PV modules, Cable from PV array to the Inverter

The voltage drop in a cable is given as:

$$V_d = \frac{\rho l}{A}.I.2 \qquad (3.18)$$

Where ρ is the resistivity of copper wire which is normally taken to be 0.0183Ωmm^2/m

l = the length of cables in meters

I = the current through the cables in amperes

A is the cross-sectional area (CSA) in mm^2
The multiplication by 2 accounts for total circuit wire length.

Changing the subject of the above formula

$$A = \frac{\rho l}{V_d}.I.2 \tag{3.19}$$

In the design of the system, a maximum cable voltage drop of 5% is used and this is the maximum allowable drop in PV grid connected systems [19].

- Sizing of AC cable:

<u>Cable from inverter to the grid</u>

The maximum current from inverter at full load on each phase (line) is given by:

$$I_{phase} = \frac{Inverter\ rated\ Power}{V_{output}.\sqrt{3}} \tag{3.20}$$

And similarly, the CSA:

$$A = \frac{\rho l}{V_d}.I_{phase}.2 \tag{3.21}$$

3.1.5 Protection of the SPV system

Protecting the system using circuit breakers in an event something goes wrong is paramount. In a grid tied system, there are 2 locations that need to put the overcurrent protection: on the DC side by the solar panels (in the combiner box) and on the AC side in the main breaker box. Circuit breakers are installed in the system to cater for over current protection and sized to not be below 125% of the current flowing through the wiring [18].

- Sizing of circuit protection between PV array and Inverter

There are generally two ways of undertaking the circuit protection between PV array and Inverter.

- Each parallel string of modules can be fused in the DC combiner box or
- The total output of the PV array is fused before being joined to the inverter

In this installation, the first option is used because that makes it easier to find suitable DC circuit breakers.

The combiner box is generally installed outside, near the solar panel. The combiner box wires the strings into parallel, and gives a place to transition the wires into conduit to make the rundown to the inverter. So also, a good place to put a surge arrester like a lightning arrester (as shown in the figure 3-4). A surge arrester is a device used in an installation to protect the other equipment from an over-voltage that can be caused by external factors such as lightning or switching events. An additional feature is available; a switch is used to turn off the DC power coming out of the panels.

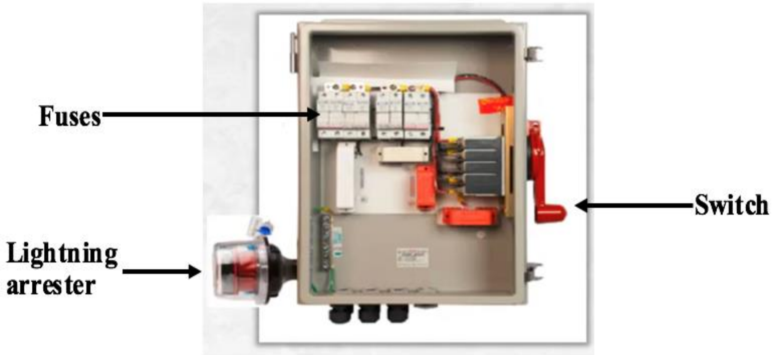


Figure 3.4:Disconnecting combiner box

<u>Fuse sizing per parallel string:</u>

The maximum current is

$$1.25 \text{ x } I_{sc} \tag{3.22}$$

Therefore, minimum rate of DC circuit protection is

$$I_{fuse} = 1.25\ x 1.25 x\ I_{sc} \tag{3.23}$$

- Sizing of circuit protection on every phase output of inverter

<u>The minimum rating of circuit breaker is:</u>

$$I_{breaker} = 1.25\ x\ I_{phase} \tag{3.24}$$

Figure 3.5:Dual pole circuit breaker

3.1.6 System wiring

The figure below illustrates the PV grid connected system wiring. 4 strings of 8 modules in this example are entering in the combiner box where they will be fused and wired in parallel. Then, wire out of the combiner box make their way to the inverter in a conduit and go through the AC circuit breaker and finally continue their way to the grid.

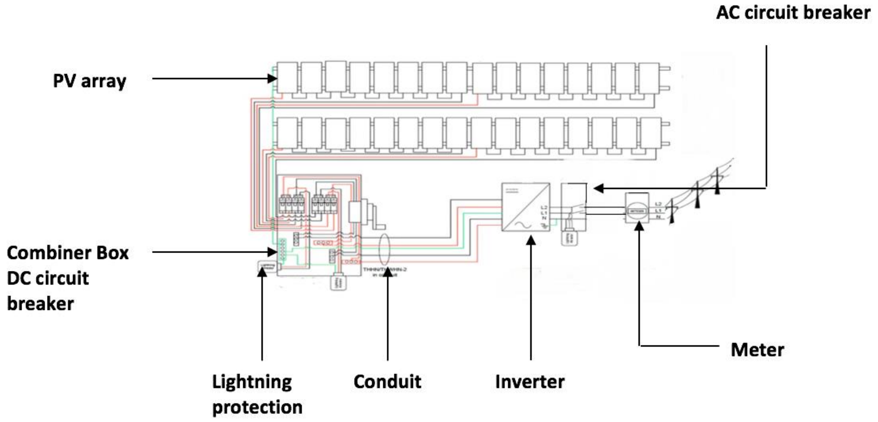


Figure 3.6:System Wiring

3.1.7 Inter-row spacing

Both near-field shading and far shading or horizon shading effects have a significant impact on a system output, up to 80 %, with the difference that horizon is easily modelled yet not adjustable, while near shading is exceptionally difficult to model but possible to avoid or mitigate. Potential shading loss can be decreased by adjusting such design variables as azimuth and tilt, panel orientation and row spacing. In common practice targeting shading losses would be 2 to 4 %. To stay within this shading limit, horizontal distance, or setback ration (SBR), should be 2:1 in lower latitudes and 3:1 in mid-latitudes. Figure 3-7 depicts the relationship between tilt angle, setback and ground coverage ratio (GCR) [26].

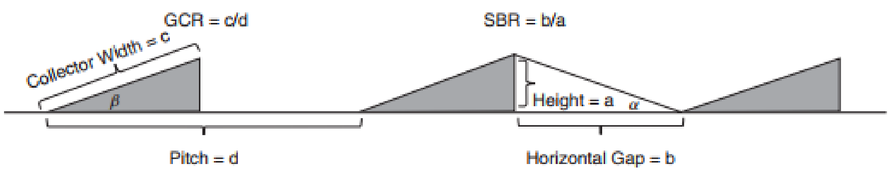


Figure 3.7:Array geometry. Source [26]

The relationship might be also expressed by the formulas:

$$SBR = \frac{b}{a} \tag{3.25}$$

$$\propto = tan^{-1}\left(\frac{1}{SBR}\right) = tan^{-1}(\frac{a}{b}) \tag{3.26}$$

$$GCR = \frac{c}{d} = (\cos(\beta) + SBR.\sin(\beta))^{-1} \tag{3.27}$$

From the above equation we obtain the pitch d

$$d = c\,(\cos(\beta) + SBR.\sin(\beta)) \tag{3.28}$$

3.1.8 PV system losses

The total PV system losses can be divided into optical losses, array losses and system losses, as illustrated in figure 3-8.

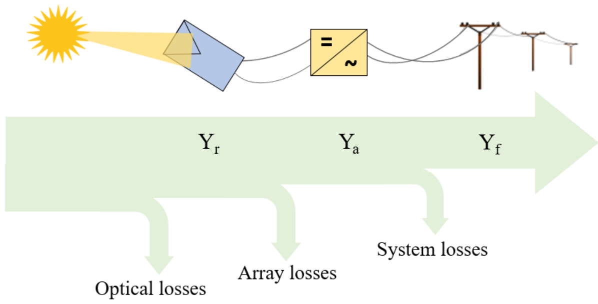


Figure 3.8:PV system loss diagram

The optical losses decrease the amount of irradiation reaching the PV array and include horizon, near shading, reflection and soiling losses. Array losses are losses in the PV array caused by increased temperature (Thermal losses), low irradiance, electrical shading, quality, mismatch and DC cable resistance (Ohmic losses). Inverter losses, unavailability and AC cabling losses are system losses.

3.1.9 Financial analysis

The major components of the system cost include the price of solar panels, inverter and infra work. The costs and benefits of the proposed solar PV system throughout its lifetime were analyzed and assessed by PVsyst using the following financial indicators.

Economic Calculations

The methodology and formulas used regarding the economic calculations are also based on the paper published by Kerkes et al [52]. The steps followed are shown below:

- Calculation of Total cost of the PV power plant ($\mathbf{C_c}$)

Capital cost is referred to one-time expenses associated with the PV power plant installation. With the purpose of estimate, the viability of any energy project it is important to calculate all the expenditures associated with the project. The first step in the economic analysis is the calculation of the total capital cost. The capital cost calculated for this project includes: the cost of the PV array, cost of the inverters, BOS cost (electrical wiring, meter, protections, junction boxes, cabinets, combiners, fuses, breaker and other non-electrical components), cost of civil work and cost of the land. The formula used to calculate the capital cost is the following:

$$C_c = \left(N_i.N_s.N_p.\frac{P_{M,STC}}{1000}.C_{PV}\right) + \left(N_i.\frac{P_{rated}}{1000}.C_{inv}\right) + \left(BOS.P_{plant,nom}.1000\right) + \left(C_{C\&i}.P_{plant,nom}.1000\right) + \left(C_{land}.n.C_{inv}\right) \quad (3.29)$$

Where, C_{PV} [$/kWp] is the cost of the PV modules, P_{rated} [W] is the power rated of the solar inverters and C_{inv} [$/kWp] is the cost of the solar inverters. $C_{C\&i}$[$/kWp] is the cost associated to construction and installation of the PV plant components. BOS [$/kWp] is the cost of the balance of system components. C_{land} [$/km^2 - year] and $land$ [km^2] are the cost of the land and the surface area required for the installation of the PV power plant respectively. n [years] is the operational lifetime of the PV plant.

- Calculation of the Maintenance cost of the PV power plant during its operational lifetime ($\mathbf{C_m}$)

Besides of knowing the total capital cost the PV power plant, the calculation of the maintenance cost during its operational lifetime it is important to know the economic framework of the project. The formula used to calculate this parameter is shown below:

$$C_m = P_{plant,nom}.M_{plant}.n \quad (3.30)$$

Where, M_{plant} [$/kWp] is the maintenance cost of the PV power plant.

- Calculation of Replacement cost (C_{rep})

Some of the components installed in the PV power plant will need to be replaced during the years of operation. The time of operation of the PV plant being designed is 25 years. The decision of which components should be replaced will be taken according the specifications of each component.

- Levelized Cost of Electricity calculation (LCOE)

LCOE is an economic parameter which it is used to quantify the price of the energy that is being produced for the specific conditions previously described. It is also one of the main parameters to compare different generating technologies. The formula used in this project is the following:

$$LCOE = \frac{C_c + C_m + C_{rep}}{E_{plant,n}} \tag{3.31}$$

Where, $E_{plant,n}$ [MWh] is the total energy produced by the PV plant over its operational lifetime.

- Gross Revenues (R_{gross})

Gross revenues are the sum of all earnings generated by the PV plant during the project lifetime. The calculation is made considering the price of the electricity over the operational lifetime of the PV plant. This price can vary depending on the electricity market of the selected location and also it is important to consider the support schemes available. The formula used for Gross Revenues is:

$$R_{gross} = P_{electricity} . E_{plant,tot} . n \tag{3.32}$$

Where, $P_{electricity}$ [$/MWh] is the price of the electricity for the operational life-time of the PV plant.

- Simple Payback Period (SPP)

Simple Payback Period (SPP) represents the number of years required for the cash flow to equal the total investment. The basic assumption of the SPP method is that the more quickly the cost of an investment can be recovered, the more desirable the investment is. The equation for SPP is given below:

$$Payback\ period = \frac{Capital\ cost\ (C_c)}{Annual\ income} \tag{3.33}$$

3.1.10 Evaluation Parameters Calculation

The parameters that are going to be described below can be seen as quality indicators of the PV solar power plant designed, also these parameters can be used to make final decisions regarding the technology used and to make comparisons between other types of energy generation technologies. The parameters described in this section are: ground coverage ratio, performance ratio, capacity factor and specific yield.

- Ground coverage ratio (GCR)

This parameter is an indicator of how the surface of installation is covered by PV modules and which percentage is used for other components. The formula to calculate this parameter based on [43] is shown below:

$$GCR = \frac{S_{array,final}}{land}.100 \tag{3.34}$$

The results obtained of GCR will be merely indicative, since the calculation of $land$ [km^2] are based on assumptions.

- Performance ratio (PR)

Performance ratio expresses the relation between the real performance of the PV solar power plant and its rated power capacity. This parameter can be seen as a quality indicator because usually it is used to compare different photovoltaic systems independently of their installed capacity. The period analysed is one year and the parameter is calculated by the following formula based on [21]

$$PR(\%) = \frac{E_{plant,tot}}{P_{plant,nom}.G_t}.100 \tag{3.35}$$

Where, $E_{plant,tot}$ [MWh] is the total energy generated for the PV power plant during one year.

- Capacity factor (CF)

This parameter is the ratio of the PV power plant actual energy output for a year and its output at nominal power during a year. It is typically expressed as percentage and the formula based on [21] describing this parameter it is shown below:

$$CF(\%) = \frac{E_{plant,tot}}{P_{plant,nom}.8760}.100 \tag{3.36}$$

- Specific yield ($Yield_{sp}$)

Specific yield of a PV solar power plant is the total energy output divided by the installed capacity [21]. This parameter expresses the number of hours that the PV array would need to operate at its rated power to generate the same energy. The formula used is shown below, the results is expressed in kWh/kWp:

$$Yield_{sp} = \frac{E_{total}}{P_{plant,nom}} \tag{3.37}$$

3.2 DESIGN OF 20 kWp GRID-CONNECTED PV SYSTEM FOR THE CASE STUDY

In this section, the procedures described above will be implemented step by step to design the 20kWp grid connected PVsystem for the case study.

3.2.1 Geographical location of the site

The coordinates of the proposed site for the installation of the PV solar power plant are: -19.38ºS and 47.43ºE corresponding to the location of Ambodiriana - Ambatolampy, 60 km away from the capital Antananarivo, Madagascar, time zone +3.0.

Figure 3.9:Ambatolampy location on Madagascar map. Source [Wikipedia]

3.2.2 Available area

First of all, an estimate of the space required for the installation of a 20 kWp PV solar power plant is made by using a simple rule of thumb: 1 kW of solar panels require approximately $10m^2$, when used on rooftops and in ground mounted installations [25]. Hence, for this project of ground mounted PV system, 200 m^2 of land is required. This is just an estimated value required to make the first project calculations, during the course of the project this value will be revised and recalculated.

In the area delimitated in red in the figure 3-10 can be appreciated that the space of 200m^2 can be obtained in this area without interfere in any area of population.

Figure 3.10:Available area for PV installation

Figure 3.11:Photograph of project site (in the Area delimited in red)

200m^2 of land is identified in the figure 3-11. No wildlife and no archaeological monument exist at the proposed site. The site is well connected by a road and no health hazards are caused by solar plant.

3.2.3 Solar resource

Madagascar in general and Ambatolampy in particular has a high solar radiation. In Figure 3-12, it can be observed that the mean solar radiation of the site selected is one of the highest in Madagascar, the annual global solar irradiation is 1965 kWh/m^2 that makes it a favourable location to install PV system [49]. Ambatolampy has an average of 2630 hours of sunlight per year with 7:20 of sunlight per day. On average, September is the sunniest and February has the lowest amount of sunshine [49]. Information on solar energy for Ambatolampy is obtained from Meteonorm 7.1 which provided monthly meteorological data that has been preloaded in PVsyst.

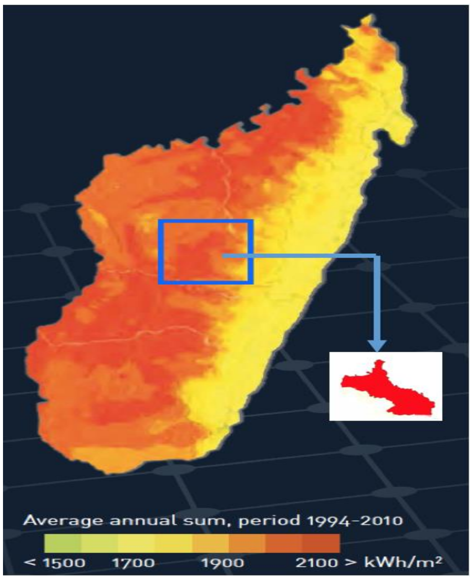


Figure 3.12:Average annual sum

The Annual Horizontal Global and Diffuse irradiance of the proposed site is shown in the table 3-2

Table 3-2:Annual Horizontal Global and Diffuse irradiance of the proposed site. Source [Meteonorm 7.1]

Month	Hor. Global (kWh/m^2.day)	Hor.diffuse (kWh/m^2.day)
January	5.40	2.94
February	5.25	2.93
March	4.90	2.55
April	4.63	2.25
May	4.3	1.56
June	4.06	1.38
July	4.13	1.27
August	4.85	1.79
September	6.09	1.83
October	5.81	2.79
November	5.61	3.00
December	5.03	3.05
Year	5.03	2.28

3.2.4 Local climate

Apart from obtaining the irradiance of the site selected, there are other aspects related with the climate important for the development of a SPV system project: temperature, wind speed, risk of flooding. The temperature of the location will determine the efficiency of the solar cells and extreme temperatures can be critical for the correct operation of the PV plant. The average ambient temperature of the location is 23.6 °C. The location selected does not have extreme temperatures neither risk of extreme wind speeds as seen in the table 3-3.

Table 3-3:Annual Temperature and wind speed of the proposed site. Source [Meteonorm 7.1]

Month	Amb. Temperature °C	Wind velocity (m/s))
January	26.9	1.4
February	26.4	1.7
March	25.8	1.6
April	24.8	1.4
May	22.8	1.5
June	20.1	1.6
July	19.4	1.9
August	20.2	1.8
September	21.5	1.7
October	23.8	1.5
November	25.1	1.6
December	26.6	1.3
Year	23.6	1.6

3.2.5 Topography

It is important to study in detail the topography of the site selected because it is directly correlated with the cost of installation and the future energy production. The ideal situation would be a flat terrain or with a slight north-facing slope, other configurations of the terrain could have a negative impact on the cost of the project due to more complex mounting structures. Besides, the presence of mountains near can produce undesirable shades. For this project, as seen in figure 3-11, the terrain where the PV modules are going to be installed is considered flat and also the presence of near mountains is neglected.

3.2.6 Environmental and social considerations

There are some countries with a specific environmental and social regulatory framework regarding the installation of PV solar plants, the aspects which are considered are the following: biodiversity, land acquisition and other social impacts. Regarding the biodiversity of the location, it is important to avoid critical habitats in order to not compromise the viability of the project. For the case of the site selected it is assumed that it is not located in a place with critical habitats.

3.2.7 Accessibility

The accessibility of the site selected for the installation of the PV solar power plant is also an important aspect. The materials needed during the construction and installation of the plant should be transported by cargo trucks, thus the availability of suitable roads is crucial. For the case of the current project, the area is well-connected by road.

3.2.8 Grid connection

There are three parameters which should be analyzed regarding the grid connection: Proximity, the distance between the grid and the PV solar power plant have a direct impact on the initial economic investment; availability, the percentage of time that the network is able to accept power from the PV solar power plant, the network operator is the responsible to provide this information; capacity, the power which the network is able to absorb. In case the capacity of the network is not enough to withstand the power generated the network should be upgraded. For this project, the grid connection is considered optimal.

3.2.9 Module soiling

The energy production of the plant can be reduced if the PV modules are covered by dust or other type of particles, this situation can be a major problem if the PV plant is located in a very dusty area, e.g. a desert area. The selected location for this project is not considered critical area.

3.2.10 Water availability

For PV power plants, the availability of water is an important factor. Large amounts of water are necessary for maintenance purposes (cleaning). Therefore, the system should be installed preferably near a water source. The availability of water is not a problem for the site selected because it is surrounded by different rivers.

3.3 SYSTEM SIZING USING PVsyst

The system design is performed using the PVsyst 6.7.0 simulation software. PVsyst was selected as the simulation software, because it is a powerful tool for studying, sizing and analyzing data of a PV system. It contains databases of both meteorological data and PV system components from several manufacturers. PVsyst has two options for the dimensioning of the PV system: to either size by planned power, or available area. For this project, the system design is based on planned power and the specifications of selected components (PV modules and inverter). Figure 3-13 shows an outline of the different steps in performing a PV system design and simulation in PVsyst. See appendix 2 for the case study PVsyst desing steps.

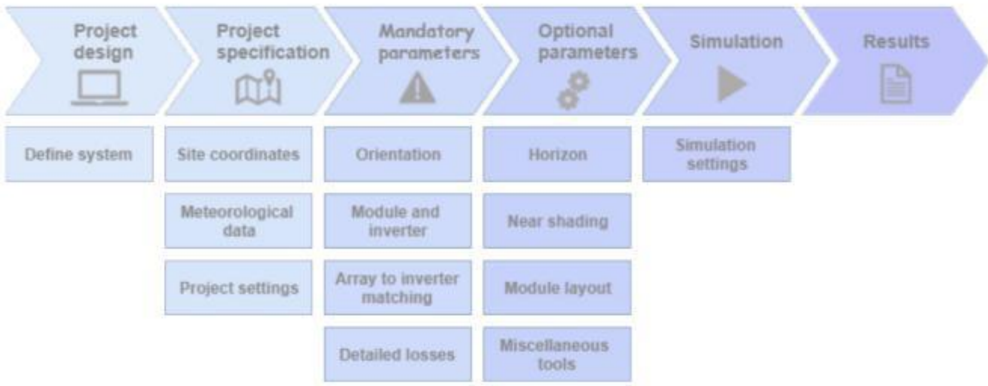


Figure 3.13:Project design steps in PVsyst. Source [38]

3.4 MOUNTING STRUCTURES, ORIENTATION AND TILT

Although energy production is optimum using PV tracking system compare to fixed tilted plane, for this project, fixed tilted plane using pole mounts is preferred because this option is the least expensive and the maintenance is not complex. Fig 3-14 shows the effect of varying the tilt angles and azimuth to the yearly irradiation yield. It appears that a tilt equal to the latitude 19° and an azimuth of 0° (North oriented) generate the least amount of losses.

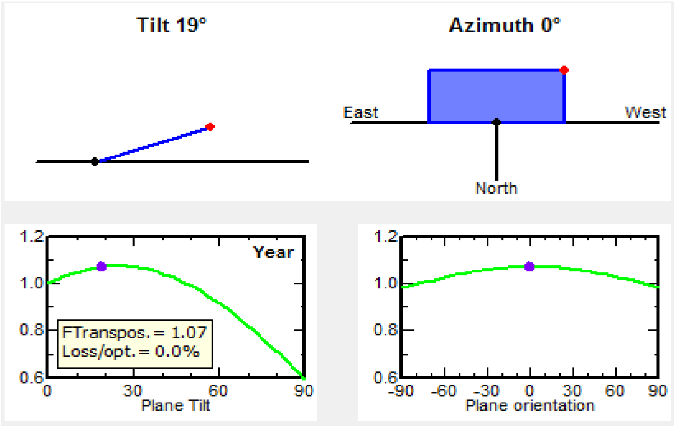


Figure 3.14:Collector plane orientation PVsyst screen capture

3.5 SIZING CONDITION

3.5.1 Array to inverter matching

Matching array output to inverter input ensures that the inverter captures as much as possible of the array power during all environmental conditions anticipated at the site. The inverter should operate at or near full power during normal operating conditions. In a well-designed system, the array's operating voltage, current and power output will be within the inverter's operating range at all times.

The number of modules in each string and strings in each array depends on the electrical characteristics of the module, the input voltage and current range of the inverter, and the expected high and low ambient temperatures of the site. The technical specifications from the manufacturer of the inverter provides information on sizing and installation. The system and connection concepts determine the number, voltage level and power class of the inverters [44].

3.5.2 Voltage sizing

Module temperature and irradiance affect the IV curve of a module and the optimal operating point. Temperature affects the generated voltage, while irradiance aspects the generated current. Module voltage increases at low temperatures and decreases at high temperatures. The operating range of the inverter should be matched with the IV curve of the PV array, with MPP of the array found within the MPP voltage range of the inverter. It is not possible to keep the array voltage within the MPP voltage range of the inverter at all operating temperatures.

The voltage of the PV array depends on the temperature, so the extreme cases of winter and summer operation are used when sizing the system [44]. When sizing a PV system, the following design criteria should be met [44, 38].

- The minimum and maximum array operating voltages (MPP voltages) should be within the inverter MPP voltage range, which is the range in which the inverter can search for the MPP.
- The absolute maximum array voltage should stay below the absolute maximum inverter input voltage and the maximum system voltage specified for the PV module.

If the array voltage falls below the minimum MPP inverter voltage, the inverter may not be able to find the MPP of the array and, in worst case, switch off. Therefore, the operating temperature of the array should be taken into consideration when sizing the string. One need to make sure that the minimum array voltage matching with the maximum array temperature is higher than the inverter minimum permissible voltage, otherwise the inverter will switch off and the AC output power will be zero.

The maximum and minimum number of modules in a string can be calculated based on these design criteria.

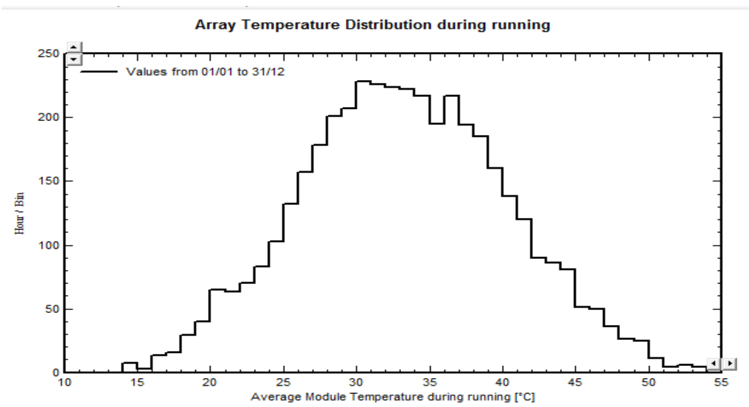


Figure 3.15:Suntech STP 240-20/Wd Array temperature distribution during running PVsyst screen capture

3.5.3 Current sizing

The maximum PV array current should not exceed the maximum inverter input current [44]. In most cases, the maximum string current is the short-circuit current at STC [44].

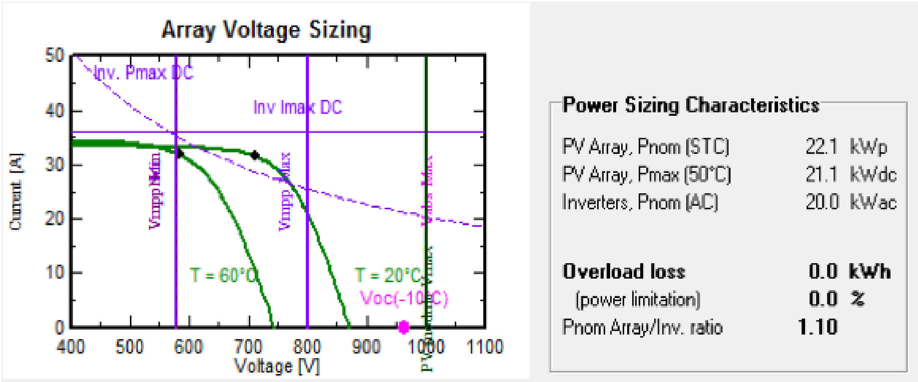


Figure 3.16:Voltage/Current Sizing condition PVsyst screen capture (for the case study)

The maximum and minimum number of strings can be calculated based on this design criterion.

3.5.4 DC and AC power matching

The sizing ratio between the nominal PV array power at STC and the nominal AC inverter power is called the P_{nom} ratio, and describes the capacity utilization of the inverter.

It is given by:

$$P_{nom\ ratio} = \frac{P_{nom\ array}}{P_{inv\ AC}} \tag{3.38}$$

where P_{nom} array is the nominal PV array power at STC [W] and P_{inv} AC is the nominal AC inverter power [W].

If P_{nom} ratio is 1 the systems DC and AC capacity matches, if P_{nom} ratio is lower than 1 the inverter is oversized and if P_{nom} ratio is larger than 1 the inverter is undersized. The AC nominal power is the power that the inverter can continuously feed into the grid without cutting out at an ambient temperature of 25°C [44]. The nominal power of inverters can be within ± 20% of the PV array power at STC, depending on the inverter and module technology, and the environmental conditions [44]. This gives the following power range for optimizing the performance [44].

$$0.8P_{nom\ array} < P_{inv\ AC} < 1.2P_{nom\ array}$$

which results in the following $P_{nom\ ratio}$,

$$0.83 < P_{nom\ ratio} < 1.25$$

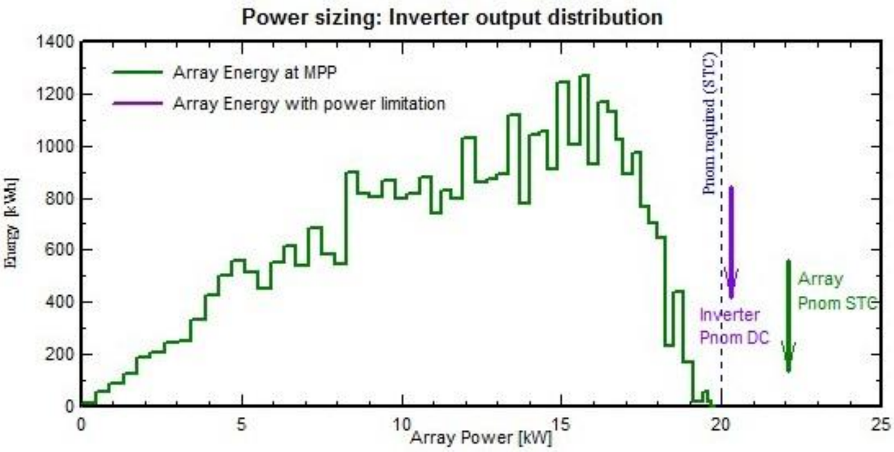


Figure 3.17:Power Sizing PVsyst screen capture (for the case study)

Inverters installed on the roof or outside may need to be undersized, due to exposure to high ambient temperatures. Systems without optimal alignment or partial shading can have a smaller inverter, taking into account the overload characteristics of inverters. Frequent, continuous overloading decreases the life of the inverter.

A system is undersized when the PV module capacity is greater than the inverter capacity. By undersizing a system, slightly more energy is produced in mornings and afternoons, as the inverter reaches its nominal AC power earlier in the day and continue to operate at that point until later in the afternoon. Slightly less energy is produced during the mid-day, as the power output is cut-off at the inverter's nominal capacity. Undersizing also lowers the specific cost of energy delivered and the inverter cost. Undersizing the PV inverter is also endorsed by inverter manufacturer SMA, one of the largest manufacturers in the industry [45]. When undersizing the inverter, it is important to consider the inverter input conditions and inverter operating efficiency and heat generation [45]. NEC and IEC standards recommends a P_{nom} ratio of 1.25[54].

4 CHAPTER 4: RESULTS AND DISCUSSIONS

The simulation results of designed PV grid-connected system are displayed comprehensively through the created report by PVsyst (see appendix 3). The report includes the optimum PV array and inverter sizes for the designed grid, the number of elements depicting the total potential energy that could be harvested for each month of the year, the energy injected into the grid per year, the effective energy at the output of the array, percentage efficiency of the array and percentage efficiency of the system and the detailed losses of the system.

4.1 SIMULATION RESULTS

The grid connected photovoltaic system for 20kW power plant was simulated in the PVsyst software. From the simulation it is found that 92 modules and one central inverter are required. 23 PV modules are connected in series and form a string. 4 strings of 23PV modules are used in the system. For the placement of the modules, an area of 150m^2 is required. The output of the PV system depends upon the received solar radiation and temperature. At the maximum power point and under the Standard Test Condition, the array output current is equal to 32 A and the short-circuit is equal to 33.7A. At 60°C, maximum power point voltage of the array is equal to 534 V whereas at the 20°C temperature, maximum point voltage will be 626 V. The Open Circuit Voltage (at -10°C) on the other hand is equal to 962V. The array nominal power under the Standard Test Condition is equal to 22.1kWp. Pnom ratio is equal to 1.10 which is within the recommended $P_{nom\ ratio}$ range, with no overload loss. Figure 4-1 depicts the System Design PVsyst screen capture.

<u>Land occupied by the pv solar power plant</u>

As solar modules are not energy-dense, they require a substantial amount of space in order to work. For the 92 solar modules selected, a total modules area of 150 m^2 is needed. Although the panels have a total area of 150 m^2, in order to obtain the total space required for the PV system, the space for the components, balance of system, and the space between the panels need to be accounted for (as these panels require stands).

The land occupied by the PV plant is calculated using formula (3.14):

$$Land = 20000\ x\ 1\ x\ 0.036 = 720m^2$$

Therefore,720m^2 of land is required for the whole PV plant.

Ground coverage ratio (GCR)

The ground coverage ratio is calculated using formula (3.34):

$$GCR = \frac{150}{720}.100 = 20\%$$

This means that 20% of the land occupied by the PV solar power plant is covered with the PV modules.

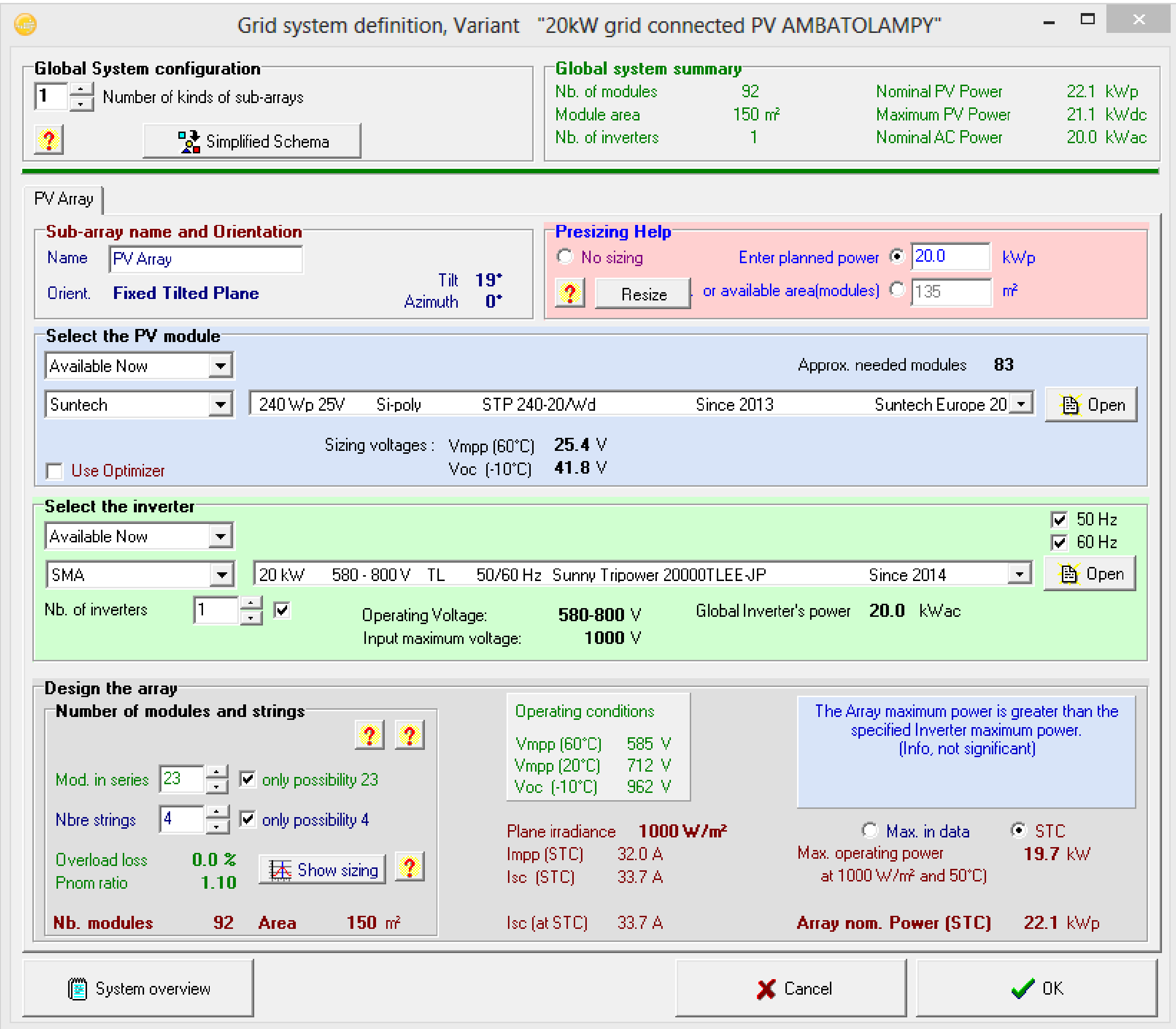


Figure 4.1:System Design PVsyst screen capture

SUMMARY OF PROPOSED DESIGN CALCULATION

The summary of proposed design is given in table 4-1.

Table 4-1:Summary of proposed design

SYSTEM OVERVIEW	
Peak power	20kWp
Number of modules	92
Number of strings	4
Number of modules per string	23
Number of inverter	1
Array output voltage	534 V at 60°C and 626 V at 20°C
Array output current	32A
Array output power	22.1kWp (under STC)
Array open circuit voltage	962V
Array short circuit current	33.7A
Inverter output Voltage	3 x 400V
Inverter output current	29A
Inverter maximum output power	20kW
Area required(modules)	150m^2
Land occupied by the PV solar power plant	720m^2
GCR	20%

4.2 PERFORMANCE EVALUATION OF THE SYSTEM

This section shows the performance evaluation of the system which are : the system's energy losses, the hourly production, the monthly normalized production and the performance ratio.

4.2.1 Daily input/output diagram

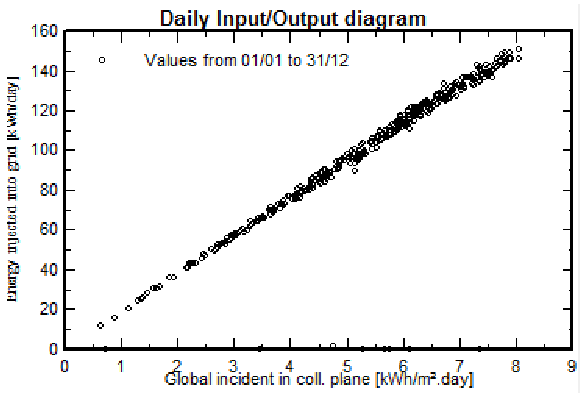


Figure 4.2:Scatterplot according to the PVsyst simulation

Figure 4-2 shows that the system is sized correctly, because there is a good correlation between the irradiance and the energy production, with minimal dispersion.

4.2.2 The system’s energy losses throughout the year

PVsyst calculates the losses and shows them in a loss diagram as illustrated in figure 4-3. The upper parts of the diagram are optical losses, the middle parts are array losses, and lower part are system losses.

From 40.35MWh of energy produced annualy, after deducting the optical losses, only 35.48MWh is available at the output of the array due to the array losses. Then, 1.6% of the energy from the PV array is lost in the inverter (efficiency of the inverter) and decrease the energy from the array down to 34.90MWh. Ultimately, only 34.20MWh of energy is available to the grid in a year by deducting the system unavailability due to downtime and maintenance.

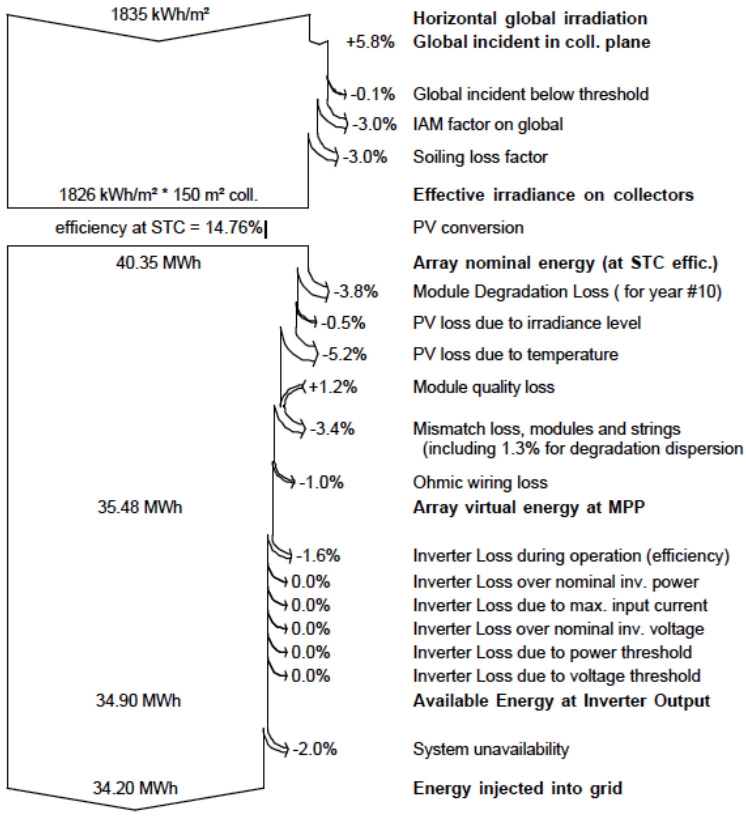


Figure 4.3:Detailed losses occur in the proposed grid connected PV system

Those various losses are explained in details below.

Optical losses

The power output delivered from a photovoltaic module highly depends on the amount of irradiance, which reaches the solar cells. First of all, about 1835 kWh/m^2 radiation is incident on the solar panels but only 1826kWh/m^2 is captured by the PV array due to the optical losses which are the soilling loss and IAM loss or the Incidence Angle Modifier loss.

Soiling losses refer to loss in power resulting from snow, dirt, dust and other particles that cover the surface of the PV module. Shading due to soiling is divided in two categories, namely, soft shading such as air pollution, and hard shading which occurs when a solid such as accumulated dust blocks the sunlight. Soft shading affects the current provided by the PV module, but the voltage remains the same. In hard shading, the performance of the PV module depends on whether some cells are shaded or all cells of the PV module are shaded. If some cells are shaded, then as long as the unshaded cells receive solar irradiance, there will be some output although there will be a decrease in the voltage output of the PV module. That is why frequent cleaning of the PV array is necessary. The overall soiling losses for this simulationis is set to 3%.

IAM losses corresponds to the decrease of the irradiance really reaching the PV cells's surface, with respect to irradiance under normal incidence. This decrease is mainly due to reflexions on the glass cover, which increases with the incidence angle. The transmission loss is a general phenomenon, due to the reflexion and transmission of the sun's ray at each material interface (air-glass, glass-encapsulation, encapsulation-cell), as well as some absorption in the glass. This arises for any incidence ray. For normal incidence, the reflexion is of the order of 5%, and is included in the measured STC performance. By default, PVsyst will take the values specified for the PV module.

Array Losses

Module degradation loss (ageing), also refered as time losses is the decline of PV module output power over time. A standard silicon solar panel consists of silicon wafers, connecting busbars, encapsulant material, glass, and polymer backing sheets, and other electrical connection components. Over time, these components will be worn down and damaged by the effects of thermal expansion and contraction, UV light, and damage from windblow particles. Weaker electrical connections cause resistive losses within a cell, decreased shunt resistance allows current to ‘’leak ‘’ within a cell instead of being used to power loads, and discoloration and damage to the layers in front of the cells reduces the available light. The value of module degradation loss for the selected Suntech STP 240-20/Wd PV module for the period of ten years is equal to 3.8%.

The largest Array losses is thermal loss (5.2%) due to the high annual average temperature in the location. The module performance at high temperatures depends on the thermal loss factor (Uvalue) of the system and the temperature behavior of the PV module. Ground mounted, free-standing systems, have a lower efficiency loss due to temperature than roof mounted systems. This is expected, as the specified U-value for ground and roof mounted systems are different and reflects how well ventilated the system is.

The efficiency loss/gain due to irradiance levels different from STC depends on the module characteristics and the irradiance intensity. The efficiency behavior at different irradiance levels in PVsyst is an application of the one-diode model, with the specified shunt and series resistance (Rsh and Rs) of the module. Rsh increases exponentially with decreasing irradiance. A lower shunt resistance at STC, results in higher module efficiency at low irradiance levels. Rs increases with power. A higher Rs at STC, results in higher module efficiency at low irradiance levels. Thus, modules with low Rsh and high Rs performs better under low irradiance conditions, compared to STC. The Suntech STP 240-20/Wd showed a 0.5% loss in efficiency due to irradiance levels different than STC. This may be due to the combination of a higher shunt resistance(1200Ohm) compared to the other modules, which ranged from 350 Ohm to 630 Ohm.

A positive module quality loss result in a power gain, which can be explained by the modules positive tolerance. By default, PVsyst initializes the module quality loss according to the PV module manufacturer’s tolerance specification: PVsyst will choose a quarter of the difference between the lower and the higher value. Suntech STP 240-20/Wd has a module quality loss of +1.2%.

When PV modules with different characteristics (I & V) are connected together they provide a total output power less than the power achieved by summing the output power provided by each of the modules. PV modules with same ratings coming out of one production line in a factory do not possess identical current–voltage characteristics for many reasons. This inequality causes PV modules to compromise on common voltage and current when they are connected in series or parallel in an array. This compromise results in a type of power losses known as mismatch losses. Mismatch losses for Suntech STP 240-20/Wd module is equal to 3.4%.

System Losses

The inverter SMA, Sunny tripower 20000TLEE-JP loss during operation is equal to 1.6%. Unavailability loss should reflect the expected time period of system downtime due to maintenance or system failure. The energy loss due to unavailability is dependent on the season and the weather during the season. System failure occurring during rainy seasons will result in higher unavailability loss. The unavailability loss varied from 1.2% to 2.9%. In this simulation, the unavailability loss is equal to 2%

4.2.3 Hourly production each month for a full year

Table 4-2:Hourly production for each month of the PV system in kWh

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
0H	0	0	0	0	0	0	0	0	0	0	0	0	0
1H	0	0	0	0	0	0	0	0	0	0	0	0	0
2H	0	0	0	0	0	0	0	0	0	0	0	0	0
3H	0	0	0	0	0	0	0	0	0	0	0	0	0
5H	0	0	0	0	0	0	0	0	0	1	5	6	12
6H	52	34	28	10	3	0	0	4	59	85	86	78	439
7H	147	133	124	135	132	108	112	138	197	200	186	173	1784
8H	253	228	234	250	244	233	242	269	330	309	273	249	3113
9H	324	305	316	330	334	326	344	379	435	386	322	307	4108
10H	376	383	394	397	390	380	415	445	512	444	370	356	4861
11H	373	344	394	403	407	399	445	472	521	460	337	369	4925
12H	367	330	415	397	396	390	440	484	502	439	334	355	4850
13H	337	307	356	351	357	353	415	428	451	401	281	335	4372
14H	285	254	301	294	300	286	338	360	372	325	209	260	3584
15H	215	190	213	207	204	184	232	246	250	222	151	192	2505
16H	128	113	116	96	87	77	102	115	118	104	74	110	1239
17H	45	39	22	2	0	0	0	1	1	6	9	28	153
18H	0	0	0	0	0	0	0	0	0	0	0	0	0
19H	0	0	0	0	0	0	0	0	0	0	0	0	0
20H	0	0	0	0	0	0	0	0	0	0	0	0	0
21H	0	0	0	0	0	0	0	0	0	0	0	0	0
22H	0	0	0	0	0	0	0	0	0	0	0	0	0
23H	0	0	0	0	0	0	0	0	0	0	0	0	0
24H	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 4.2 shows total hourly production each month for a full year. The numbers indicate that the production follows the normal production pattern of solar power with peak production

around mid-day. There is more production during a longer time period in summer months (September) due to the longer sunlight hours and less production during a shorter time period in winter (June). The peak power output is higher in summer (September), that indicates that the high irradiance contributes to a better cell efficiency.

4.2.4 Daily system output energy

The figure 4-4 shows that the highest power generation achieved is an average output energy of 150kWh/day in the month of September with the recorded insulation, average module temperature of 6.07 kWh/m^2/day, 21.51°C respectively. The decline in the energy generation in May and June is mainly because of the number of cloudy days during the winter period. However, the decline in energy in November is due to the rainy season. There is a fluctuation in energy production almost throughout the year exept during summer period (clear sky), this is expected because of the intermittency due to the rain and cloudy days in these seasons. This will of course have a negative impact on grid stability.

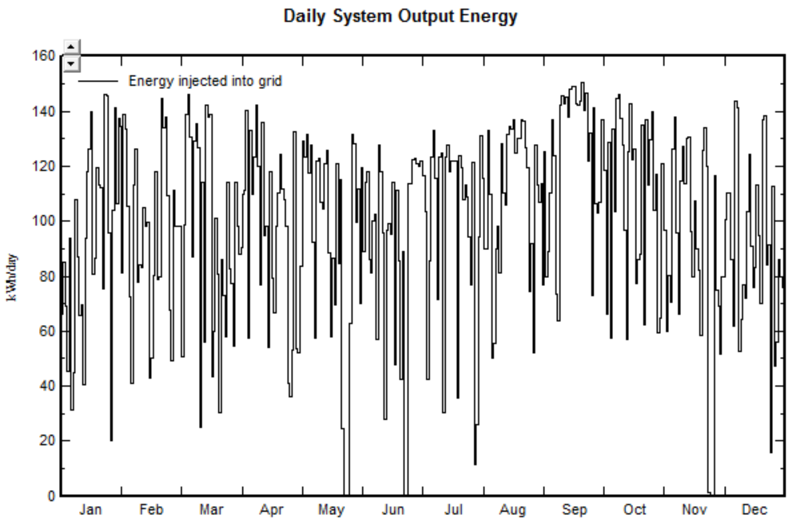


Figure 4.4:Daily system output Energy

4.2.5 The monthly normalized production for the system

Figure 4-5 shows that the mean daily energy supplied to the grid is 4.24 kWh/kWp/day, the PV array loss is 0.92 kWh/kWp/day while system loss is 0.16 kWh/kWp/day. The collector loss is lower during winter months (June, July) and increase significantly during summer months (August-October), as it includes the efficiency loss due to temperature, however, energy production is high in summer, this is justified by the fact that insulation is high in summer. A marked increase in system losses can be observed in May, June and November, which corresponds to the unavailability periods.

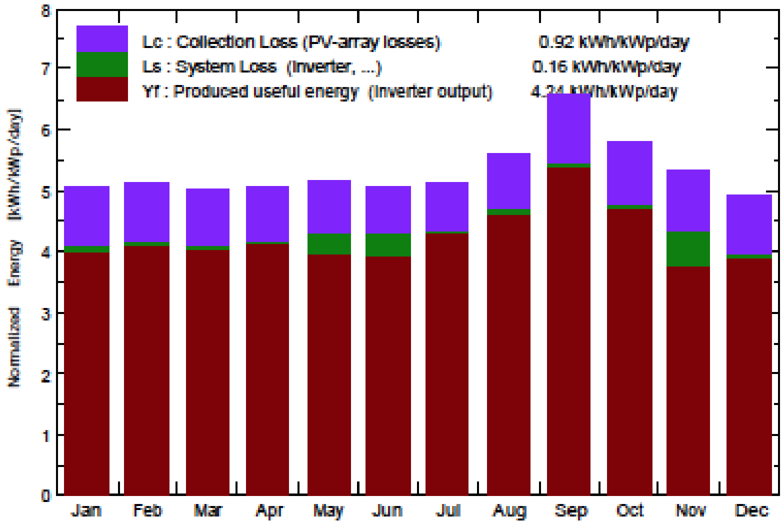


Figure 4.5:Monthly normalized energy production

4.2.6 Monthly energy generated from designed PV grid connected system

Table 4-3 summarized the system performance throughout the year. The annual Global Horizontal Irradiation available is 1,835.3 kWh/m^2 but only 1,826.4 kWh/m^2 is effectively available at PV array plane. By the proposed grid connected system, 35.483MWh of energy for the entire year is is generated from the PV array, out of that only 34.196MWh is available to the grid due to several losses. The maximum energy is generated in the month of September (3.569 MWh) and minimum energy is in the month of November (2.508 MWh).

Table 4-3:Monthly electricity production by the proposed system

	GlobHor kWh/m²	DiffHor kWh/m²	T Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_Grid MWh	PR
January	167.4	91.05	26.87	157.0	146.7	2.808	2.761	0.797
February	147.1	82.14	26.41	143.0	133.8	2.574	2.531	0.802
March	151.8	79.20	25.79	156.1	146.5	2.814	2.768	0.803
April	139.0	67.61	24.23	152.7	143.9	2.779	2.733	0.811
May	133.2	48.31	22.75	160.2	151.1	2.947	2.714	0.767
June	121.7	41.53	20.08	152.6	143.9	2.854	2.601	0.772
July	128.0	39.31	19.35	158.4	149.6	2.982	2.934	0.839
August	150.3	55.55	20.24	173.3	163.7	3.230	3.178	0.831
September	182.8	54.90	21.51	197.3	186.6	3.627	3.569	0.819
October	180.0	86.39	23.75	179.9	169.1	3.271	3.218	0.810
November	168.4	90.14	25.15	159.2	149.1	2.871	2.508	0.713
December	165.7	94.64	26.64	152.6	142.4	2.726	2.680	0.795
Year	1835.3	830.76	23.55	1942.3	1826.4	35.483	34.196	0.797

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

4.2.7 Performance ratio (PR)

The overall performance ratio as shown in Figure 4-6 is 79.7%

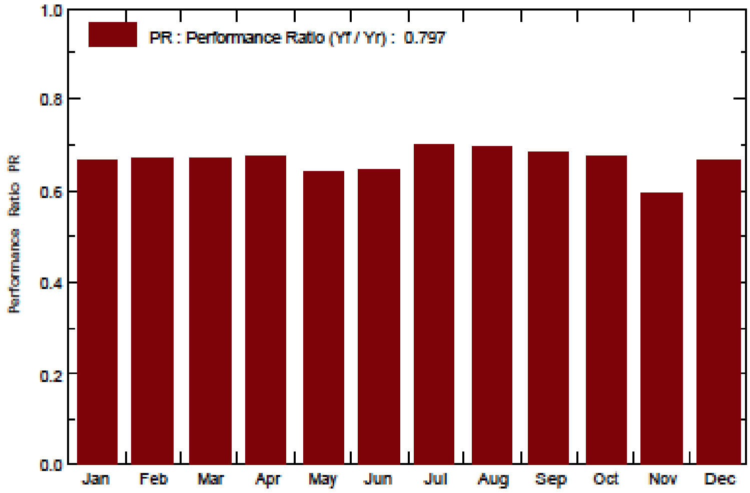


Figure 4.6:Performance Ratio

Performance ratio indicates the overall effects of losses on the array rated output power due to array temperature, ineffective utilization of the irradiation and system component inefficiencies or system failure or system downtime. The overall performance ratio in the simulation environment in one year is 0.797, meaning that 20% are the overall losses of the PV system including system losses and module losses (solar radiance not converted into useful energy, Thermal losses, Ohmic losses, inverter losses…). The performance ratio is higher during winter months than during summer months, as can be observed in figure 4-6. This is expected as winter months have lower temperatures and soiling, resulting in lower losses. However, there is a dip in performance ratio in May, June and November. These dips correspond to months with unavailability periods.

4.2.8 Capacity factor (CF)

The Capacity factor is calculated using formula (3.36):

$$CF(\%) = \frac{34.20 \text{ x } 1000}{20 \ x \ 8760} x100 = 19.52\%$$

This means that the overall efficiency of the plant is equal to 19.52%.

SUMMARY OF EVALUATION OF THE SYSTEM

Table 4.4 shows the System evaluation results for the case study.

Table 4-4:System evaluation results

System Yearly Energy Production	34.20 MWh/yr
Specific Production/Annual specific yield	1549 kWh/kWp/yr
Performance Ratio	0.7973
Normalized Production	4.24 kWh/kWp/day
Array Losses	0.92 kWh/kWp/day
System Losses	0.16 kWh/kWp/day
Capacity factor	19.52%

4.3 CABLES SIZING

Cables seen in the grid connected PV system are a set of DC and AC cable. The sizing of the cable for the grid connected PV sytem for the case study is presented below.

4.3.1 Sizing of DC cables

Sizing cables between PV modules

The cable is sized based on the following information:

Length of cable: 1.5 m

The maximum current is 1.25 x short circuit current of modules (8.43 amperes) = 1.25 x 8.43 = 10.54A

The maximum allowable voltage drop:

$$\frac{5}{100} \text{ x } 30.2 = 1.5 \text{ V}$$

CSA of the cable in mm^2 is calculated using equation (3.19):

$$\text{A} = \frac{0.0183 \text{ x } 1.5}{1.5} \text{ x } 10.54 \text{ x } 2 = 0{,}38\text{mm}^2$$

This means that any cable of cross-sectional area above $0.38mm^2$ can be used for the wiring between PV modules.

Cable from PV array to the Inverter

The cable is sized based on the following information:

Length of cable: 200 m

The maximum current is 1.25 x 8.43 x 4 = 42.15A

The maximum voltage drop:

$$\frac{5}{100} \text{x } 664 = 33.2 \text{ V}$$

CSA of the cable in mm^2 is equal to:

$$A = \frac{0.0183 \ x \ 200}{33.2} \ x \ 42.15 \ x \ 2 = 9{,}3 mm^2$$

This means that any cable of cross-sectional area above 9,3 mm^2 can be used for the wiring between PV array and inverter.

4.3.2 Sizing of AC cables

Cable from inverter to the grid

The cable is sized based on the following information

Maximum Length of cable is 200m

The maximum current from inverter at full load on each phase (line) is calculated using equation (3.20):

$$I_{phase} = \frac{20000}{400.\sqrt{3}} = 28.87A$$

The maximum voltage drop:

$$\frac{5}{100} \text{x } 400 = 20 \text{ V}$$

And similarly to DC cable, CSA is calculated using equation (3.21):

$$A = \frac{0.0183 \ x \ 200}{20} \ x \ 28.87 \ x \ 2 = 10.57 mm^2$$

This means that any cable of cross-sectional area above 10.57mm^2 can be used for the wiring between inverter to the grid**.**

4.4 PROTECTION OF THE PV SYSTEM

Like mentioned in the section 3.1.5, the sizing of the protection of a grid connected PV system consists of sizing the fuses in the combiner box and the circuit breaker at the AC side.

4.4.1 Sizing of circuit protection between PV array and Inverter

The minimum rate of DC circuit protection is calculated using equation (3.23):

$$I_{fuse} = 1.25 \ x 1.25 x \ 8.43 = 13.17 \ A$$

Hence, a 15A fuse can be used in the combiner box to wire the strings into parallel.

4.4.2 Sizing of circuit protection on every phase output of inverter

The minimum rating of circuit breaker is calculated using equation (3.24):

$$I_{breaker} = 1.25\ x\ 28.87 = 36\ A$$

4.5 INTER-ROW SPACING

Calculation of pitch

The pitch is determined based on the following information:

- Setback ration (SBR) = 2:1 for lower latitudes (-19.38°S Madagascar)
- ß (tilt) =19°
- c: module width = 1640mm

And the pitch is calculated using equation (3.28):

$$d = 1.640\ x\ \left(cos(19) + \frac{2}{1} sin(19)\right) = 2.62m$$

4.6 SYSTEM WIRING

It is vital in all system works to have a clear understanding of the wiring connections required in the system. Some components do not allow for trial and error since they burn out immediately when not connected properly.

Wiring layout of grid connected PV system and its components

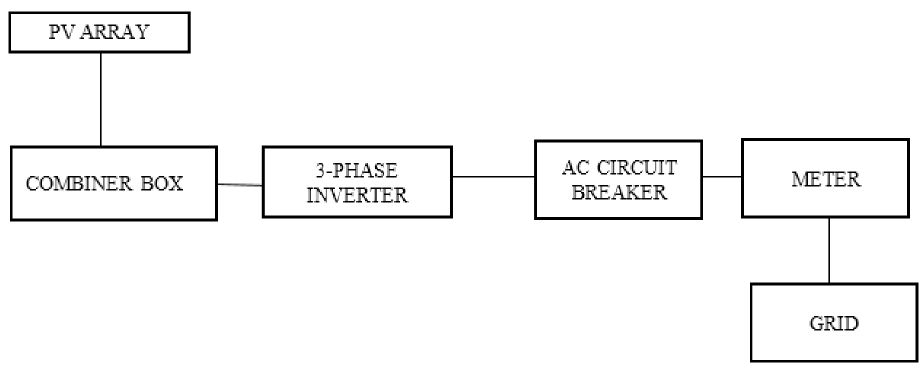


Figure 4-7:Single wiring diagram of grid connected PV system

Wiring diagram of PV array

The PV array is made up of 92 modules of 4 parallel strings of 23 modules in series.

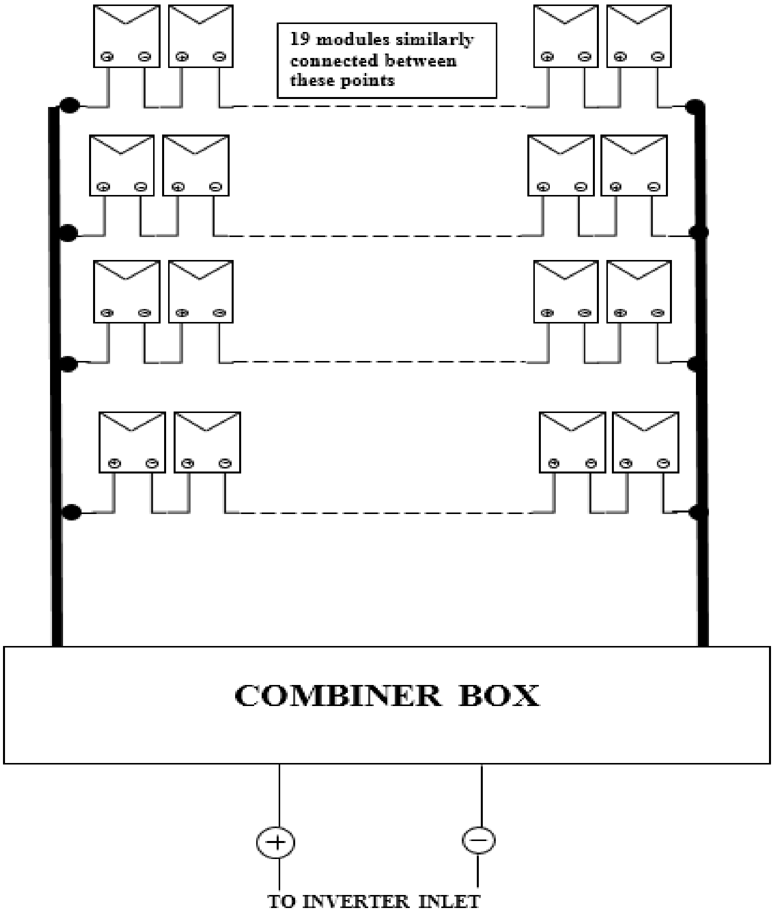


Figure 4.8:Wiring diagram of PV array

Wiring diagram of connection of inverter output to AC the circuit breaker

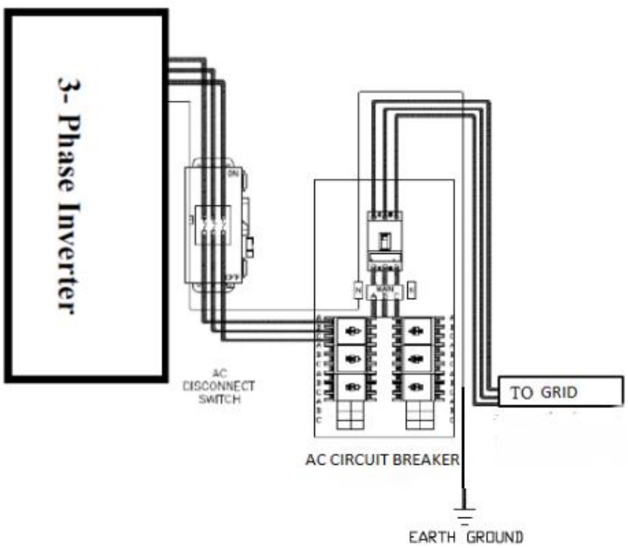


Figure 4.9:Wiring diagram of connection of inverter output to the AC circuit breaker

4.7 ECONOMIC EVALUATION

After simulation, an economic evaluation of the system was performed on the basis of the defined parameters and the simulation results. Costs are defined globally in price list from components database and manufacturer online quotation.

4.7.1 Economical assumptions

Table 4-5:Economical assumptions

Investment				
	Qty.	Price/Unit (Ariary)	Total (Ariary)	Total (USD)
PV modules	92	1,440,933/module	132,565,836	36023
Supports/Integration		110,456/module	10,161,952	2761
Inverters	1	12,678,006	12,678,006	3445
Settings, wiring, …			8,522,383	2315
Electrical Installation			5,744,705	1561
Project Management			2,346,280	637
Commissioning			189,390	51
Transport and assembly			1,067,933	290
Engineering and draughting			431,383	117
Gross Investment (without taxes)			173,707,868	47203
Financing				
	Ariary			USD
Gross investment (without taxes)	173,707,868			47203
Taxes on Investment (VAT)	Rate 9.2%		15,981,124	4342
Gross Investment (including VAT)	189,688,992			51546
Subsidies	20,000,000			5434
Net Investment (all taxes included)	169,688,992			
Annuities	Loan 5.0% over 16 years		15,657,188	46111
Annual running cost: Maintenance, insurances……	953,223			259
Total yearly cost	16,610,411			4513
Tarification strategy				
Fixed Feeding tariff	450Ariary/kWh			0.12$/kWh
Annual production reduction	1%			
Annual tariff depreciation	2%			
Duration of tariff Warranty	25 years			
Selling tariff drop after warranty	50%			
Energy Cost				
Produced Energy	34.2MWh/year			
Cost of produced energy	486Ariary/kWh			0.13$/kWh

Prices are defined based on the manufacturer's cost. The net investment for the owner is derived from the gross investment by subtracting potential subsidies and adding a tax percentage (VAT). Choosing loan duration and interest rate, PVsyst computes the annual financial cost, supposing a loan pay back as constant annuities. The loan duration for this project is equal to 16 years. The sum of the annuities and the running costs is the total annual cost. Divided by the effectively produced and used energy, it gives an evaluation of the energy cost (price of the used kWh).

4.7.2 Economic evaluation results

Table 4-6 shows the result of the calculation of payback time and cumulative balance. The system lifetime is assumed to be equal to the module lifetime. The International Energy Agency (IEA) assumes a PV system lifetime of 25 years.

Table 4-6:Payback time and cumulative balance

Payback Time	11.02 Years	
Cumulative balance	164,767,000 Ariary	$ 44774

The economical evaluation shows that it will take 11 years to make the invested money back, the cumulative balance is positive which assures good profitability. As a result, the investment cost will be paid back during the system lifetime.

Graphs 4-8 shows the Yearly Financial balance in kAriary and Cumulative Financial balance or Net profit from the plant after the successful running of the plant for the desired time. The X-Axis shows Lifetime and the Y-axis shows the total profit

- YEARLY FINANCIAL BALANCE and CUMULATED FINANCIAL BALANCE

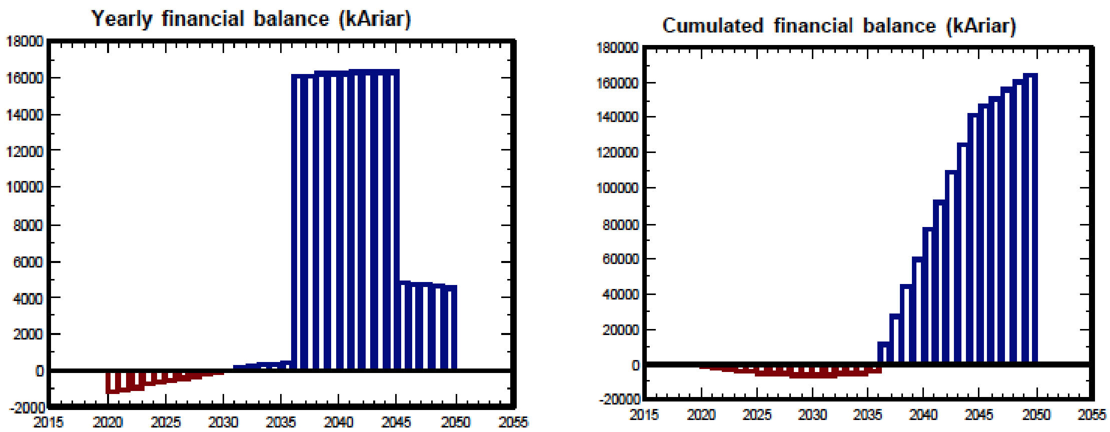


Figure 4-10:Yearly Financial Balance & Cumulated Financial Balance

Figure 4-8 has a climbing graph due to the fact that there is an annual tariff augmentation of 2% though the annual depreciation in the energy produced by the solar power plant is 1%. After the end of 25 years, there is a significant drop in the yearly financial balance due to lower factor deviation, the tariff at which energy is sold in depreciated by 50%. At the begining of the project in 2020 till 2036, the sold energy is used to pay the annuity. But from 2020 till 2031, the sold energy is lower than the annuity, as a result, the project doesn't make any profit yet. But from 2031, the sold energy is a bit higher than the annuity, hence the project starts to make a profit. After paying off the loan in 2036, the project takes all of the sold energy and make a huge profit from it.

- LONG TERM ECONOMIC BALANCE

Table 4-7:Long term economic evaluation

Long term economic balance

Year	Loan 5.0 %	Running costs	Sold energy	Yearly Balance	Cumul. Balance
2020	15657	953	15388	-1222	-1222
2021	15657	953	15539	-1071	-2293
2022	15657	953	15684	-927	-3220
2023	15657	953	15822	-788	-4008
2024	15657	953	15955	-656	-4663
2025	15657	953	16081	-530	-5193
2026	15657	953	16201	-409	-5602
2027	15657	953	16315	-296	-5898
2028	15657	953	16423	-188	-6086
2029	15657	953	16524	-86	-6172
2030	15657	953	16619	9	-6163
2031	15657	953	16709	98	-6065
2032	15657	953	16792	181	-5883
2033	15657	953	16869	258	-5625
2034	15657	953	16940	329	-5296
2035	15657	953	17004	394	-4902
2036	0	953	17063	16109	11207
2037	0	953	17115	16162	27369
2038	0	953	17161	16208	43577
2039	0	953	17201	16248	59825
2040	0	953	17235	16282	76107
2041	0	953	17263	16310	92416
2042	0	953	17284	16331	108747
2043	0	953	17300	16346	125094
2044	0	953	17309	16356	141449
2045	0	953	5771	4817	146267
2046	0	953	5694	4740	151007
2047	0	953	5617	4664	155671
2048	0	953	5540	4587	160258
2049	0	953	5463	4510	164767

The total cost of the project is estimated around 169,688,992 Ariary. The levelized cost of electricity (LCOE) is 486 Ariary per kWh. This LCOE level is a bit higher compared to the feed in tariff price which is 450 Ariary per kWh. Despite drawback at LCOE level, the project is perfectly able to pay back the loan in 16 years and start to generate money. At the end of the project (2050), the project makes a net profit of 164,767,000Ariary which is almost equal to the project net investment.

4.8 CO_2 SAVING

Based on the PVsyst simulation result, the annual energy production for the PV plant is 34.2 MWh/year. The carbon dioxide avoidance factor for a diesel power plant is 0.764 kg of CO_2 per kilowatt-hour. Therefore, upon installation of the facility, it will have a total of 22,080 kg or 22.080 tons of CO_2 avoidance per year. Throughout the PV system lifetime of 25 years, the saved CO_2 emission is equal to 555,200 kg or 555.2 tons. This is a huge incentive to lessen greenhouse gas emission where carbon dioxide plays the most in volume.

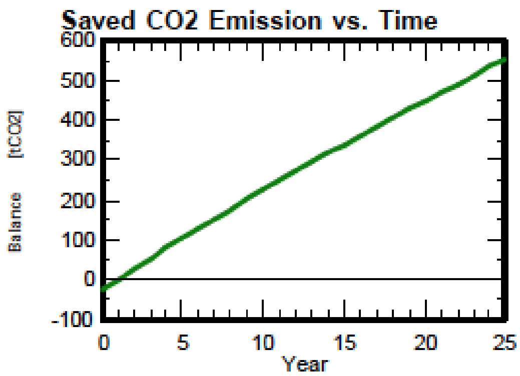


Figure 4.11:Saved CO_2 emission

4.9 SYSTEM INSTALLATION

The system installation section is the final step to putting into operation the grid connected SPV system. This section includes installation preparation practices, equipment installation practices, safety equipment and practices and finally system commissioning activities.

<u>Installation preparation</u>

The preparation for installation involves two main steps

- Determination of equipment location
- Preparation and use of installation checklist

<u>Equipment location</u>

Maximum wiring distances between all components of the system have been determined and used for cable sizing and these distances must be maintained in the installation.

<u>Installation checklist</u>

To prevent the halting of the installation process due to the absence of any installation equipment, an installation checklist is prepared.

The installation checklist is prepared to

a) obtain all the relevant equipment

b) Ensure all tools and equipment is loaded and ready for transport to site.

The checklist is ticked to represent the presence of the tool or equipment.

Table 4-8:Installation Checklist

Item No	Type of item	Number required	OK
1	PV module (Suntech STP 240-20/Wd model)	92	
2	Solar array mounting structure/ frame	-	
3	Hardware for connecting module to frame	-	
4	Hardware for connecting frame to floor	-	
5	Cable between PV modules ($1.5mm^2$)	276m	
6	Cable between PV array and Inverter ($9.3mm^2$)	200m	
7	Conduit	200m	
8	Fastening hardware for cables/ conduit	-	
9	SMA, Sunny tripower 20000TLEE-JP inverter	1	
10	Wooden stand for inverter	1	
11	Disconecting combiner box	1	
12	AC disconnect switch	1	
13	Dual pole AC circuit breaker (36A)	1	
14	Cable runs from Inverter to main junction ($10.57smm^2$)	200m	
15	Meter	1	
16	Installation toolbox	5	

Equipment installation

In this section the main rules with respect to the installation of the individual components of the grid connected PV system are summarized.

Solar Array

The solar array should be

- Mounted facing true North 0 degree.
- Mounted at a tilt angle of 19°.
- Sited to minimize shading by trees and buildings.

Inverter

The inverter will generally be installed as follows;

- Installed in a dust free environment

- Mechanically supported where placed
- Not installed in a wet or damp environment
- Installed in a location where the inverter is not in excessive temperature.
- Mounted in an area that is free from hydrogen accumulation

4.10 SYSTEM MAINTENANCE AND TROUBLE SHOOTING

This section seeks to outline the major maintenance activities and also create a fault-finding tree that makes it easier to identify faults and solve them in the shortest possible time.

4.10.1 System maintenance

In a solar system, like any other equipment installation, the lifetime of the system is shortened if the system is not well maintained. Considering the cost of such system, it is more than essential for the system to be maintained. In addition, like any other electrical equipment or system, troubles do occur and trouble shooting if not well planned can become both tedious and time consuming.

- Maintenance schedule for each component

For each major component in the grid connected PV system, the major maintenance schedule is outlined as follows

Solar Array

Table 4-9:Maintenance schedule for Solar Array

Clean modules	Every three months
Check all cabling for loose connections and mechanical damage	Every three months
Check mechanical security of the array structure	Every three months
Check output voltage and current of each parallel string of the array and compare to the expected output under the same conditions	Every three months
Check for shading by trees and houses around modules	Every three months

Inverter

Table 4-10:Maintenance schedule for Inverter

Maintenance activity	Recommended period
Check if the all the units have not been invaded by spiders, rodents or insects	Every month
Cleaning all units to minimize dust build up	Every month
Check that all electrical connections are clean and tight	Every month

- Maintenance logbooks

To have historical information about each of the equipment which can help show abnormal variations, future problems and changes in performance over time, all maintenance activities and their records must be kept.

A book usually called a log book made up of loose sheets is used to keep these records.

The following are the individual log books prepared for this system. These sheets are ticked to show that that particular activity has been undertaken.

Solar array log sheet

Table 4-11:Solar array log sheet

Date	Modules cleaned	Cabling in good condition	Array structure OK	Output voltage	Output Current	No shading	Comments

Inverter, AC circuit breaker log sheets

Table 4-12:Inverter, AC disconnect

Appliance	Activity	Date	Date	Date	Date
Inverter	No insect evasion				
	All connection tight				
	The appliance is cleaned				
AC circuit breaker	No insect evasion				
	All connection tight				
	The appliance is cleaned				

4.10.2 System faultfinding

The faultfinding process for a system can be both tedious and time consuming. In this section major fault occurrences likely to be encountered by operating each of the components is stated and the logical process to ascertain the fault cause is listed.

- Solar Array Faults

Most likely fault occurrence:
Solar array does not give similar current output under similar irradiation conditions in the past.
Logical process for identifying fault cause:

1. Check for shading of the modules
2. Check for dirt on modules
3. Check for any loose wires
4. Check current output for each string and check if any of the strings give an unrealistic low figure.
5. If an underperforming string is identified, identify the particular module by shading each module successively and checking the relative changes in the ammeter reading. The module that when shaded does not result in any change in ammeter reading is faulty.

- Inverter faults

Most likely fault occurrence:
Inverter does not give required voltage output
Logical process for identifying fault cause:
1. Check for loose connections at input of Inverter
2. Then the fault is in the circuit board of the inverter and since the SMA Sunny tripower 20000TLEE-JP inverter comes with a 10-year warranty, the manufacturers are contacted for further instructions.

- Grid connected PV system troubleshooting tree

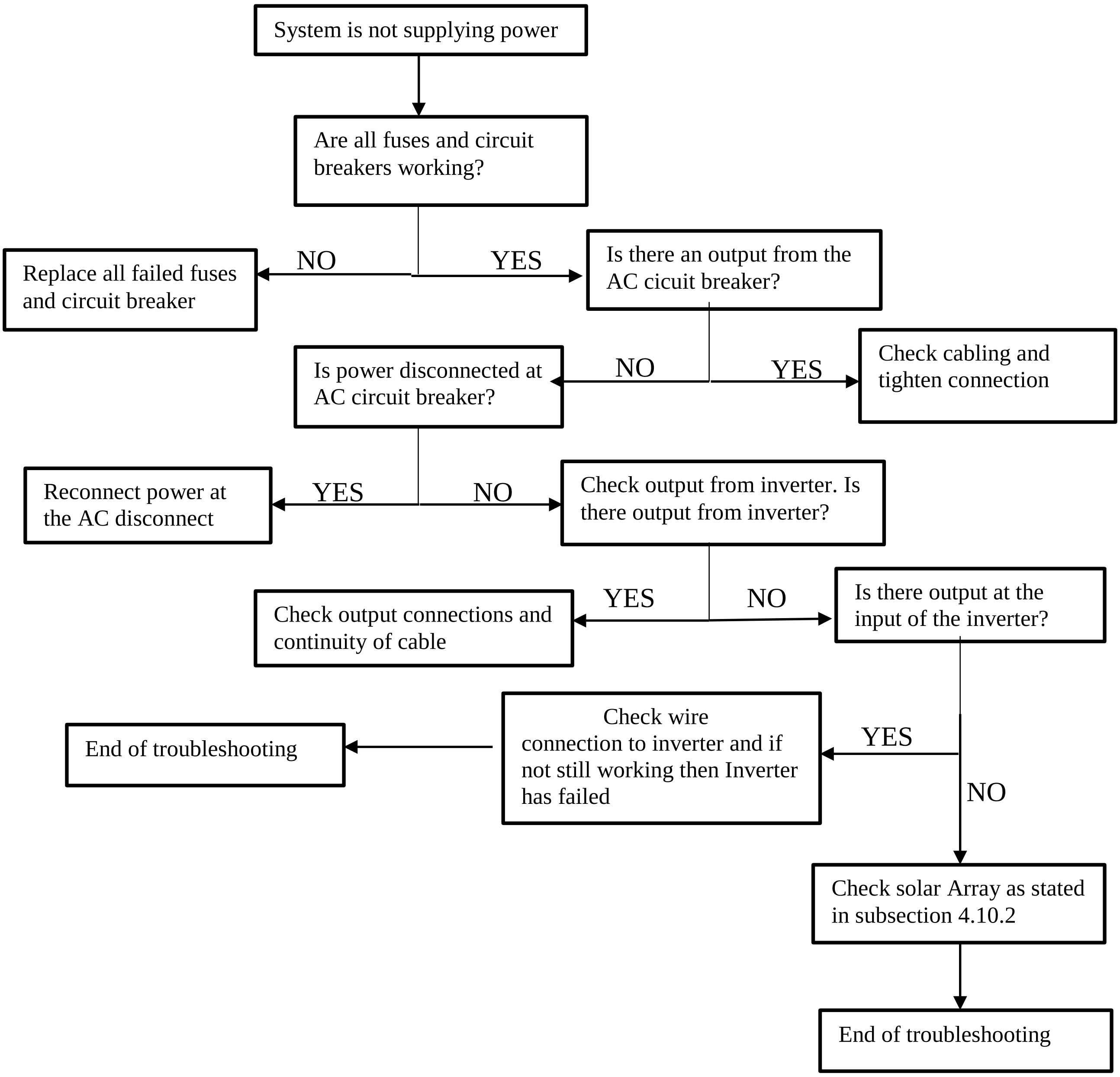


Figure 4-12: Grid connected PV system troubleshooting tree

CHAPTER 5: GENERAL CONCLUSION AND PERSPECTIVE

This chapter contains the summary of the findings, recommendations, conclusions, and areas for further studies that the study identified. The summary of the findings was done in line with the study objectives.

5.1 CONCLUSIONS

This thesis presents an extensive study and design of a ground-mounted SPV grid-connected electricity generation plant of size capacity 20kWp in Ambatolampy, Madagascar. Simulations of the designed system is performed with PVsyst software. It is used to obtain information on energy production, efficiency of system and energy loss by PV system. The findings of the study are very optimistic.

From technical point of view, after analyzing several criteria like the solar ressource, local climate, available area, topography, environmental and social considerations, accessibility, module soiling, water availability; Ambodiriana - Ambatolampy appears to be the favourable location to install the system. The location receives about 4.30kWh/m^2/day according to the Meteonorm 7.1 data. The ground assessment revealed that, a 20kWp solar system would require a total of about 720m^2 of total land for the installation. PV panels must be oriented northwards with a tilt angle of 19° in order to receive the maximum amount of solar radiation. The analysis of the PVsyst simulation results revealed that, the system will generate an average of about 34200 kWh of electricity a year; with maximum production of 3569 kWh in the month of September. The annual average performance ratio is 79.7%, peaking in the month of July to 83.9%. The normalized value of energy production is 4.24 kWh/kWp/day.

From economic point of view, despite that levelised cost of energy from the simulated project of 486Ariary/kWh, is a bit higher than the fixed feed in tariff cost of 450Ariary/kWh, the project still ensures a good profitability for the investor since the project simple payback period is 11 years which is less than the project life span. At the end of the project, the investor will earn a cumulative balance of 164,767,000 Ariary which makes the feasibility of this project unignorable.

From the environmental point of view, the project stands the chance of saving about 555.2 tons of CO_2 over entire life span of the project which would have been emitted by a crude oil-fired thermal power plant generating the same amount of electricity that is a significant figure of mitigation of GHG emissions. It is obvious that PV system as a future candidate is an effective tool to replace the conventional power generation and capable to combat climate change. This project will promote clean and contribute to the reduction of pollutant emission released to the environment.

Overall, the investigation confirms that the planned SPV system at the proposed site will provide the operational benefits with good profitability to the installer or owner. All the invested money was gained within 11 years of running of plant successfully. Furthermore, the proposed SPV plant will be an ideal opportunity to support current Madagascar Government' s target of granting access to electricity to up to 70% of households, and at covering 85% of its energy mix with renewables by 2030.

5.2 PERSPECTIVES

The future scope of present research work is identified as:

- Study and simulate the project for seasonal tilt orientation and find the variation in energy output and change in cost of generation.
- Also, the project can be studied and implemented using the sun tracking systems and compute the change in energy production, add the additional costs of the sun tracking systems and finally calculate the new cost of generation.
- Try to execute the calculation methodology developed with other PV panels, inverters, with different tracking system or located in another site, and examine if the results are in accordance with the results previously obtained.
- As this is a feasibility study, more detailed information regarding the dimensioning for the mounting structure and an analysis of the ground soiling type is needed before constructing the system.
- And finally, further research is to be done to validate the accurateness and predictability of the software with field data.

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Appendix 1: Component specifications

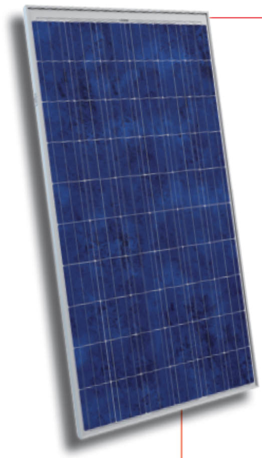
Suntech STP 240-20/Wd

STP240 - 20/Wd
STP235 - 20/Wd
STP230 - 20/Wd

SUNTECH

240 watts

MODULE SOLAIRE POLYCRISTALLIN



Caractéristiques

Module à haut rendement de conversion (14.8%)
Rendement du module jusqu'à 14,8% grâce à une technologie de cellule et à des capacités de fabrication de pointe

Excellente performance par faible luminosité (Weak light)
Excellente performance dans des conditions de faible luminosité

Tolérance positive (0/+5%)
Plus grande fiabilité des puissances de sortie grâce à la tolérance positive pouvant atteindre 5 %

Processus de tri du courant Suntech (2%)
Puissance de sortie du système optimisée en réduisant jusqu'à 2 % les pertes liées à la disparité du courant avec les modules triés et conditionnés par classe de courant

Résiste à une pression de vent et à une charge de neige élevées (3800Pa 5400Pa)
Le module est certifié résistant à un vent (3 800 pascals) et à des charges de neige (5 400 pascals) extrêmes *

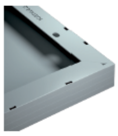
Résistance à un environnement rude (Harsh environment)
Qualité et fiabilité signifient une meilleure durabilité même dans des environnements rudes comme les déserts, les fermes et les zones côtières

Certifications et standards :
IEC 61215, IEC 61730, conformité CE

IEC CE PV CYCLE**

Faites confiance à Suntech pour fournir une performance fiable dans le temps

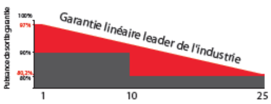
- Fabricant de 1er rang de modules photovoltaïques en silicium cristallin
- Une capacité de production inégalée et une technologie de pointe
- Un contrôle de qualité rigoureux satisfaisant aux normes internationales les plus sévères : ISO 9001: 2008, ISO 14001: 2004 et ISO 17025: 2005
- Contrôle régulier du processus de production par un institut international / une société internationale accrédité(e)
- Testé pour des environnements rudes (tests de corrosion au brouillard salin, à l'ammoniac et au sable : IEC 61701, DIN 50916:1985 T2, DIN EN 60068-2-68)***



Conception compacte et durable du cadre

Le cadre compact nouvellement conçu par Suntech est léger et plus facile à manier pendant l'installation. Le profilé creux, rigide et solide garantit la même performance fiable à long terme.

Garantie leader de l'industrie basée sur la puissance nominale



- 97 % la première année puis, de la deuxième (2) à la vingt-cinquième (25) année, 0,7 % maximum de réduction de la puissance de sortie nominale du MODULE par an, pour arriver à 80,2 % la 25ème année suivant la DATE DE DÉBUT DE LA GARANTIE.****
- 10 ans de garantie matériel couvrant les vices cachés

Boîte de jonction de classe IP67

IP67

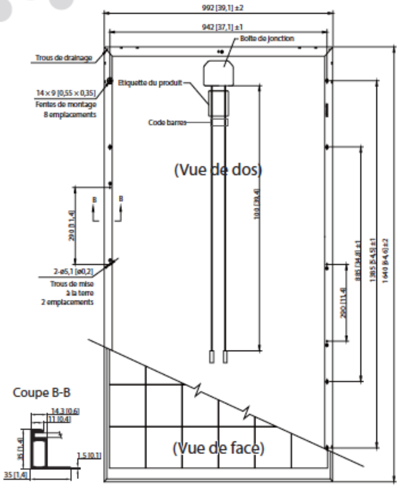
Peut être installée dans plusieurs positions. Des connecteurs très fiables à faible résistance assurent une puissance de sortie maximum, pour une production d'énergie la plus élevée possible.

* Pour plus de détails, veuillez vous reporter au Manuel d'installation du module standard Suntech. **PV Cycle uniquement pour le marché de l'UE.
*** Pour plus de détails, veuillez vous reporter à « Suntech Product Near-coast Installation Manual ». **** Pour plus de détails, veuillez vous reporter à la Garantie de produit Suntech.

www.suntech-power.com IEC-STD-Wd-NO1.01-Rév 2013

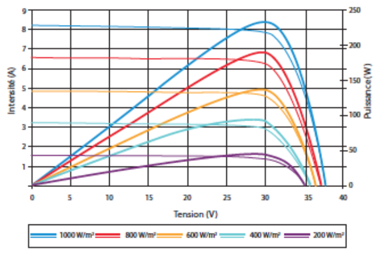
STP240 - 20/Wd
STP235 - 20/Wd
STP230 - 20/Wd

SUNTECH



Note : mm [pouces]

Courbes intensité-tension et puissance-tension (230-20)



Excellente performance dans les environnements à faible luminosité : à une intensité d'éclairement énergétique de 200 W/m² (AM 1,5, 25 °C), 95,5 % ou plus de l'efficacité STC (1 000 W/m²) sont atteints

Cadre réservé au revendeur

Caractéristiques électriques

Conditions de tests standard (STC)	STP240-20/Wd	STP235-20/Wd	STP230-20/Wd
Puissance maximale en conditions de tests standard (STC) (Pmax)	240 W	235 W	230 W
Tension de fonctionnement optimale (Vmp)	30,2 V	30,2 V	29,8 V
Intensité de fonctionnement optimale (Imp)	7,95 A	7,79 A	7,72 A
Tension en circuit ouvert (Voc)	37,2 V	37,0 V	36,8 V
Intensité de court-circuit (Isc)	8,43 A	8,35 A	8,25 A
Rendement du module	14,8 %	14,4 %	14,1 %
Température de fonctionnement du module	-40 °C à +85 °C		
Tension maximale du système	1 000 V CC (IEC)		
Calibre unitaire des fusibles en série/courant inverse	20 A		
Tolérance de puissance	0/+5 %		

Conditions de tests standard (STC) : éclairement énergétique 1 000 W/m², température du module 25 °C, AM = 1,5 ;
Meilleurs résultats dans un simulateur solaire de classe AAA (IEC 60904-9) utilisé, l'incertitude de mesure de puissance étant de +/- 3 %

NOCT	STP240 - 20/Wd	STP235-20/Wd	STP230-20/Wd
Puissance maximale à la température de fonctionnement nominale de la cellule (NOCT) (Pmax)	178 W	173 W	169 W
Tension de fonctionnement optimale (Vmp)	27,6 V	27,4 V	27,1 V
Intensité de fonctionnement optimale (Imp)	6,44 A	6,30 A	6,22 A
Tension en circuit ouvert (Voc)	34,1 V	34,0 V	33,9 V
Intensité de court-circuit (Isc)	6,86 A	6,83 A	6,69 A

NOCT : éclairement énergétique 800 W/m², température ambiante 20 °C, AM = 1,5, vitesse du vent 1 m/s ;
Meilleurs résultats dans un simulateur solaire de classe AAA (IEC 60904-9) utilisé, l'incertitude de mesure de puissance étant de +/- 3 %

Caractéristiques de température

Température de fonctionnement nominale de la cellule (**NOCT**)	45 ±2 °C
Coefficient de température de Pmax	-0,43 %/°C
Coefficient de température de Voc	-0,33 %/°C
Coefficient de température d'Isc	0,067 %/°C

Caractéristiques mécaniques

Cellule solaire	Silicium polycristallin 156 x 156 mm (6 pouces)
Nombre de cellules	60 (6 x 10)
Dimensions	1640 x 992 x 35 mm (64,6 x 39,1 x 1,4 pouces)
Poids	18,2 kg (40,1 lbs.)
Verre face avant	Verre trempé de 3,2 mm (0,13 pouces)
Châssis	Alliage d'aluminium anodisé
Boîte de jonction	Classe IP67 (3 diodes de bypass)
Câbles de sortie	TÜV (2Pfg1169:2007) 4,0 mm² (0,006 pouces²), longueurs symétriques (-) 1 000 mm (39,4 pouces) et (+) 1 000 mm (39,4 pouces)
Connecteurs	Connecteurs MC4

Configuration de l'emballage

Conteneur	20' GP	40' HC
Unités par palette	30	30
Palettes par conteneur	6	28
Unités par conteneur	180	840

Les informations concernant la manière d'installer et de faire fonctionner ce produit sont fournies dans les instructions d'installation. Toutes les valeurs indiquées dans cette fiche technique peuvent être modifiées sans préavis. Les spécifications peuvent varier légèrement. Toutes les spécifications sont conformes à la norme EN 50380. Des différences de couleur des modules par rapport aux illustrations ainsi que des décolorations des/dans les modules n'altérant pas leur bon fonctionnement sont possibles et ne constituent pas un écart par rapport à la spécification.

Courriel : sales@suntech-power.com

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SMA, Sunny tripower 20000TLEE-JP

SMA

SUNNY TRIPOWER 20000TLEE-JP

STP 20000TLEE-JP-11

Efficient
- Efficiency of 97.5% (as per JIS C 8962)
- Peak efficiency of 98.5%
- Excellent price-performance ratio

Safe
- Maximum robustness and best level of protection thanks to degree of protection IP65 (outdoor)
- Integrated display showing energy yield values and daily power generation trend

Innovative
- Operating temperature range from −25 °C to +60 °C through active OptiCool temperature management
- Straightforward system visualization and monitoring thanks to Webconnect and Sunny Portal

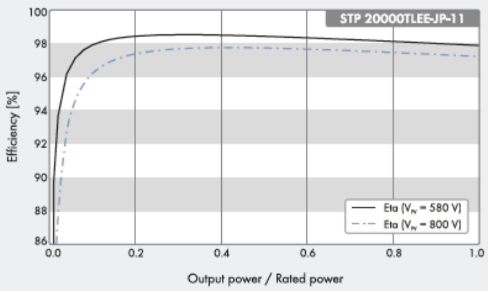
Convenient
- Efficient remote monitoring and maintenance via SMA Cluster Controller and Sunny Portal for medium-sized and large-scale systems

SUNNY TRIPOWER 20000TLEE-JP

The high-performance solution for medium-voltage applications

The Sunny Tripower 20000TLEE-JP was specifically developed for use in larger, decentralized PV systems in Japan. Its robust outdoor enclosure meets the strict specifications of the IP65 device classification and offers exceptionally solid protection from dirt, water and salt-containing atmospheres. The three-phase inverter enables new design dimensions for large-scale PV power plants through maximum efficiency of 98.5 percent and an expanded input voltage range of up to 1000 V. The optional SMA Cluster Controller enables efficient system monitoring with Sunny Portal and allows personalized parameterization of systems using Modbus.

Efficiency Curve



Accessory

Blue or white cover

SMA Power Control Module
PWCMOD-10

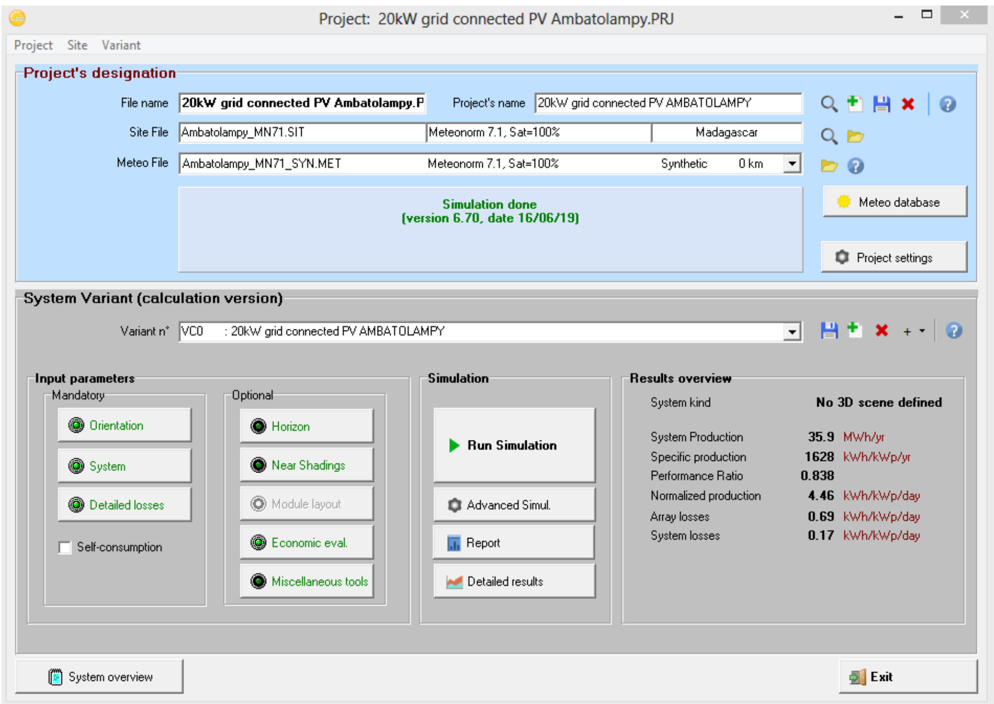
Multifunction relay
MFR01-10

	Sunny Tripower 20000TLEE-JP
Input (DC)	
Max. DC power (at cos φ = 1)	20450 W
Max. input voltage	1000 V
MPP voltage range at grid voltage (400 V) / rated input voltage	580 V to 800 V / 580 V
Min. input voltage / initial input voltage	570 V / 610 V
Max. input current	36 A
Max. input current per string	36 A
Number of independent MPP inputs / strings per MPP input	1 / 6
Output (AC)	
Rated power (at 400 V, 50 Hz)	20000 W
Max. apparent AC power	20000 VA
Nominal AC voltage	3/PE, 400 V
AC voltage range	320 V to 480 V
AC power frequency / range	50 Hz, 60 Hz / ± 2%
Rated power frequency / rated grid voltage	50 Hz / 400 V
Max. output current	29 A
Power factor at rated power	1
Adjustable displacement power factor	0.8 overexcited to 0.8 underexcited
Feed-in phases / connection phases	3 / 3
Efficiency	
Max. efficiency / efficiency as per JIS C 8962	98.5% / 97.5%
Protective devices	
DC-side disconnection point	●
Ground fault monitoring / grid monitoring	● / ●
DC reverse polarity protection / AC short-circuit current capability / galvanically isolated	● / ● / –
All-pole sensitive residual-current monitoring unit	●
Protection class (as per IEC 61140) / overvoltage category (as per IEC 60664-1)	I / AC: III; DC: II
General Data	
Dimensions (W / H / D)	665 / 680 / 265 mm (26.2 / 26.8 / 10.4 inch)
Weight	45 kg (99.2 lb)
Operating temperature range	−25 °C to +60 °C (−13 °F to +140 °F)
Noise emission, typical	51 dB(A)
Self-consumption (at night)	1 W
Topology / cooling concept	Transformerless / OptiCool
Degree of protection (as per IEC 60529)	IP65
Climatic category (as per IEC 60721-3-4)	4K4H
Max. permissible value for relative humidity (non-condensing)	100%
Features	
DC connection	Connecting terminal plate
AC connection	Spring-cage terminal
Display	LC graphic display
Interfaces: Speedwire / Webconnect	●
Multifunction relay / Power Control Module	○/○
Warranty: 5 / 10 / 15 / 20 years	●/○/○/○
● Standard features ○ Optional features — Not available, data at nominal conditions	
Type designation	STP 20000TLEE-JP-11

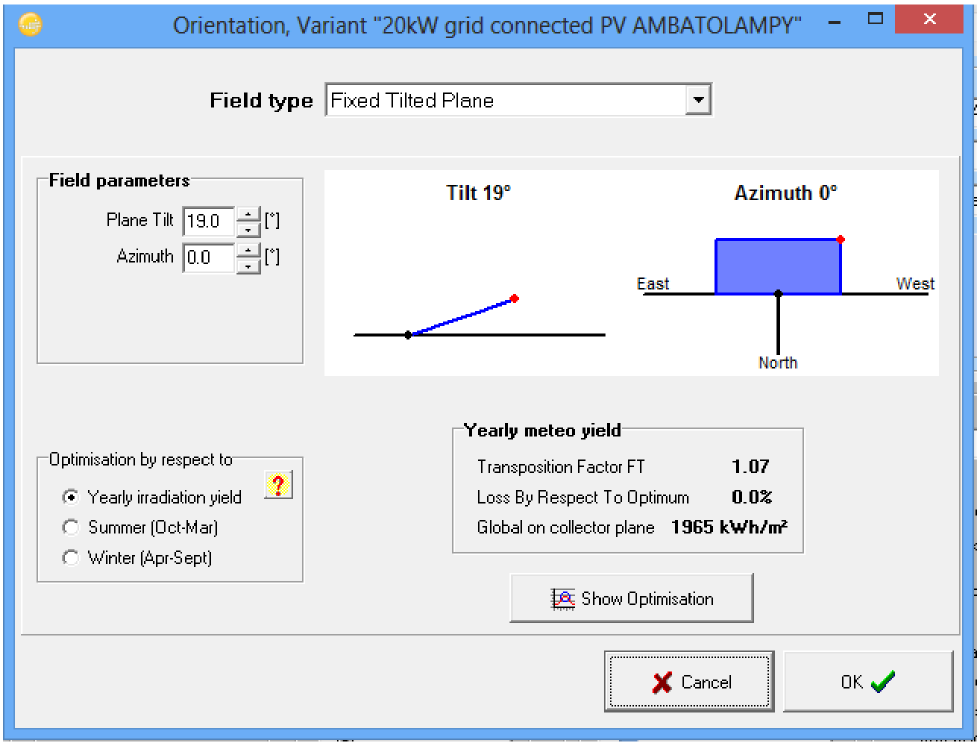
<u>Appendix 2</u>: PVsyst design steps

1-Defining the project

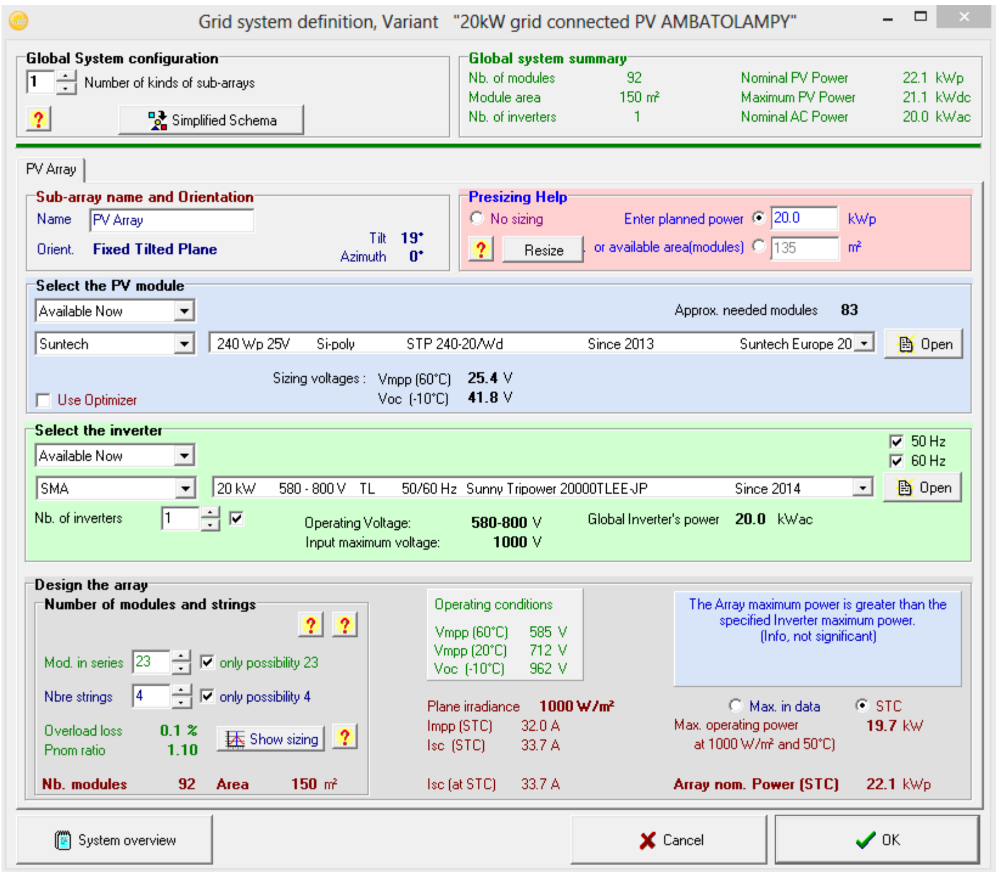
2-Upload the site coordinates and its meteorological data



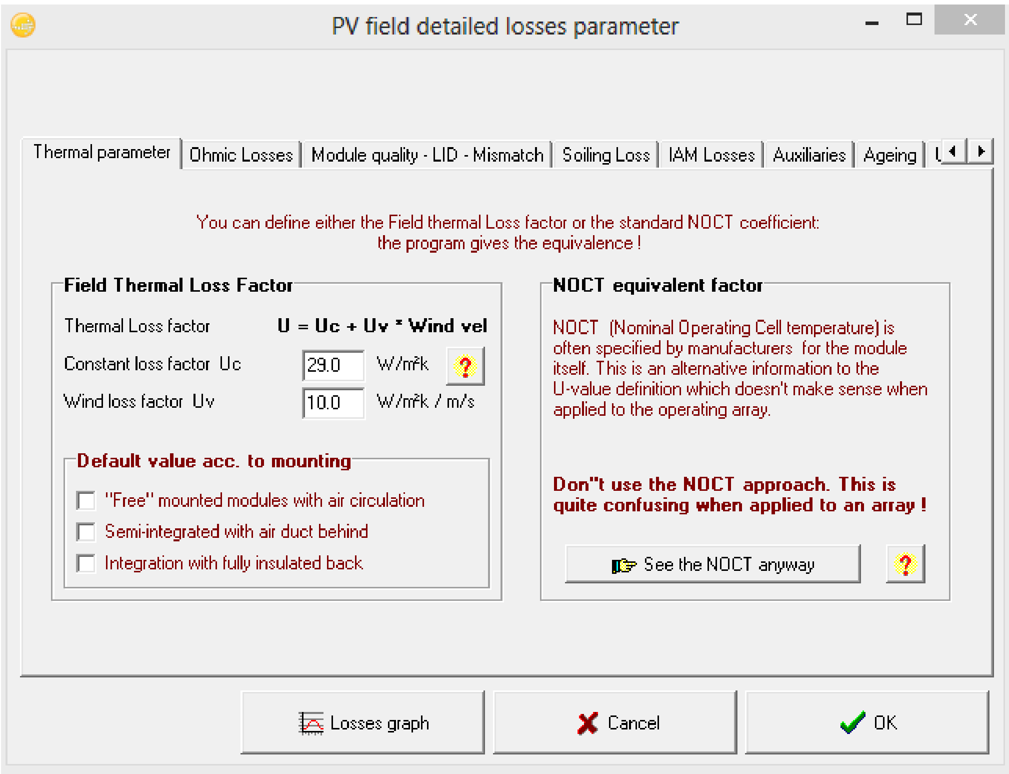
3-Define the orientation



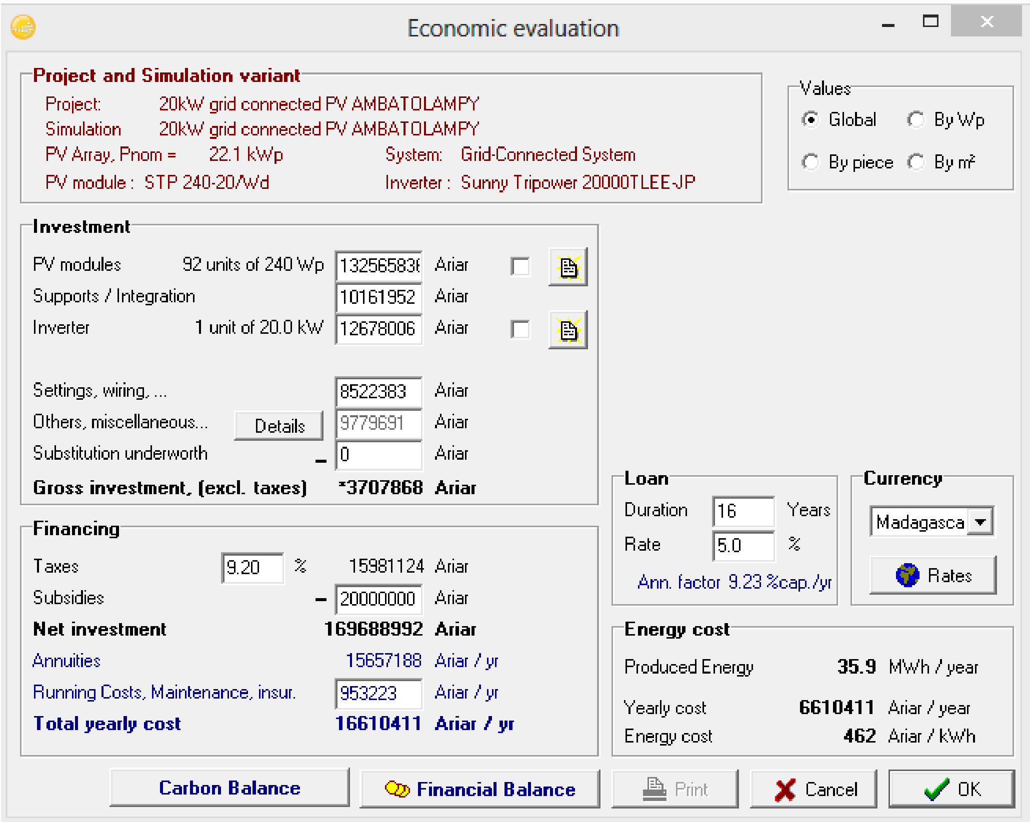
4-Define the system



5- Detailed Losses



6- Economical Evaluation



Appendix 3: PVsyst pdf report

PVSYST V6.70		16/06/19	Page 1/6

Grid-Connected System: Simulation parameters

Project :	**20kW grid connected PV AMBATOLAMPY**			
Geographical Site	**Ambatolampy**		Country	**Madagascar**
Situation	Latitude	-19.38° S	Longitude	47.43° E
Time defined as	Legal Time	Time zone UT+3	Altitude	0 m
	Albedo	0.20		
Meteo data:	**Ambatolampy**	Meteonorm 7.1, Sat=100% - Synthetic		

Simulation variant :	**20kW grid connected PV AMBATOLAMPY**			
	Simulation date	16/06/19 21h02		
	Simulation for the	**10th year of operation**		

Simulation parameters	System type	**No 3D scene defined**		
Collector Plane Orientation	Tilt	19°	Azimuth	0°
Models used	Transposition	Perez	Diffuse	Perez, Meteonorm
Horizon	Free Horizon			
Near Shadings	No Shadings			
PV Array Characteristics				
PV module Si-poly	Model	**STP 240-20/Wd**		
Custom parameters definition	Manufacturer	Suntech		
Number of PV modules	In series	23 modules	In parallel	4 strings
Total number of PV modules	Nb. modules	92	Unit Nom. Power	240 Wp
Array global power	Nominal (STC)	**22.08 kWp**	At operating cond.	19.71 kWp (50°C)
Array operating characteristics (50°C)	U mpp	617 V	I mpp	32 A
Total area	Module area	**150 m²**	Cell area	134 m²
Inverter	Model	**Sunny Tripower 20000TLEE-JP**		
Custom parameters definition	Manufacturer	SMA		
Characteristics	Operating Voltage	580-800 V	Unit Nom. Power	20.0 kWac
Inverter pack	Nb. of inverters	1 units	Total Power	20 kWac
			Pnom ratio	1.10
PV Array loss factors				
Array Soiling Losses			Loss Fraction	3.0 %
Thermal Loss factor	Uc (const)	29.0 W/m²K	Uv (wind)	10.0 W/m²K / m/s
Wiring Ohmic Loss	Global array res.	330 mOhm	Loss Fraction	1.5 % at STC
Module Quality Loss			Loss Fraction	-1.3 %
Module Mismatch Losses			Loss Fraction	2.0 % at MPP
Strings Mismatch loss			Loss Fraction	0.10 %
Module average degradation	Year no	10	Loss factor	0.4 %/year
Mismatch due to degradation	Imp RMS dispersion	0.4 %/year	Vmp RMS dispersion	0.4 %/year
Incidence effect, ASHRAE parametrization	IAM =	1 - bo (1/cos i - 1)	bo Param.	0.05
Unavailability of the system	7.3 days, 3 periods		Time fraction	2.0 %
User's needs :	Unlimited load (grid)			

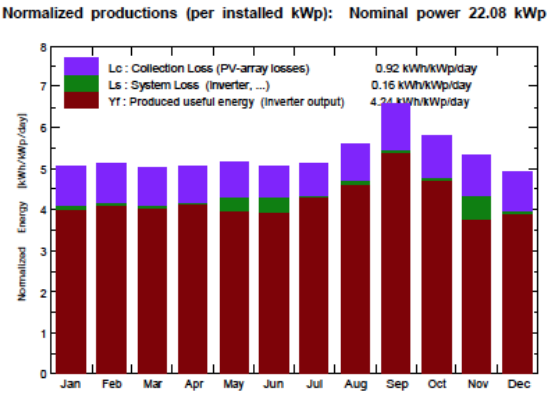
Grid-Connected System: Main results

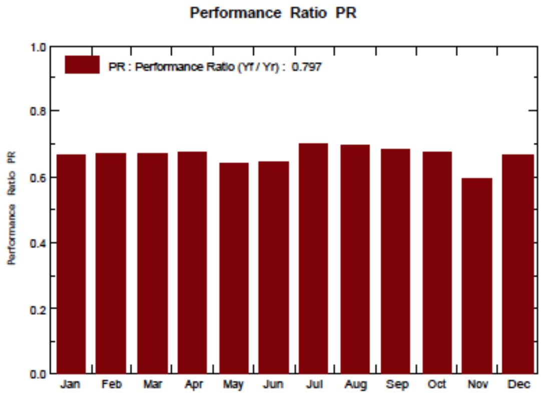
Project : **20kW grid connected PV AMBATOLAMPY**

Simulation variant : **20kW grid connected PV AMBATOLAMPY**
Simulation for the 10th year of operation

Main system parameters	System type	**Grid-Connected**		
PV Field Orientation	tilt	19°	azimuth	0°
PV modules	Model	STP 240-20/Wd	Pnom	240 Wp
PV Array	Nb. of modules	92	Pnom total	**22.08 kWp**
Inverter	Model	Sunny Tripower 20000TLEE-JP		20.00 kW ac
User's needs	Unlimited load (grid)			

Main simulation results				
System Production	**Produced Energy**	**34.20 MWh/year**	Specific prod.	1549 kWh/kWp/year
	Performance Ratio PR	79.74 %		
Investment	Global incl. taxes	169688992 Ariar	Specific	7685 Ariar/Wp
Yearly cost	Annuities (Loan 5.0%, 16 years)	15657188 Ariar/yr	Running Costs	953223 Ariar/yr
Energy cost		**486 Ariar/kWh**		





20kW grid connected PV AMBATOLAMPY
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	167.4	91.05	26.87	157.0	146.7	2.808	2.761	0.797
February	147.1	82.14	26.41	143.0	133.8	2.574	2.531	0.802
March	151.8	79.20	25.79	156.1	146.5	2.814	2.768	0.803
April	139.0	67.61	24.23	152.7	143.9	2.779	2.733	0.811
May	133.2	48.31	22.75	160.2	151.1	2.947	2.714	0.767
June	121.7	41.53	20.08	152.6	143.9	2.854	2.601	0.772
July	128.0	39.31	19.35	158.4	149.6	2.982	2.934	0.839
August	150.3	55.55	20.24	173.3	163.7	3.230	3.178	0.831
September	182.8	54.90	21.51	197.3	186.6	3.627	3.569	0.819
October	180.0	86.39	23.75	179.9	169.1	3.271	3.218	0.810
November	168.4	90.14	25.15	159.2	149.1	2.871	2.508	0.713
December	165.7	94.64	26.64	152.6	142.4	2.726	2.680	0.795
Year	1835.3	830.76	23.55	1942.3	1826.4	35.483	34.196	0.797

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

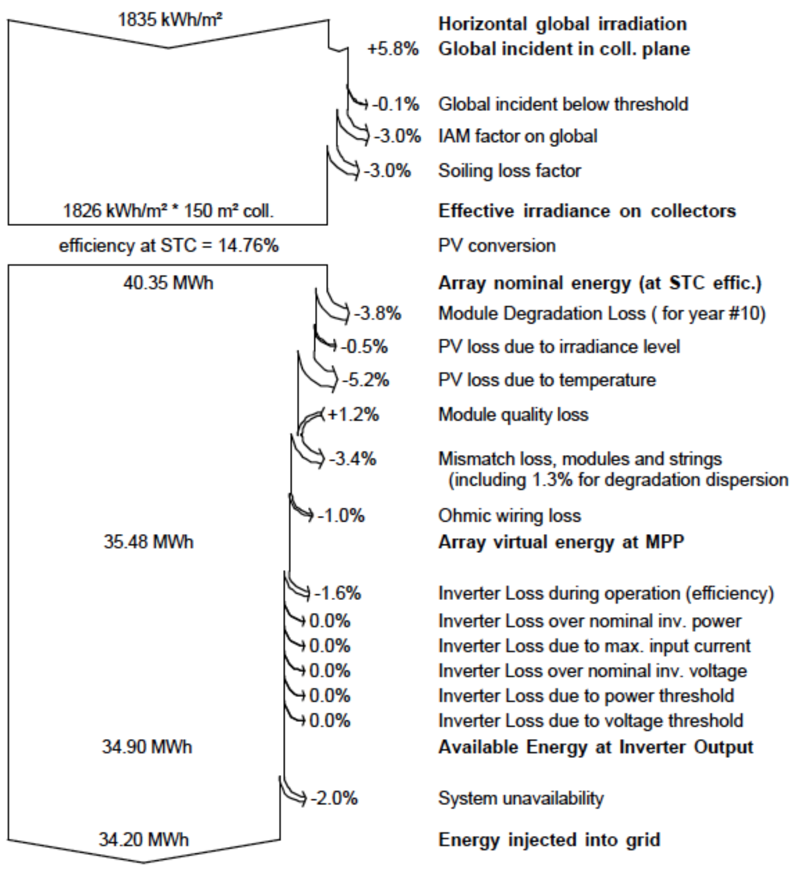
Project : **20kW grid connected PV AMBATOLAMPY**

Simulation variant : **20kW grid connected PV AMBATOLAMPY**

Simulation for the 10th year of operation

Main system parameters	System type	**Grid-Connected**		
PV Field Orientation	tilt	19°	azimuth	0°
PV modules	Model	STP 240-20/Wd	Pnom	240 Wp
PV Array	Nb. of modules	92	Pnom total	**22.08 kWp**
Inverter	Model	Sunny Tripower 20000TLEE-JP		20.00 kW ac
User's needs	Unlimited load (grid)			

Loss diagram over the whole year



Grid-Connected System: Economic evaluation

Project : **20kW grid connected PV AMBATOLAMPY**

Simulation variant : **20kW grid connected PV AMBATOLAMPY**
Simulation for the 10th year of operation

Main system parameters	System type	**Grid-Connected**		
PV Field Orientation	tilt	19°	azimuth	0°
PV modules	Model	STP 240-20/Wd	Pnom	240 Wp
PV Array	Nb. of modules	92	Pnom total	**22.08 kWp**
Inverter	Model	Sunny Tripower 20000TLEE-JP		20.00 kW ac
User's needs	Unlimited load (grid)			

Investment

PV modules (Pnom = 240 Wp)	92 units	1440933 Ariar / unit	132565836 Ariar
Supports / Integration		110456 Ariar / module	10161952 Ariar
Inverter (Pnom = 20.0 kW ac)	1 units	12678006 Ariar / unit	12678006 Ariar
Settings, wiring, ...			8522383 Ariar
Electrical installation			5744705 Ariar
Project management			2346280 Ariar
Commissioning			189390 Ariar
Transport and assembly			1067933 Ariar
Engineering			431383 Ariar
Substitution underworth			0 Ariar
Gross investment (without taxes)			**173707868 Ariar**

Financing

Gross investment (without taxes)		173707868 Ariar
Taxes on investment (VAT)	Rate 9.2 %	15981124 Ariar
Gross investment (including VAT)		189688992 Ariar
Subsidies		-20000000 Ariar
Net investment (all taxes included)		**169688992 Ariar**
Annuities	(Loan 5.0 % over 16 years)	15657188 Ariar/year
Annual running costs: maintenance, insurances ...		953223 Ariar/year
Total yearly cost		**16610411 Ariar/year**

Energy cost

Produced Energy	34.2 MWh / year
Cost of produced energy	486 Ariar / kWh

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Grid-Connected System: Long Term Financial Balance

Project : **20kW grid connected PV AMBATOLAMPY**

Simulation variant : **20kW grid connected PV AMBATOLAMPY**

Simulation for the 10th year of operation

Main system parameters	System type	**Grid-Connected**		
PV Field Orientation	tilt	19°	azimuth	0°
PV modules	Model	STP 240-20/Wd	Pnom	240 Wp
PV Array	Nb. of modules	92	Pnom total	**22.08 kWp**
Inverter	Model	Sunny Tripower 20000TLEE-JP		20.00 kW ac
User's needs	Unlimited load (grid)			

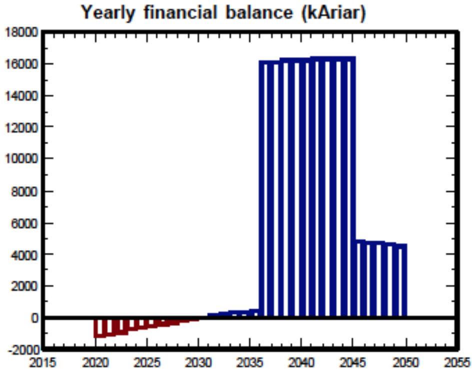
Electricity sale

Feed-in Tariff	**450.00 Ariar/kWh**	Warranty over	**25 years**
Annual connexion tax	0 Ariar		

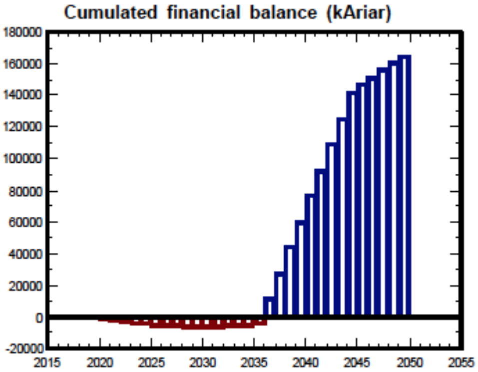
Long term balance and Running conditions

Annual sale tariff depreciation	2.0 % / year
Annual production reduction	-1.0 % / year
Feed-in tariff Warranty over	25 years
Tariff reduction after contractual warranty	**-50** %
Loan duration (payment of annuities)	16 years

Yearly financial balance (kAriar)



Cumulated financial balance (kAriar)



Long term economic balance

Year	Loan 5.0 %	Running costs	Sold energy	Yearly Balance	Cumul. Balance
2020	15657	953	15388	-1222	-1222
2021	15657	953	15539	-1071	-2293
2022	15657	953	15684	-927	-3220
2023	15657	953	15822	-788	-4008
2024	15657	953	15955	-656	-4663
2025	15657	953	16081	-530	-5193
2026	15657	953	16201	-409	-5602
2027	15657	953	16315	-296	-5898
2028	15657	953	16423	-188	-6086
2029	15657	953	16524	-86	-6172
2030	15657	953	16619	9	-6163
2031	15657	953	16709	98	-6065
2032	15657	953	16792	181	-5883
2033	15657	953	16869	258	-5625
2034	15657	953	16940	329	-5296
2035	15657	953	17004	394	-4902
2036	0	953	17063	16109	11207
2037	0	953	17115	16162	27369
2038	0	953	17161	16208	43577
2039	0	953	17201	16248	59825
2040	0	953	17235	16282	76107
2041	0	953	17263	16310	92416
2042	0	953	17284	16331	108747
2043	0	953	17300	16346	125094
2044	0	953	17309	16356	141449
2045	0	953	5771	4817	146267
2046	0	953	5694	4740	151007
2047	0	953	5617	4664	155671
2048	0	953	5540	4587	160258
2049	0	953	5463	4510	164767

Grid-Connected System: CO2 Balance

Project : **20kW grid connected PV AMBATOLAMPY**

Simulation variant : **20kW grid connected PV AMBATOLAMPY**
Simulation for the 10th year of operation

Main system parameters	System type	**Grid-Connected**		
PV Field Orientation	tilt	19°	azimuth	0°
PV modules	Model	STP 240-20/Wd	Pnom	240 Wp
PV Array	Nb. of modules	92	Pnom total	**22.08 kWp**
Inverter	Model	Sunny Tripower 20000TLEE-JP		20.00 kW ac
User's needs	Unlimited load (grid)			

Produced Emissions	**Total:**	**25.27 tCO2**		
	Source:	Detailed calculation from table below		
Replaced Emissions	**Total:**	**653.2 tCO2**		
	System production:	34.20 MWh/yr	Lifetime:	25 years
			Annual Degradation:	1.0 %
	Grid Lifecycle Emissions:	764 gCO2/kWh		
	Source:	Custom value supplied by User		
CO2 Emission Balance	**Total:**	**555.2 tCO2**		

System Lifecycle Emissions Details:

Item	Modules	Supports
LCE	1015 kgCO2/kWp	3.12 kgCO2/kg
Quantity	22.1 kWp	920 kg
Subtotal [kgCO2]	22403	2872