UNIVERSITY of RWANDA College of Science and Technology ACE-ESD AFRICAN CENTER OF EXCELLENCE IN ENERGY FOR SUSTAINABLE DEVELOPMENT

INTEGRATION OF THE SOLAR PV POWER PLANT INTO THE GRID: CASE OF MATEBE POWER PLANT IN GOMA/DRC

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DECLARATION

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

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ABSTRACT

Energy access has become a great issue for humanity. The world population is growing much faster, this implies the increase in need of energy. Electrical energy is one of the indispensable energies for the human being. In DRC, electricity represents only 2% of the energy consumed while biomass takes a great percentage. It was found according to data collection that the total power demand of Mugunga area is around 10.9 MW. To solve this issue, the use of renewable energies for generating electricity is mostly solicited. In this thesis, a large 12 MW grid-connected solar photovoltaic system was designed. This last was also found after collecting the Mugunga quarter data related to its electrical loads which were subdivided according to the activity type. Since there was no census done in the 4 past years, some estimated values were used in the calculations.

To conduct this research, the methodology consisted of site selection, which was analyzed and studied. We also defined a suitable area for solar installation. The choice was made for Mugunga. As we don’t have its specific meteorological data due to the inexistence of weather forecast institution, the entire city of Goma was been considered. The system performance to model was calculated through the performance parameters as the specific yield, the capacity factor and the performance ratio. The results from calculations led to a total investment of 14564357 US Dollar. By calculating the AEP (Annual Energy Production) of the plant, which was 21670.98 MWh, the economic analysis showed its rentability. An interest of 12524368 US Dollar was found after calculating the LCC (Life Cycle Cost).

The simulation was made using the engineering software's PV syst and MATLAB. The results obtained were not so far from the one got from calculations. In calculation, we have found the specific yield and the performance ration at 1516 kWh/kWp and 85.3% respectively. The PVsyst software calculated these values at 1501 kWh/kWp and 84.3%. The PV is performant and can supply the electricity need for the Mugunga quarter in the city of Goma.

KEYWORDS: *Solar PV power plant, electricity grid, solar PV integration, hydroelectric power plant.*

LIST OF SYMBOLS AND ACRONYMS

AC	Alternating Current
DC	Direct Current
DRC	Democratic Republic of the Congo
EPS	Electric Power System
GW	Giga Watts
HMI	Human Machine Interface
HPP	Hydro Power Plant
IEEE	Institute of Electrical and Electronics Engineers
kVA	Kilovolts Amperes
kWh	kilowatt-hours
LCOE	Levelized Cost Of Energy
MPPT	Maximum Power Point Tracking
MW	Megawatts
PF	Power factor
PV	Photovoltaic
PV-DG	Photovoltaic distributed generation
SEGIS	Solar Energy Grid Integration Systems
SNEL	Société Nationale d’Electricité
THD	Total Harmonics Distorsion
UNDP	United Nations Development Program
W	Watt

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Chapter 1 : INTRODUCTION

4.1. BACKGROUND

Nowadays the living standard is increasing worldwide, this implies the increase in energy demand. Three types of energy crisis are nowadays challenges. The first crisis is that the world highly depends on fossil fuels by its exploitation for getting energy. This last is creating significant damages to the environment at almost every level from the production up to the use. The crisis that follows is the fact that humanity has already used half of the global oil reserves and deforested some big world areas. These practices are not sustainable. The third crisis is the biomass and fossil fuel are not sufficient to supply energy for everyone. A large human population is in lack of energy.[1]

The growth of the nation can be held back by the lack of sufficient energy supply. Future energy generations should be sustainable, secure, economic and acceptable at social planning. This means that the energy sources must be developed to be secure, sustainable and affordable.[2] One of the key factor to consider is the consumption of energy per capita for any country to be a developed nation. The maximum generation of energy depends on the needs of a country, and this need can only be fulfilled when everyone gets a sufficient amount of energy in the form of electricity, transport, agriculture, etc. To satisfy these requirements, today the world is mainly dependent on conventional resources such as coal, oil, natural gas, etc.[3]

Nowadays, as conventional sources are rapidly depleting, researches are made to find the solution for this issue. The price of energy is rising and therefore renewable energies are mostly solicited. Among them, solar energy is an abundant and pollution-free source. For many years, it was applied worldwide. The contribution of new technologies in the design, performant equipment construction and production from several manufacturers and the overall system performance; has led the availability of solar everywhere in the world. Also, the great possibilities to control and supervise solar systems improve its access rate. These factors ensure high security in production and generate incomes of the amount invested. Solar power is a business today due to it generates incomes and expenditures to the investment value and it requires minimum maintenance. Solar energy can supply the gap of energy needed; it is the largest regenerative energy source. Also, it can be estimated that the total annual sun radiation (3.9×10^{24} J $= 1.08 \times 10^{18}$ kWh) is ten thousand and more times the present annual global demand in energy.[4][5][6]

A distributed power generation system consists of many power plants that are connected to a utility grid and which produces energy depending on the site demand. This system reduces the need for centralized power generation and high-voltage transmission lines. This reduced, the cost of transmission and distribution also decreases. Nevertheless, some controls and appropriate adaptations are needed to the electricity system (generation power plants, transmission and distribution lines) is needed to supply electricity on-demand with a high share of renewable energies.[7]

The renewable energy sources such as photovoltaic offer greater supply security to consumers while respecting the environment and are a good solution to balance the energy demand and generation. However, they have a fluctuating and unpredictable character. For using photovoltaic energy effectively, a lot of research has been done on the grid-connected photovoltaic systems.[8]

An interconnected network to deliver electricity from electricity generation to its utilization is called ‘a grid’.[9] The principal configurations of PV generation are whether off-grid or grid-connected. Off-grid PV configurations are attractive and their application is usually used for remote areas, means areas that are far from distribution grid. However, the utilization of off-grid PV is high capital cost comparing to the grid-connected configuration, lower efficiency, brings the challenge of requiring larger storage battery capacity, and require more maintenance operations. These costs are high than grid-connected systems.[10]

A grid-connected PV system (or grid-tie) is composed of several materials which include solar modules, inverters, a power conditioning unit and grid connection equipment.[11] Improving the distributed generations from Renewables energies such PV solar power plant can increase the access rate of electrical energy and reduce the cost of electricity for the consumer. Solar generation is one of the available renewable energy resources in the DRC, especially in the city of Goma. It can be used to replace the conventional source of power while reducing the energy cost for consumers. Because of its intermittence behavior, its performance must be studied and analyzed to make it the energy for the future.

1.2. STATEMENT OF THE PROBLEM

In 2011, the DRC had 72.8 million inhabitants with an average population growth rate of around 3.5% / year, including 25.5 million city dwellers and 47.3 million rural people, all in relative decrease and absolute growth. The urban population is growing much faster, due to urbanization and the rural exodus, than the rural population. This demographic growth and especially the change in the distribution of the population between rural and urban will have a very big impact on the amount of needed energy and the structure of energy consumption.[12]

The city of Goma, located in the DRC, is facing a major problem of electricity supply. Even though the power lines of the Ruzizi and Matebe hydroelectric plants supply Goma, most people still lack electricity, even to light their homes. This situation is linked to the insufficient electrical power produced by the RUZIZI I hydropower station managed by SNEL[1] and others two private power stations recently installed: MATEBE Hydropower and NURU solar power plants. Given the size of the city of Goma, its population, its activities and especially the major problem of the inexistence of the nearest hydraulic resource, the city of Goma needs electrical energy from PV solar to ensure its electrical energy independence. The electrical energy needs for the city of Goma are around 50 MW, but it receives around 12 MW. Briefly, the lack of electrical energy in the city of Goma, especially in Mugunga area, is the problem that faces this dissertation.

Based on the problem statement, the dissertation will answer the following research questions:

- Shifting from fossil to renewable energy sources is it a sure way to mitigate climate change and energy sustainability issues?

- Regarding available generation sources of electrical energy in the city of Goma, is a solar PV power plant suited to respond to the high energy need of Mugunga area in the city of Goma?

- Designing a solar PV power plant can increase the access rate of Electricity in Mugunga area?

[1] SNEL « Société Nationale d'Electricité » is a public company which manages electricity in the DRC.

1.3. OBJECTIVES

1.3.1. Major Objective

The major objective of the present thesis is the design of a solar PV power plant interconnected to the existing network coming from the Matebe hydroelectric power station located in Rutshuru territory to supply Mugunga area in the city of Goma.

1.3.2. Specific Objectives

- Data collection to find the electricity demand in Mugunga area in the city of Goma,
- Design of the Solar PV system using PVSyst and MATLAB/SIMULINK software.
- Describe some of the challenges of the designed solar PV integration and mitigation solutions.

1.4. HYPOTHESIS

To achieve the above objectives, the following hypotheses were formulated:

- Using Renewables energy is nowadays the best way to keep safe the environment and this practice helps to reduce air pollution compared to conventional sources of electrical energy.

- As the city of Goma does not have the nearest river or hydroelectric resource, the choice is made of using Solar energy. It is the available source of electrical power since the sun is available and the city of Goma is located in the region with medium insolation level in the Democratic Republic of Congo.

- As the low electricity access rate paralyzes many activities in the city of Goma, a power plant that meets the demand of electricity in Mugunga area integrated into the Matebe hydroelectric network can improve social development and reduce unemployment.

1.5. OUTLINES OF THE THESIS

Chapter one is the introduction. The research questions and some related hypothesis were formulated.

Chapter two describes the literature review. It handles firstly basic principles of solar energy, electrical grid and the solar PV integration into the electricity grid and some related challenges. Secondly, some works done in the past related to the Solar PV grid-connected are involved.

Chapter three discusses the electrical energy situation in the DRC and especially in the city of Goma. Here the electricity demand of Mugunga area in the city of Goma is calculated to see how the amount of electrical power is needed to increase the electricity access rate of this area. This chapter discusses also the Virunga electrification projects. As this thesis focuses on solar PV integration into the grid, a general overview and descriptions of existing solar energy sources in the city of Goma are described.

Chapter four is concerning the modelling of the Solar PV power plant that will integrate the Matebe grid using calculations coming from the literature related to Solar PV System integration.

Chapter five is the simulation and results obtained of the project using the PV system (PVSyst) and MATLAB/SIMULINK engineering software. Also, a comparison is made between modelling and simulation results. This chapter concludes the thesis by giving some recommendations for future works.

Chapter 2 : LITERATURE REVIEW

This part consists of several points related to solar PV power plant integration into the grid. These points are solar PV technologies, Grid-connected PV Systems, grid integration into the electricity grid, challenges of a solar PV grid-connected, mitigation solutions and a review of past researches related to solar PV power plant integration into the grid. Every point is developed apart and gives essential information related.

2.1. SOLAR GENERATION TYPES

Solar generation can be classified into two types to be integrated into the grid:

- Concentrated Solar power (CSP)
- Photovoltaic (PV) power

The Concentrated Solar power is also called "solar thermal power generation". It is somehow identic to conventional thermal power generation in the way that it converts thermal energy (steam) into electrical energy. Nevertheless, PV solar modules are different from the solar thermal due to 'Photovoltaic effect' for generating electricity. Means that the suns light is used instead of the suns heat to produce electricity.

Thermal energy is not produced or stored by PV systems. These last generate directly the electricity which cannot be stored easily at large power plants. However, in the CSP generation, energy can be stored in the thermal form. This possibility to store energy has increased its penetration in the electric power industry and helped to solve the issue of solar PV intermittence. Due to this issue, CSP is attractive for large scale plants as its thermal energy storage technologies. Although this technology requires high investment in term of equipment, this limits its expansion. It also requires both steam and solar plant installation, which are expensive. The reduced cost of PV and even its energy market requirements are currently favouring the use of Photovoltaic installations.[13]

2.2. SOLAR PV TECHNOLOGIES

2.2.1. Introduction

In the recent past, an increase of curiosity for using renewables energies such as PV or wind energies has remarked. Their generation is accepted widely[14]. Among them, solar energy has been a subject for many kinds of research' areas, both for grid-tie and for stand-alone configurations. Its rapid growth rate is explained due to the increase in of modern grid-connected inverters topologies.[15]

2.2.2. Solar cell

It is defined as an electronic device that can converts directly sunlight into electrical energy. The voltage and current are both produced for generating electric power. Its principle is based on the absorption of sunlight. The light absorbed raises an electron from lower to a higher energy state and this allows the electron to move to the external circuit by generating a voltage across solar cells. This process is the PV effect. Some variety of materials are required to satisfy this photovoltaic conversion. As shown in Figure 2-1, a crystalline-based solar cell features a p-n junction. The manufacturing process includes the melting, doping, metallization and texturing processes. To produce high voltage and more power, PV cells are interconnected and laminated together because a single cell voltage is low than 1V. [16]

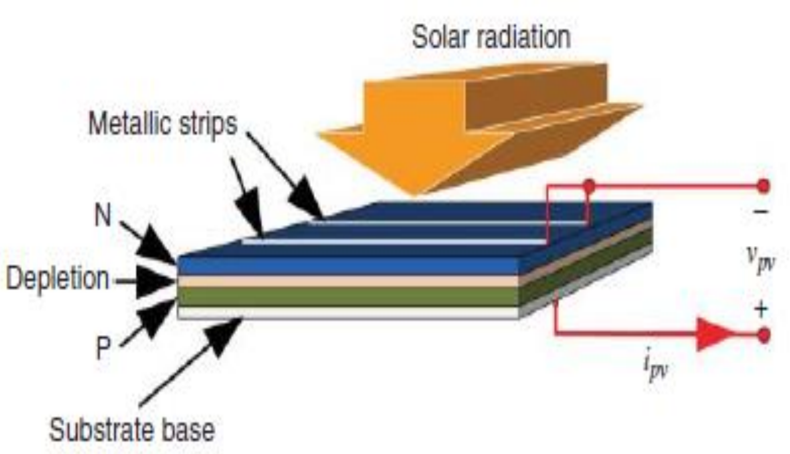


Figure 2-1:Typical PV cell constitution [17]

Nowadays, the manufacturers supply different models and sizes of solar modules (solar panels) that usually incorporate 48, 54, 60, or 72 cells. The cables and connectors are usually integrated with the module for interconnection and to facilitate the installation [17].

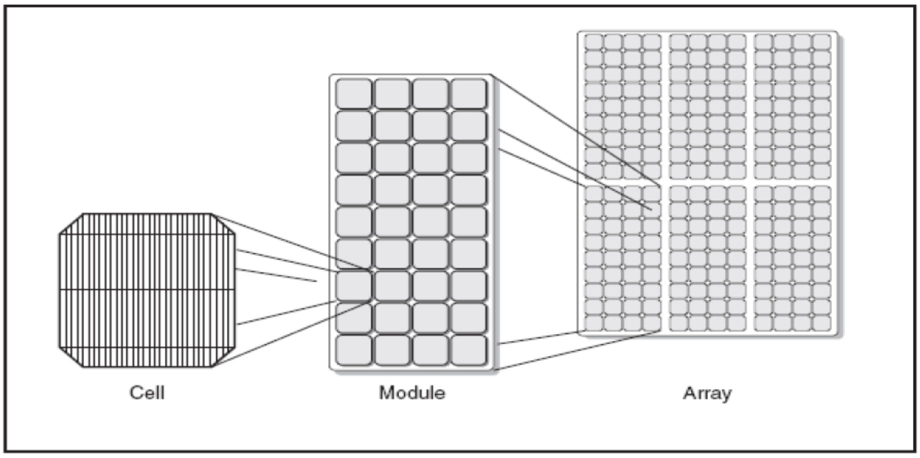


Figure 2-2:PV cell, PV module and PV array[18]

As illustrated in Figure 2-3; a PV panel is formed when PV cells are sandwiched. The superstrate and substrate play the role of protection for the device.

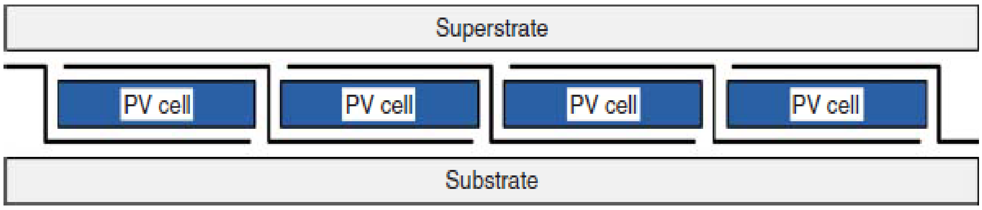


Figure 2-3:Lamination of PV module [17]

2.2.3. PV Efficiency and mathematical model

Many materials which absorb light and turn it into electricity can make the PV effect. Solar cells are manufactured for strong PV effect. However, efficiency is taken into consideration. If a solar cell efficiency is 15%, the electric output power of a 1 m^2 cell which receives 1000 W/m^2 irradiance at a temperature of 25°C; would be 150 W. The fundamental building block of Solar PV array is shown in Figure 2-4. It consists of a photodiode that generates DC current from the solar irradiance through the photovoltaic effect.[19]

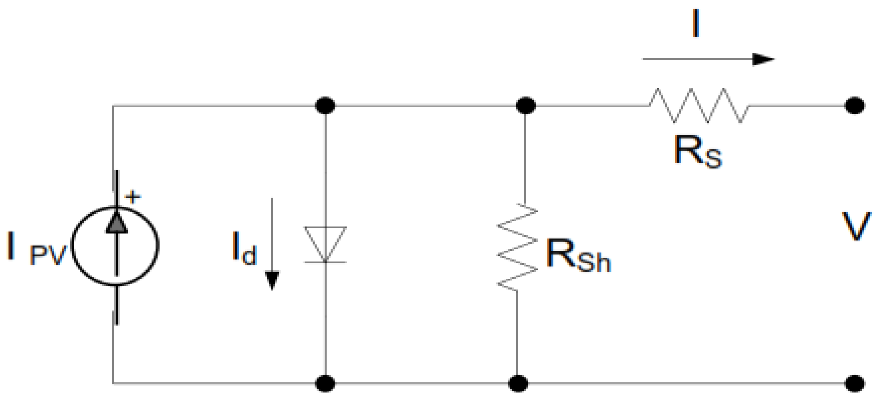


Figure 2-4:One diode equivalent circuit of Solar PV

The practical PV array is constituted by several solar cells. The I-V characteristics of a solar array, as shown in Figure 2-5, is expressed by Equation 2.1:

$$I = I_{PV} - I_O \left[exp\left(\frac{V + R_S I}{V_{therm} a}\right) - 1\right] - \frac{V + R_S I}{R_{sh}} \qquad (2.1)$$

Where I_{PV} and I_O are respectively the photo current and the diode saturation current, with

$$V_{therm} = N_S kT/q \qquad (2.2)$$

V_{therm} is the thermal voltage of the PV array, N_S the number of cells connected in series for greater output voltage, k is the Boltzmann constant ($1.3806503 * 10^{-23}$ J/K), T (Kelvin) is the temperature value, and q ($1.60217646 * 10^{-19}$ J/K) is the electron charge. Also, R_S and R_{sh} are the equivalent series and shunt resistances of the array, respectively, and a is the ideality factor which is usually chosen between 1 included up to 1.5 included.

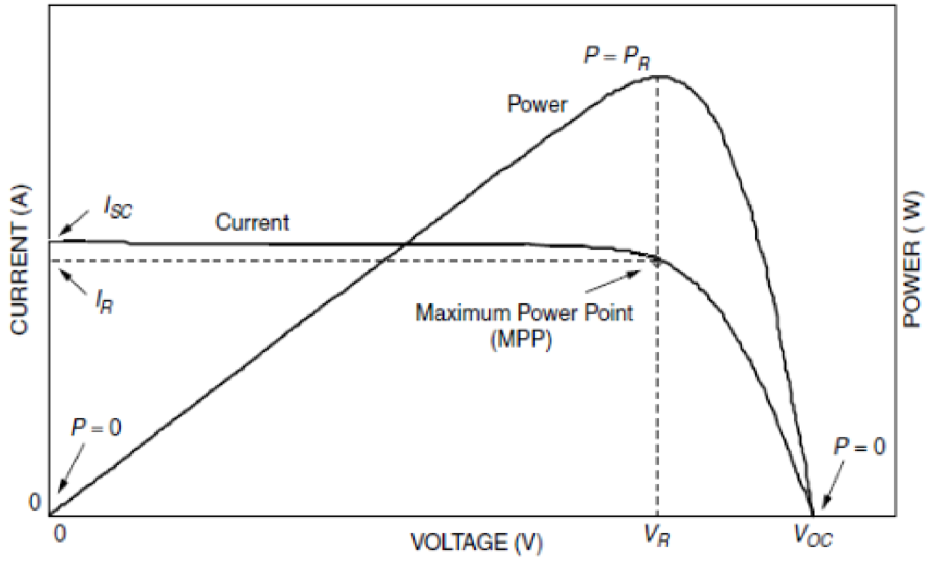


Figure 2-5:Solar PV characteristics

2.2.4. Solar PV technologies

New technologies are developed with the increase in solar system demand. PV cells can be classified into four types: monocrystalline, poly-crystalline, Thin film and Amorphous silicon. The two first types are also called single-crystalline and multi-crystalline silicon, respectively. The counterparts of crystalline silicon cells are thin-film cells. These types in Table 2-1. [17] [20]

- **Single-crystalline or monocrystalline cell:** It is widely applied and also it is the cell material with high efficiency than others. Each cell is cut from a single crystal.

- **Polycrystalline cells:** They are manufactured by the same silicon material than the single-crystalline buy here they are melted and poured into a mould.

- **Thin-film panels:** These consist of solar cell technology recently introduced. Here can be included the copper indium dieseline, cadmium telluride, and gallium arsenide. They are directly deposited on glass, stainless steel, or other compatible substrate materials. Under low light, some of them are performing slightly better than crystalline modules. A thin film is very thin-a few micrometers or less.

- **Amorphous Silicon:** Here vapour is deposited on a couple of micrometre thick amorphous films on stainless steel rolls. This technology uses about 1% of the material comparing to the crystalline silicon.

Table 2-1:Efficiency of different types of solar cells

Cell type	Efficiency [%]	Acronym
Mono-crystalline	12 to 18	Mono-c-Si
Multi-crystalline	12 to 18	Poly-c-Si
Thin film	8 to 10	TF-Si
Amorphous Silicon	6 to 8	a-Si

2.3. GRID CONNECTED PV SYSTEMS

2.3.1. The Electric power grid

Modern power systems are now complex interconnected networks (Figure 2-6). An electricity grid is composed of four main parts: The production, the transmission line, the distribution, and the loads.

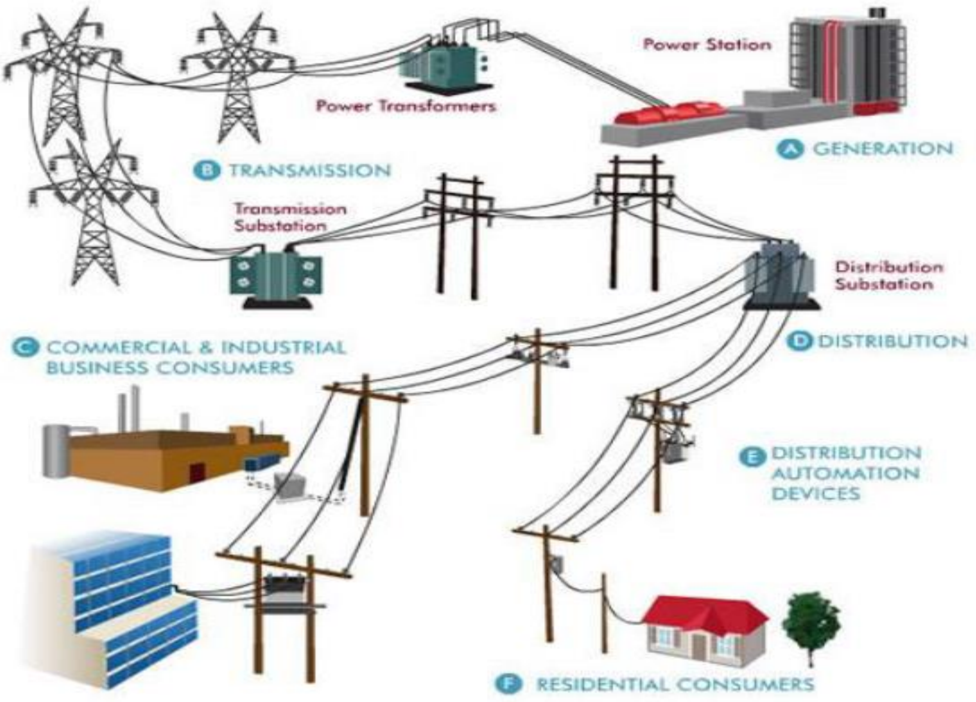


Figure 2-6:The electricity power grid [21]

Large generators are producing electricity. Then the overhead transmission network transfers that energy at various locations to the distribution network. Step down transformers are connecting the distribution network (medium to low voltage) to a high voltage transmission network. Several feeders are supplied by each transformer.

2.3.2. Distributed generation

Distributed generation (DG) consist of electric power generation that uses a set of small-sized generators. These are mainly designed to be connected directly to the distribution network near load centres. Figure 2-7 shows a typical arrangement of distributed generation.

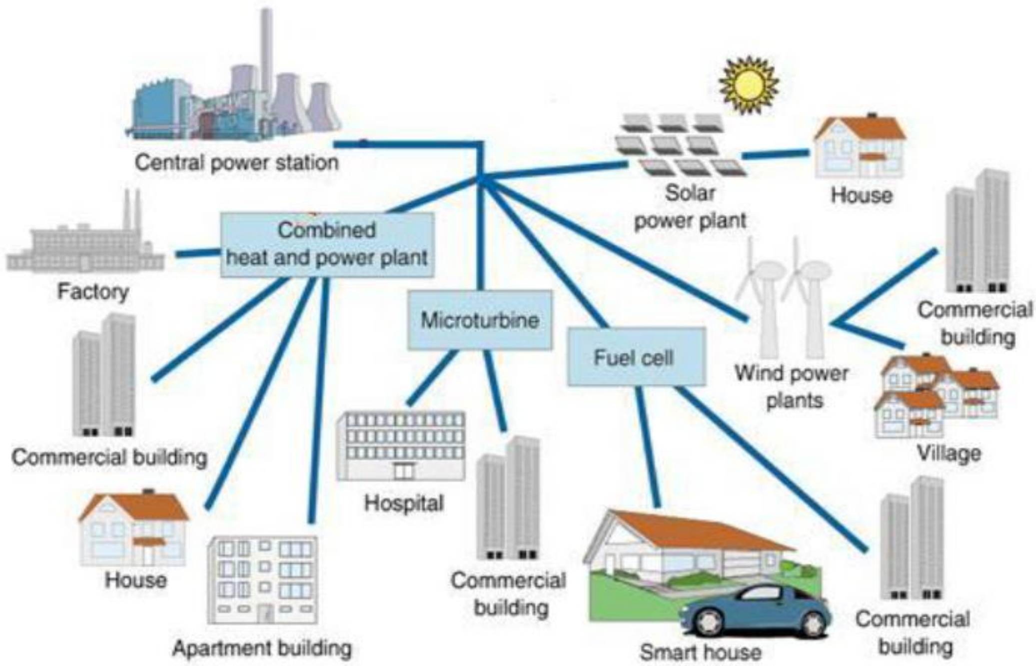


Figure 2-7:Distributed Generation [21]

In the IEA-PVPS countries, the installed power has increased from 500 MW to 7000 MW between the years 2000 and 2007[22]. Most of the systems installed recently are grid-connected distributed systems at LV (0.4 kV) to supply customers from residential areas.

2.4. SOLAR PV INTEGRATION INTO THE GRID

2.4.1. Overview of the solar PV integration

Solar-grid integration consists of a network that allows the penetration of PV generation into the utility grid. This practice is applied now in many countries as they need clean energy. In the interconnection process, an inverter, which is the most important equipment and also the brain for the integration system, plays the role of power electronics interface between the array and utility network. It ensures many functions for the system to operate correctly. Other system components of a solar grid integration are PV modules, transformers, meters, DC and AC wiring, etc.[13]

The PV inverters are required to supply constant voltage and frequency instead of the changing load conditions. It also needs to supply or absorb reactive power in the case of reactive loads. Inverters are also playing the role of the human-machine interface (HMI) for many PV systems, and often perform data collection duties to track and communicate the system performance to the owners and operators.[13][23]

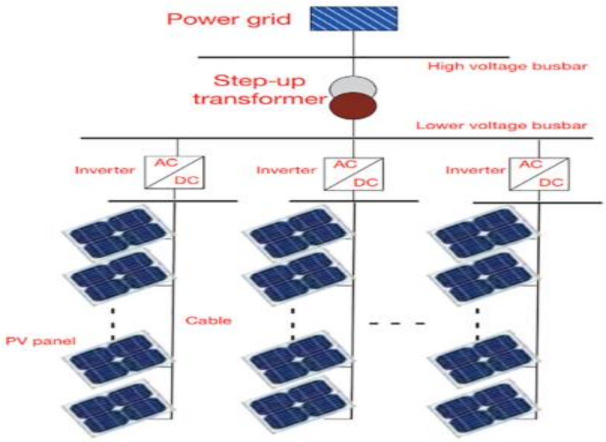


Figure 2-8:Diagram of a grid-connected PV Power Station [13]

2.4.2. PV penetration level

The penetration level for a PV power plant has been defined differently in past researches. It is defined as the ratio between the maximum PV power and the maximum apparent power of the load. It is expressed by Equation (2.3) [24][25]:

$$PV\ penetration\ Level = \frac{PV\ generated\ capacity(kWh\ or\ MWh)}{Network\ Peak\ Load(kWh\ or\ MWh)} \tag{2.3}$$

Past works gave percentages values for a high penetration level for PV. Authors suggest values that are greater than 20% of total generation, while high penetration is considered from others at the levels going up to 15% and 50%, respectively. Although no standard says what percentage constitutes a high PV penetration, many types of research precise that at penetration above 15%, the challenges of high PV penetrations become noticeable.

2.5. CHALLENGES OF THE LARGE-SCALE SOLAR INTEGRATION

The impacts of the integration of solar energy into the grid need high attention from utility companies and researchers. These impacts cannot be generalized for all the types of grids around the world. Studies are needed to be carried out before the integration process[25]. Some of the challenges are discussed in the following paragraphs:

2.5.1. Reverse power flow

In many power systems, the flow of power is done in one direction. This comes from centralized generators up to substations and then to consumers. This is not the same for solar PV power systems. Here, the flow of power can be done in both directions. Since that many electric distributions were not designed for such operation, even small amounts of PV may affect system parameters. When the generation coming from PV exceeds local energy demand, energy will move through the distribution feeder and possibly through the local substation, increasing the potential for damage to the utility grid. Other customers served by the same distribution circuit are also impacted.[13].

2.5.2. Power quality issues

Some challenges include problems of voltage stability, frequency stability, and overall power quality. When the load of the system is greater than 10 MW, the distributed system is considered large-scale. Many issues related to power quality occur with a system under 10 MW. However, large-scale systems also face power quality challenges. The production and demand of electrical energy can be matched for a conventional power system. Photovoltaic energy does not have the luxury of producing power according to the demand. Power quality is assimilated to water quality; just as water suppliers must meet certain conditions for bacteria and pollutant levels, utility power is consistently supplied at a certain voltage and frequency.

In the DRC, residences, commercials, buildings and industries receive single-phase AC power at 220/380 V and 50 Hz or higher voltage three-phase power, depending on the size and the types of loads. Appliances and electronic devices are manufactured to be supplied by a certain range of voltage and frequency. Damages occur with deviations outside those ranges. This shows the importance of Power quality.[25][26]

- **Harmonics**

The harmonics problem is one of the power quality issues, it is generated mainly from power inverters. They are created by some loads which introduce frequencies that are multiples of the fundamental frequency and can cause equipment to not operate as intended. The sum of all the distortions, at the various harmonic frequencies, is called Total harmonic distortion (THD).

Non-linear loads can be the cause of generating harmonics. Modern interconnection requires to include limits on harmonic injection from DG, and devices evaluated to meet IEEE 1547.1 standards will have a minimal harmonic impact.

- **Power factor**

The Power factor (PF) is a measure of apparent power that is delivered when voltage and current waveforms are out of synch. It is also defined as the ratio of true electric power, in watts, to the apparent power, in volt-amperes (VA). Loads with motors typically cause reduced (or lagging) power factor. The terms leading and lagging are describing whether the current wave is ahead of or behind the voltage wave.

- **DC injection**

When the inverter transfers undesirable DC current into the AC (or output) side, DC injection occurs. This can be prevented when galvanic isolation is incorporated through a transformer within the inverter design.

- **Voltage fluctuations**

Voltage quality issues that must be also considered as a challenge. Voltage oscillations are caused by changes in the power drawn by a load or output from a DG system. Disturbances classified as short-duration voltage variations are voltage sag, voltage swell, and short interruption, whereas disturbances classified as long-duration voltage variations, include sustained interruption, undervoltage, and overvoltage. The synchronization requirement in IEEE 1547-2003 allows for a 5% voltage fluctuation. The PV plant should be adaptable to voltage sags just as conventional power plants. The operating condition under equilibrium must be restored by the grid between the load demand and supply. If this does not happen and the voltages at some buses or points in the power system rise or falls beyond the limit, then instability occurs. [13][27]

- **Variability of insolation**

The quantity of generating for the PV depends on the insolation level at a given site and time. The grid instability is coming from both over-generation and under-generation.

2.5.3. Islanding

Islanding describes a portion of the grid that is unintentionally energized. When the grid loses power for intentional (scheduled maintenance) or unintentional (blackout caused by network trip or damaged lines) reasons, interconnected DG solar PV systems will produce power and may feed into the grid. This scenario poses safety concerns for utility line workers, first-responders, and others that interact with power lines during grid failure, who need to know when lines are energized. Islanding from DG solar PV is unusual, as inverters are designed to disconnect from the grid during power failure events.[28]

2.5.4. Cost of implementation

When a customer (residential, commercial, or industrial) wants to build DG solar PV and connect to the electricity grid, this process is called interconnection. Customers must get approval from their utility before they can build a solar PV system and interconnect to the grid. The purpose of the interconnection process is to maintain safety and reliability, as well as makes sure that any additional costs such as technology upgrades are accurately allocated. The size and location of the solar PV installation, characteristics of the feeder line, and proximity to other DG solar PV installations and substations all impact the results of the interconnection screen.

The interconnection process often includes a series of “technical screens” to address concerns about safety, reliability, and impacts on the grid. Additional screens or studies may be needed if a proposed system does not pass the initial technical screen; often at the cost to the developer or property owner who is applying for interconnection. These additional screens may include an interconnection feasibility study, an impact study, and a facilities study. Similarly, delayed interconnection processes add to the total time it takes from conception to completion of the project, which increases the soft costs of solar. Some customers may be allowed to interconnect only if they install costly technology or pay for improvements. Potential customers may also be deterred from installing solar if they know that interacting with their utility through the interconnection process may be lengthy, difficult, or ultimately add to the cost of solar. For large-scale PV projects or farms, most of which are located in remote areas, they often require long transmission lines. This also requires more investment.[25] [28]

2.6. MITIGATION SOLUTIONS OF INTEGRATION CHALLENGES

To overcome these above issues, storage solutions along with other instantaneous power-producing solutions are under research and development. Some possible solutions that could mitigate problems:

- Reactive power/voltage control by use of either series or shunt flexible alternating current transmission systems (FACTS) devices in distribution grids (SVC or DSTATCOM). Also, the use of the minimum import relays (MIR) and the Reverse Power Flow Relay (RPFR) is encouraged for grid-tie systems.

- Use of advanced inverter control of voltage, active and reactive power could solve the impacts under different operating conditions for the PV plant.

- Distribution grid re-organisation/re-arrangement. That is the conversion of a radial grid to a meshed or loop distribution grid to increase the hosting capacity and to control voltage levels. [15].

Others challenge mitigation solutions for integrating solar PV are listed as follow:

- A study must be done to predict the behaviour of the system when integrating solar PV
- Install solar across a large geographic area to reduce the variability of generation due to shading effects or local cloud cover.
- Store the excess electricity for a later use
- To make sense to customers by using electrical power when it is necessary. This can shift the demand.

2.7. REI GRID INTERFACES

Distributed generation systems are generally classified according to the type of generator that plays the role of the system interface to the grid. These can be:

- Solid-state or static inverters,
- Induction machines, and
- Synchronous machines.

These can be summarized in the following table.

Table 2-2:DG System Types and Characteristics

	Inverter	Induction Machine	Synchronous Machine
General Characteristics	Commonly current source-like (strictly, voltage regulated, current-controlled) in grid-tie mode; voltage source in stand-alone mode, sometimes within the same unit. Low inertia (capable of high-speed response).	Inherently current source; can be made to act as a voltage source with external excitation. High inertia (relatively slow response)	Voltage source. High inertia
Fault-current capabilities	Low (typically <1.2 times the normal current).	Medium (6 times the normal current).	High (10 times the normal current).

Power quality	Total Harmonic Distortion and DC injection must be controlled, controllable power factor.	Low Total Harmonic Distortion, power factor must be corrected.	Low Total Harmonic Distortion, controllable power factor.
Examples	Fuel cells, PV, microturbines, some wind turbines.	Some wind turbines, CHP.	Solar thermal electric, diesel generators, traditional utility generators.

Since inverters are power electronic devices, the possibility is there to incorporate safety and operational features into their controls, such to provide fail-safe designs that prevent the inverter from operating unless its protective functions are working properly. The interconnection devices could be tested to assure that they could reliably provide standard utility protective functions (voltage and frequency trip), as well as additional safety features such as anti-islanding.

2.8. PREVIOUS WORKS

We cannot research without a look at the previous works related to solar power, electricity grid, integration of solar into the electrical grid, the energy situation in the Democratic Republic of Congo. Several researchers have studied solar-grid integration:

Amal A. Hassan et al. [29], an overview of the grid-connected solar system was detailed through components explanation. A computer simulation using Matlab/Simulink and "Sim Power System" tool to monitor its performance during a selected day in the year was implemented. The Kharga Oasis site was the case study, in Egypt.

Manel Hammami et al. [8] presented the design of a PV conversion system conditioning with grid connection and RLC load by using a three-phase inverter. To control the quality and quantity of the injected power to the grid, the control system included an MPPT based on perturb and observe algorithm which helped to track available power continuously. They also proposed a control strategy to the voltage source inverter (VSI) which was interfaced with the electrical grid. Simulation algorithms have been implemented in Matlab/Simulink.

Hassan Zuhair Al Garni in [30] evaluated renewable resources and prioritized their importance towards sustainable power generation. Also, an optimal design of a grid-connected solar PV system was performed using HOMER software. A case study for Saudi Arabia was conducted.

Kanchan Matiyali and Alaknanda Ashok [31] gave a performance evaluation of a 400 kW grid-connected solar PV power plant at Dhalipur (India) and provided a substantial inducement for installation of solar PV power plants. The performance ratio and the several types of power losses were calculated.

ZHENG Fei et al. [32] showed the dynamic modelling and control strategy of grid-connected PV power stations based on DIgSILENT. Based on a 10MW grid-connected PV power station in the northwest of China, simulations were done to verify the dynamic model and control strategy of the PV power station.

Montaser Abd El-Sattar Mohammed [33]; presented a modified conventional P&O algorithm to overcome some drawbacks of a solar PV system and improved MPPT performance using a modifying technique based on constant load technique to enable it tracking maximum power of PV module during rapid-change of irradiance and steady operating PV conditions.

Kevin N. Nwaigwe et al. [13] identified the current solar-grid integration technologies, described the solar-grid integration advantages. They addressed the integration challenges and compatibility of solar and grid generations.

Al Basir et al. [34] studied the energy efficiency analysis for a medium office building and also at the same time they remodelled the building to develop the energy efficiency by using Sketch Up, Open Studio, EnergyPlus and RETScreen.

Nhamo Dhlamini and S.P Daniel Chowdhury [35] attempted to highlight the steady-state integration impacts of solar PV generation to existing transmission and distribution grids. The study was carried out in the Northern Cape region of South Africa.

Enock Mulenga [25] investigated the steady-state impacts of solar PV integration to an existing distribution grid in Sweden i.e. Mölndal Energy (mostly urban cable grid) and Orust Energy (mostly rural grid) and proposed some mitigation solutions.

The World Bank report [36] explored the current state of the electricity sector in the DRC focused on principles and priorities to proceed to increase the development of future power sector. It finally presented a set of recommendations.

K. Kusakana in his paper [37] presented a comprehensive review of the current energy resources and showed the status of the electricity in the DRC. This paper demonstrated that the Democratic Republic of Congo is blessed with abundant fossil fuels and renewable energy resources and only 11% of the country is electrified mainly through hydropower plants, while the remaining part of the population uses inefficient biomass fuels for their basic energy needs such as cooking, lighting or heating causing deforestation and indoor air pollution affecting the living conditions of the users. The author said that most of the hydropower plants supplying the main cities in electrical power are no longer performing at their maximum design capacities and need major maintenance repairs or replacement. It is also written that the DRC together with foreign partners has initiated projects to implement urgent repairs and substantial rehabilitation mainly to the Inga I and II power stations and some existing transmission lines, as well as to develop the new Inga III and the Grand Inga dam, able to respond to the economic and industrial development needs of many African countries from Egypt to South Africa through a vast electrical grid.

2.9. METHODOLOGY

To understand the research problem, specific procedures or techniques were applied to identify, collect, select, and analyze related information. This study will use multiple research methods. Both qualitative and quantitative methods will be implemented in the current work.

As known, quantitative research is based on the measurement of quantity or amount. This is applicable to phenomena that can be expressed in terms of quantity, amount, size or weight etc. Quantitative method is implemented in our research in the way that we cannot plan for integrating a solar PV power plant into the existing grid of Matebe without knowing first what is the amount of power that is needed to satisfy to the area where the solar PV power plant will be implemented and to ensure high electricity access of its inhabitants. Designing such a system implies to collect some data in term of amount, size of the plant, energy which will be injected to the grid, etc.

Also, a qualitative method was used in this research. It concerns qualitative phenomena, means something relating to or involving quality. In the research done, we can find out how people feel or what they think about a new Solar PV power plant integrated into the existing line of Matebe in the city of Goma. In that way, we are dealing with qualitative research.

The research strategy of the dissertation will be a grounded theory. The results of the grounded theory phase are used in the content analysis of the literature. Moreover, the simulation will be applied to predict the behaviour of the system. Simulation refers to the application of computational models to the study and prediction of physical events or the behaviour of engineered systems. The simulation also provides a powerful alternative to the techniques of experimental science and observation when phenomena are not observable or when measurements are impracticable or too expensive. [38]

MATLAB/SIMULINK and PVSYST are engineering software that will be applied in this thesis to analyze the feasibility of the grid-connected solar PV power plant.

2.10. Partial conclusion

In this part was described the overall literature review related to the solar PV integration into the electricity grid. Solar energy was developed and its technologies. We showed also the integration challenge of PV into the utility grid. Some past researches have been also presented to have a look at what has been done previously related to the current research. This chapter ended with the applied methodology to conduct this research.

Chapter 3 : ENERGY SITUATION AND SOLAR PROJECTS ACHIEVEMENTS IN THE CITY OF GOMA/ DRC

3.1. INTRODUCTION

Since the adoption of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992, actions in favour of energy and climate have multiplied[39]. According to the forecast of international energy agency EURO-JRC, renewable energy use in the entire global energy structure will exceed 50% in 2050.[40]

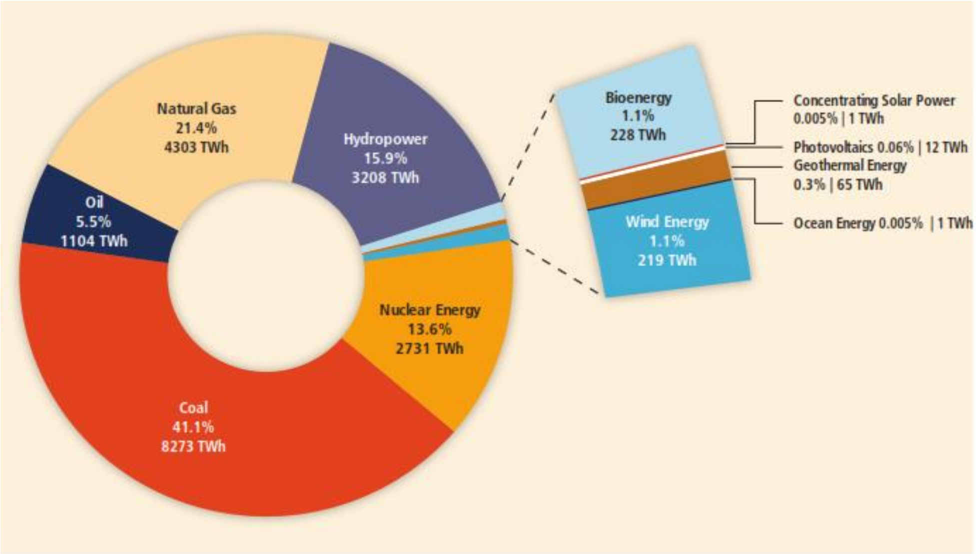


Figure 3-1:Electricity generation in the world in 2008

In this chapter, the overview of the energy situation in the DRC is described presenting the actual power plants (hydro and Solar PV) of the entire country and especially for the city of Goma. Since the study is oriented to the city of Goma, the need for energy will be calculated in the Mugunga quarter because of its less access rate to the electricity supply. After that, the Virunga electrification projects in the North Kivu province will be discussed. The chapter ends with a partial conclusion.

As our study concerns integration of solar power plant in the electric network of the city of Goma, we thought about renewable energies like solar energy to mitigate the lack of electricity in this region of the country. We cannot analyze Goma electrification before having a look at the electrification state of the entire DRC.

3.2. STATUS OF ELECTRICITY IN THE DRC

3.2.1. Presentation of the country

The DRC is a country which is located in the centre of the African continent. The bordering countries of the DRC are Tanzania, Angola, the Central African Republic, Republic of Congo, Uganda, South Sudan, Rwanda, Zambia, as well as Burundi. The country has a total land area of 2,267,048 km² and inland water of about 77,810 km², which makes it the largest country in Sub-Saharan Africa.

Some 67.9 % of the DRC land area is covered by forest. From 1990 to 2000 alone, the country lost over 2,000 km² of its forest area. In the past ten years, the DRC's forest area has been reduced by an average of 1,900 km² annually. Deforestation is one of the major sources of greenhouse gas, after energy production, causing around 18% of the world annual global emissions. Figure 3-2 shows the available energy resources used in the DRC.

Protecting DRC forests can be a key opportunity in the fight against climate change; however, this increases the vulnerability of the local impoverished communities, as they depend on the exploitation of the forests as their primary energy source and as a source of income. It has been proved that access to clean energy helps to reduce extreme poverty, as well as improves the environment and living conditions of poor communities in the region.[37]

In this thesis, two types of electricity generation will be analyzed: Hydropower plant and solar power plant. Both are available in the DRC.

3.2.2. DRC Hydropower plants (HPPs)

The DRC total installed electricity production is mainly from hydro-electric power stations, which accounts for 98.7% of total generation, and 1.3% from non-renewable sources. The country has a huge hydroelectric potential due to its rich hydrographical location. The Congo River can be favourably used for power generation due to the following characteristics, it has[39]:

- An average flow of 42 000 m^3/s, making it the second most powerful river of the world after the Amazon;

- The relative stability of its water flow, which varies only from a factor of two between the low water and the annual flood;

- It is the only big river in the world to present a very steep slope on its lower course. In total, the country has an estimated 100,000 MW potential, which is almost 13 per cent of the world's hydropower potential.

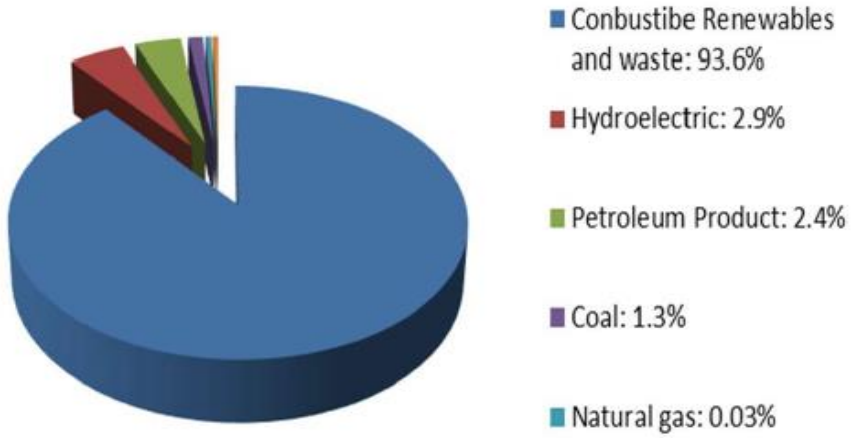


Figure 3-2: DRC Energy Resources [37]

The DRC hydro potential is 100 GW (the greatest in Africa) and only 2.5% of this potential has been developed. About large amount, 40% of this potential is concentrated in the Inga Falls area, which are located at 140 miles southwest of Kinshasa. Two dams (Inga 1 and Inga 2) of 351 MW and 1,424 MW potentials were completed in 1972 and 1982. A third dam (Inga 3) has a capacity of 4,500MW potential and it is still under development. Other existing major plants are Nseke (248.4MW), Nzilo (108MW), Zongo 1 (75MW), Mwadingusha (68 MW), Ruzizi 1 and 2 (29.8 MW and 44 MW) and Koni (42 MW). Most of these hydro powers were built 40 years ago plants are running under their capacity because of the maintenance lack.

Several existing isolated mini-grids are hydro-powered, such as the *Electricité du Congo* (EDC) grid in the city of Tshikapa (1.5 MW), the Virunga SARL grids in Mutwanga (0.4 MW) and Matebe (12.6 MW), the *Société d'énergie du Kasaï* (Enerka) grid in Mbuji-Mayi (18.48 MW) and the *Société des Mines d'Or de Kilo-Moto* (SOKIMO) grid in Bunia and Mongbwalu (11 MW). SNEL also operates two hydro mini-grids in the cities of Kindu and Kisangani. Nevertheless, most of the potential remains untapped.

The United Nations Development Program (UNDP) produced a Renewable Energy Atlas in 2014 that identified 317 potential small hydro sites. Although data on location and estimated potential is incomplete, 183 sites across the country with a total potential of 1.1 GW were identified. Power sector planning led at a national level encouraged the development of large production centres with one main interconnected grid.[36][41]

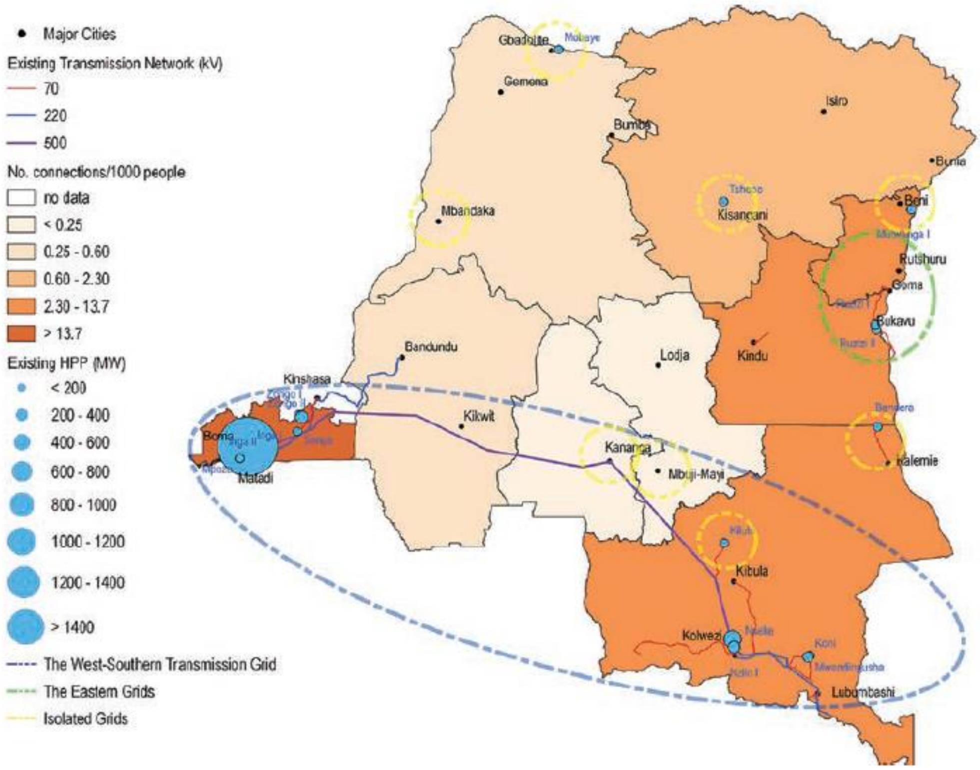


Figure 3-3:DRC power system development [36]

3.2.3. The solar power plants in DRC

The DRC solar potential can be subdivided into three regions. (Figure 3-4). Three categories of solar irradiation are given: Exceptional irradiation in Kolwezi or Lubumbashi (more than 2,000 kWh/m^2) which is equivalent to the best resources in the world like southern Spain or Arizona (USA), good irradiation (1,860 to 1,900 kWh/m^2) in Bandundu or Kikwit and the Medium irradiation (1,810 to 1,830 kWh/m^2) in Goma, Kinshasa and Kisangani, analogous to the solar quality in northern Morocco or eastern India.

This classification shows that Solar energy is abundant in DRC. The Average daily irradiation is ranged from 3.5 to 5.5 kWh/m^2. In the southern provinces, the average daily solar irradiance reaches 5 kWh/m^2/day and up to 6.75 kWh/m^2.

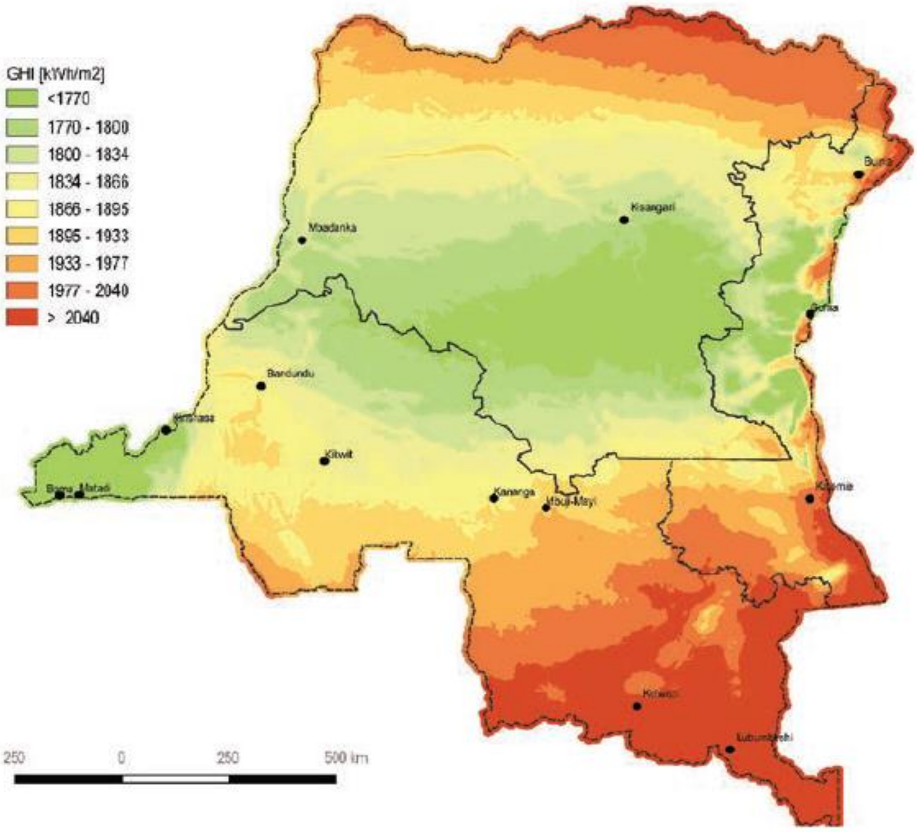


Figure 3-4:Photovoltaic Electricity Potential (GHI, kWh/m2)[36]

The main existing solar project is a 1 MW hybrid plant developed by ENERKAC and powering SNEL's Kananga mini-grid in the Kasaï Central province. The DFID Essor programme aims at promoting up to 33 solar mini-grids supplying each between 100 and 300 thousand people with 3 to 10 MW as installed capacity.[36][41]

3.3. ELECTRICITY STATUS IN GOMA

3.3.1. The geographical location of the city of Goma

The city of Goma is located at an altitude of 1872 m from the sea level. It is at the south of Lake Kivu and 29 ° East longitude and 1 ° 45 ' North latitude. It covers an area of 75.72 km^2 composed of 2 communes forming 18 quarters. This city has a temperate climate softened by the wind blowing from Lake Kivu and volcanic mountains in Virunga Park. Following decree n ° 84/127 of May 22, 1989, fixing the number of names of urban areas, the city of Goma is limited to the north by the territory of Nyiragongo, to the south by Lake Kivu, to the east by the Republic of Rwanda and the west by the territory of Masisi. With his location in the eastern highlands near the Republics of Uganda and Rwanda, the Virunga National Park, Lake Kivu, this city is a real tourist site but also a point convergence which attracts many people even from the outside and offers it a lot of advantage.

3.3.2. Historical background

Traditionally speaking, Goma is the deformation of the word "NGOMA" which means in Swahili (drum), the same word given about the noise assimilated to that of the "drum" which resounds. The resonance referred here was the loud noise similar to the sound of the drum (bang) caused by the volcanic eruption. Thus, in memory of this great noise, the first village that was established was named "NGOMA". According to this legend; we tend to say that after the primitive volcanic eruption, this village disappeared and its inhabitants would be dispersed and built three new villages namely: MUNGOMA, the current Goma, Matcha, the city of SAKE and MUTI, the village of MUNIGI.[42]

Around 1900, Goma had contact with the colonizers. In 1906 the post of Goma was founded opposite the German post of Gisenyi. This post was expected to play the military role and then later it became a State Office. The creation of the City of Goma was especially favoured by its strategic position and its tourist beauty. It was declared the capital of the province of North Kivu at the end of the territorial division of the former region of Kivu by ordinance law N ° 88/176 of November 15, 1988, in the favor of the reform movement of the Territorial Administration of Congo. The City of Goma had the opportunity to make world history in 1994 for hosting almost a million Rwandan refugees.

3.3.3. Administrative subdivision

The city of Goma is subdivided into two communes: GOMA and KARISIMBI. Each commune is composed of many quarters:

- Commune of Karisimbi: Mabanga Nord, Kahembe, Kasika, Bujovu, Virunga, Mabanga Sud, Katoyi, Ndosho Murara, Mugunga and Majengo.

- Commune of Goma: Les Volcans, Mikeno, Mapendo, Katindo, Himbi, Kyeshero and Lac Vert.

3.3.4. Goma population

The city of Goma has been the centre of population movements. According to the 1984 census, the city had about 80,000 people. Goma has recorded average annual growth above 10 per cent since 1984. Goma has now a population estimated at 1.9 million people. [36][43]

3.3.5. Goma Electrical energy status

Some private developers are now working in the city of Goma and have installed isolated grids. The developer Virunga SARL currently has 5,160 clients in Rutshuru / Kiwanja, 1,360 in Goma which are powered by Matebe HPP (13.1 MW) and 1,170 clients in Mutwanga supplied by two plants of 1.7 MW as total capacity. Virunga SARL got a grant to connect 6,000 clients in Goma through a subsidy fund financed by a World Bank project. Its plant in Matebe supplies Goma through a partnership with the local industrial group SOCODEE[2].

The company Nuru (ex-Kivu Green Energy) supplies 48 customers with a 55 kW micro-grid in Beni and recently built a 1.3 MW solar power plant in the Ndosho district for serving electrical energy for around 4,000 customers in Goma. Construction was completed in 6 months with the inauguration of the plant in early 2020. [36]

3.4. VIRUNGA PROJECTS FOR ELECTRIFICATION

3.4.1. Introduction

Seeking to facilitate additional economic opportunities, to improve overall well-being and decrease the youth participation in armed groups active within the park, the Virunga Foundation has implemented several community developments projects (Figure 3-5). Four main sectors are concerned:

1) sustainable energy,
2) sustainable fisheries,
3) agro-industry, and
4) tourism.

The initiatives in these sectors have brought about 3000 jobs in the last 10 years. The jobs created have been taken up by now-former combatants. "***Every MW of electricity generated empowers the community, by creating 1.000 jobs, 5–10% of which goes to ex-combatants. When people are empowered, they have the choice to control their future and move into productive society, away from armed groups". Emmanuel de Merode, director, Virunga National Park.*** [44][45]

3.4.2. The Virunga National Park

Located in the DRC, particularly in the Nord Kivu province, the Virunga National Park is the oldest in Africa. In the past 20 years, an estimated number of two dozen armed groups have been operating in this region.

[2] SOCODEE is a private company which purchases 5 MW from Virunga s.a.r.l and supply also some of customers in the city of Goma.

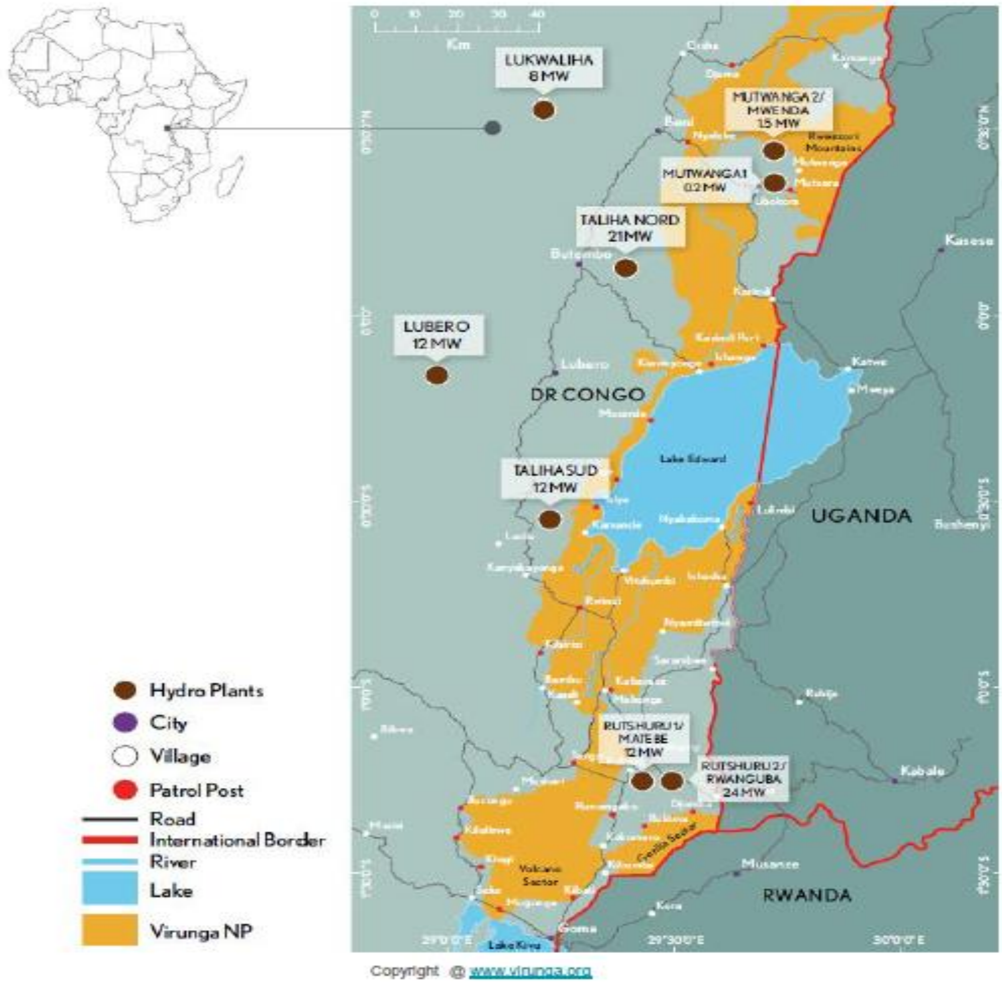


Figure 3-5:Virunga National Park HPPs [24]

Through the creation of seven hydro-electricity plants around Virunga National Park (See Figure 3-5), the illegal extraction of charcoal within the borders of the park and the number of young populations enrolled in the armed group by getting jobs are reduced. To achieve this, the park management has created a private enterprise, Virunga SARL, to execute the project and to commercialize the electricity to households and businesses back to the park.[45]

3.4.3. Matebe hydroelectric power plant

The Matebe HPP has a 12.6 MW capacity (three turbines of 4.8 MW each). The network of Matebe has 40 km MV line, which connects the HPP at Matebe to Rugari and another 30 km MV up to the city of Goma. But this line is still under development because there is a possibility to build an HV line and replace the previous one.[46]

3.4.4. Mutwanga hydroelectric power plant

The Mutwanga plant is a mini-HPP (run of river) commissioned in August 2013 with a capacity of 0.38MW. It is the first and smaller project compared with the other project. It was intended to be a pilot from which to gain experience and build local expertise.

3.4.5. Lubero and Taliha HPPs

Lubero HPP has a capacity of 11.5 MW to supply Lubero city, surrounding areas and Butembo (40 km connection). Taliha Nord is a 20.6 MW HPP to supply the city of Butembo.

3.5. CALCULATION OF THE ENERGY DEMAND FOR THE MUGUNGA AREA

The city of Goma has 18 quarters as described in the introduction of this chapter. Among them, the choice to build the solar PV power plant was made to Mugunga due to it has some vast unoccupied places, also it has few people connected to the electricity grid. As the population is growing mush fast, people are buying lands in this area and we estimate that many activities will be developed in the coming years. In this research, the electrical loads of the Mugunga quarter (in the commune of Karisimbi) will be considered. These loads can be subdivided into 4 types according to the activities which are considered: The Domestic loads, commercial loads, industrial loads and municipal loads.

3.5.1. Domestic loads

This type of loads takes into consideration the general houses lighting, cooking equipment, dryer loads and other home appliances (TV, refrigerators, etc.). Most of these loads are only connected some hours during the day. The number of populations will help to find how many households are going to be supplied by the grid-connected solar PV power plant. According to collected data, the population of Mugunga was at 17670 in the year 2016.[42]. As there is no census since that time, the population will be considered with an increment per cent of 2.5%. By taking into consideration this hypothesis and doing the calculation in the excel software, we have the following table:

Table 3-1:Evolution of the Mugunga population from 2016

Year	Mugunga population
2016	17670
2017	18111
2018	18565
2019	19029
2020	19505

These data can be shown in the following graph (Figure 3-6):

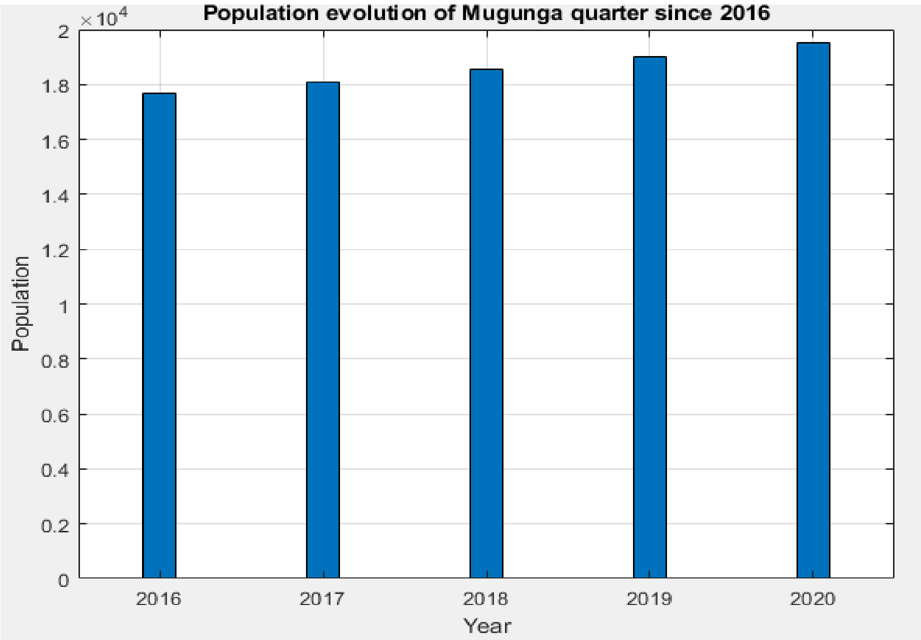


Figure 3-6:Estimation of the Mugunga population

Knowing that the average density per household in the Mugunga and Lac Vert quarters is 9 persons we have an estimated total of 2167 households. Only a few households have access to the utility grid that is why the total number of the households is taken into consideration for the design. The domestic load calculations are shown in the following table for a 'modest' household by using the demand factor because all the loads are not connected at the same time.

Table 3-2: Load consumption per household

Loads	Number of units	Rated power (in Watts)	DF (Demand factor)	Total power (Watts)
Electric Iron	1	1000	1	1000
Electric stove	1	1200	0.7	840
Lightning	8	5	0.6	24
TOTAL				1864

The needed power for all households is then calculated as follow. The total demand in electrical energy for all the households is then estimated at 4039288 W means 4.04 MW.

3.5.2. Commercial loads

In this type are included restaurants, shops, malls, etc. Briefly, these loads meant to be used commercially. It is a type of load that occur for more hours during the day as compared to the domestic load.

Table 3-3: Estimated commercial loads

Loads	Number of units	Rated power(KW)	Demand factor	Total loads(KW)
Shops	20	1	0,75	15
cold storage	5	10	0,75	37,5
Hotels &Restaurants		500		500
Others		1000		1000
TOTAL				1552,5

The total commercial loads are estimated to 1.5 MW.

3.5.3. Industrial loads

They consist of electricity demand from various industries. It includes all the electrical loads used in industries along with the machinery employed. This type can be connected for the whole day.

Table 3-4:Industrial loads calculation for the Mugunga area

Loads	Units	Power (kW)	Total loads (kW)	DF	Total Demand (kW)
Mill	10	50	500	0,8	400
Sawmill	5	30	150	0,6	90
Small craft	10	3	30	0,5	15
Carpentry	10	15	150	0,75	112,5
Juice industry	2	80	160	0,75	120
Telecommunication Sites	2	20	40	0,75	30
Soap industries	5	100	500	0,75	375
Other small industries	25	100	2500	0,75	1875
Total					3017,5

The total electricity demand for industries is then 3.017 MW.

3.5.4. Public loads

Public loads consist of water supply, public schools, street lighting, drainage systems, etc. Street lighting is practically constant during the night hours.

Table 3-5:Mugunga municipal loads calculations

Loads	units	Power per unit (Kw)	Total loads(kW)	DF	Total demand (kW)
Street lighting	100	3	300	0,5	150
Shcools and universities	18	60	1080	0,75	810

water supply (pumps,electrical machinery)	**2**	**700**	**1400**	**0,75**	**1050**
Hospitals	**4**	**100**	**400**	**0,75**	**300**
Theatre halls	**2**	**5**	**10**	**0,75**	**7,5**
Public offices	**5**	**2**	**10**	**0,75**	**7,5**
TOTAL					**2325**

The total demand of public or municipal infrastructures is estimated at 2325 kW which is 2.3 MW.

After all the load types described, the total electrical energy demand for the Mugunga quarter in the city of Goma is then estimated at 10.9 MW. Assuming that all the electrical loads are not connected at the same time and taking into consideration the expansion of the network in the coming years, a 12 MW electrical power can be designed to supply this demand. In Figure 3-7 is shown the load demand in the Mugunga quarter in the city of Goma.

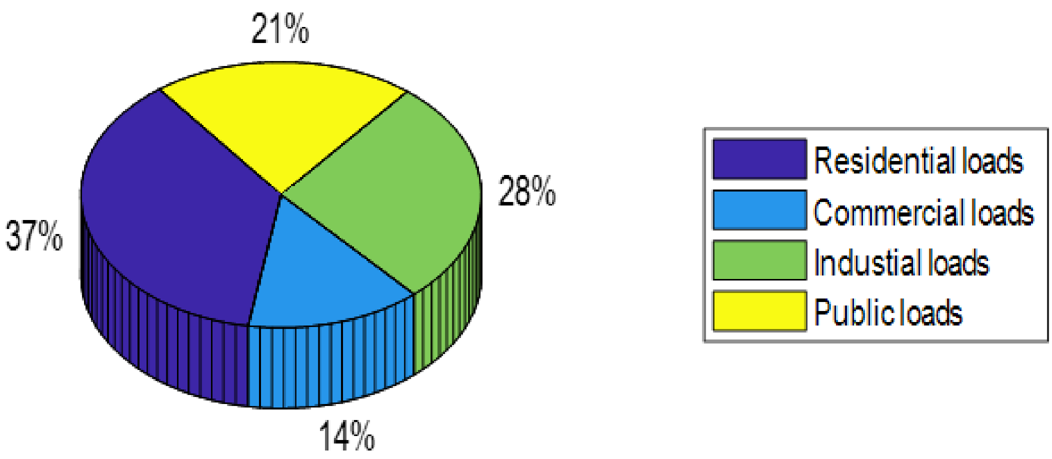


Figure 3-7:Loads repartition in the Mugunga quarter

3.6. PARTIAL CONCLUSION

In this chapter was developed the overall electricity status of the DRC. This concerned the two electricity resources mostly available in the country and used in this thesis: Solar PV and hydropower. After a description of the country and its potential in hydropower energy; the city of Goma was described. As remarked, the city of Goma is in lack of electricity supply. We have two lines coming from Ruzizi I and Matebe hydroelectric power plants but the population is still increasing and this implies also the need for electrical energy. As this city is in the eastern region of the DRC, it also benefices some advantages of the Virunga electrification projects. Here, the Matebe hydropower plant was detailed and its electric line which comes from Rutshuru territory up to the city of Goma. After the presentation of the Virunga projects, calculations were made to find the total electricity demand of Mugunga. This was estimated at 10.9 MW after calculating all the loads according to their types. The value of the demand found helped us to find the power of the solar PV to design in this area of the city of Goma.

Chapter 4 : DESIGN AND CHOICE OF COMPONENTS FOR THE PV POWER PLANT

4.2. INTRODUCTION

In this chapter, the modelling of the project is involved. Its starts with the site selection and explains what makes the city of Goma a proper place to design a solar PV power plant and also shows the designs of solar panels which are used to increase the performance of the system. At the end of this chapter, a discussion is made as a conclusion of the obtained results after calculations.

4.3. SITE SELECTION AND METROLOGICAL DATA

4.3.1. Selected site

The site under study is located in Mugunga area. This last is one of the 18 quarters that constitute the city of Goma. As Mugunga quarter area has some vast unoccupied areas, it is a suited place to implement the proposed solar PV power plant. Another reason is that the line coming from Matebe tends to supply a few inhabitants of this area. As calculated in the previous chapter, a solar 12 MW solar PV at Mugunga integrated into the grid of Matebe will help people to access electrical energy. Since we don’t have some specifics data related to the Mugunga quarter, the entire Goma will be taken into consideration through the calculations to design the power plant.

The city of Goma is located at 29.2 ° longitude East and 1.7 ° latitude South. The annual solar irradiation of this city is around 4.87 $kWh/m^2/day$. According to research conducted in the previous chapter, Goma has medium irradiation according to the classifications of regions related to their irradiation level. This irradiation makes the city of Goma a suitable place to design a solar PV system. [47] The city has two seasons namely the rainy season which begins around September 15 until May 15 and the dry season which runs from May 15 to September 15. Average precipitation is around 1027 mm. Furthermore, its temperature varies between 17 ° 15 'and 20 ° 16'. It is entirely covered with layers of lava due to previous volcanic eruptions. Volcanic sand, gravel and basalts are doable for masonry. In addition to the primitive volcanic eruptions, the city also experienced the eruption of Nyiragongo on January 17, 2002. These lavas destroyed 80% of the economic fabric including 40% of its buildings. This situation inevitably resulted in nearly 450,000 people seeking refuge in Rwanda and on their return to Goma, 250,000 people were left homeless.[48]

4.3.2. Irradiance and insolation

The amount of solar energy that strikes a given area is called "insolation"[49]. For any location, the irradiance is given by the equation that follows:

$$Irradiance = \frac{Average\ insolation}{Average\ daily\ bright\ sunshine\ hours}\quad in\ \ kWh/m^2 \qquad (4.1)$$

The city of Goma irradiance is calculated by knowing its average solar insolation and its average daily bright sunshine hours. These can be obtained using Table 4-1 and Figure 4-1 related to the city of Goma.

Table 4-1:Monthly global solar insolation of the city of Goma [50]

Months	Solar insolation (kWh/m^2)
January	4.9
February	5.17
March	5.03
April	4.93
May	4.80
June	4.81
July	4.90
August	4.92
September	5.00
October	4.69
November	4.64
December	4.69

The annual average insolation is 4.87 kWh/m^2.

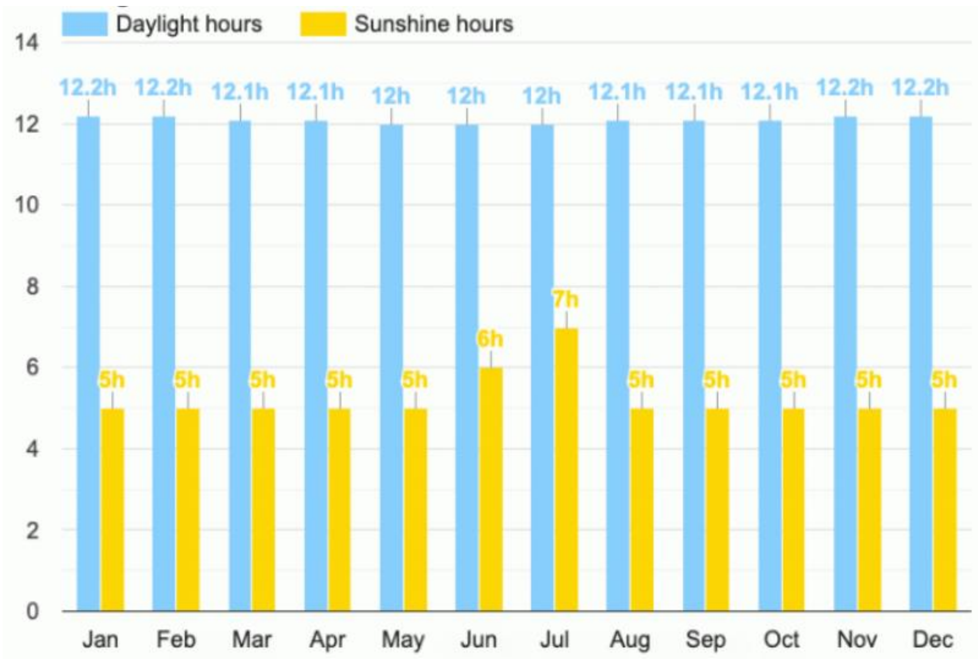


Figure 4-1:Goma Average sun hours of each month[51]

From the table below, the daily average of the city of Goma is 5.25 h means 5h15'.

Then, from the Equation (4.1), we get:

$$Irradiance = \frac{4.87\ kWh/m^2}{5.25\ h} = 927.6\ W/m^2,$$

which is the irradiance of the city of Goma that will be used in the modelling calculations.

4.4. SOLAR PANEL

4.4.1. Solar PV selection

It is important to select the components which are going to be used in the design. The PV module and the inverters are necessary to be known due to they intervene in the calculation process through their technical specifications. The selected solar PV module for this project is « JAP6-72-330/3BB », it is a polycrystalline PV type. This choice is explained for the fact that we have already implemented such solar modules in an existent solar PV in Goma (Nuru solar power plant) which produces 1,1 MW and they are working properly.

Table 4-2:The main characteristics of the JA Solar

Manufacturer	**JA Solar**
Model	**JAP6-72-330/3BB**
Type of technology	**Polycrystalline solar cells**
Module size	**0.991 x 1.956 m^2**
Weight	**22.5 kg**

Number of cells	**72**
Maximum open circuit voltage	**46 V**
Maximum short circuit current	**9.15 A**
Peak power	**330 Wp**
Module efficiency	**17 %**

For additional data about the PV module, consult the technical datasheet [49].

4.4.2. Calculation of PV modules number

The number of Solar PV modules that are going to be used in this project is calculated by the following formula:

$$N_{PV} = \frac{P_{Design}}{P_{M,STC}} \tag{4.2}$$

$$We\ have\ N_{PV} = \frac{12 * 10^6\ W}{330\ W} = 36\ 363.63 \simeq 36\ 364$$

Where P_{Design} is the power plant design capacity (12 MW) and $P_{M,STC}$ is the PV module power rating. We have 36 364 modules for all the PV Power plant to produce 12 MW when the peak power (particular module capacity) is 330 W. [49]

4.4.3. Area of the Solar Power plant

The design area for the Solar Power Plant is determined by:

$$Area = \frac{P_{Design}}{PSI * \eta_{PV}} \tag{4.3}$$

$$Area = \frac{12 * 10^6\ W}{1000\ W/m^2 * 0.17} = 70\ 588.235\ m^2$$

where PSI (Peak Sun Insolation) is 1000 W/m^2 at STC (Standard Test Condition) and η_{PV} the PV efficiency.

4.4.4. Energy produced

At 927.6 W/m^2 insolation (Irradiance of the city of Goma) the selected PV module can produce 304.5 W:

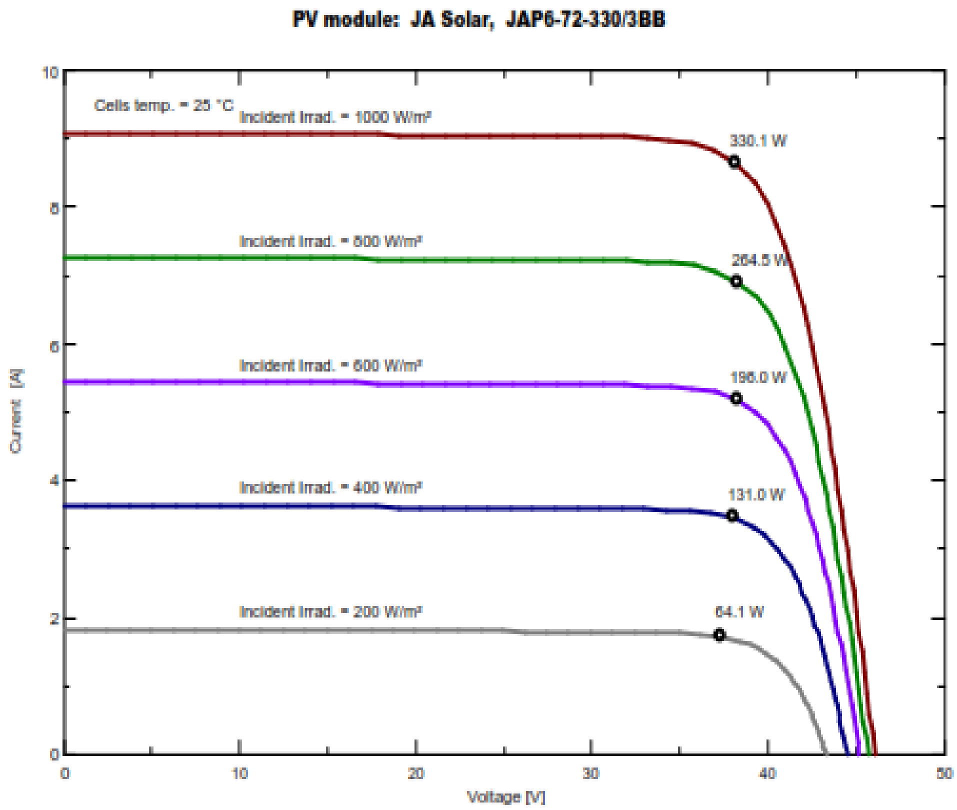


Figure 4-2:Power-Irradiance characteristics of the PV Solar power plant

The daily average sunshine hour at 5.25 hours and the total number of modules at 36 364. With these values, the monthly energy generation is calculated as follow:

$$\text{Monthly energy generation} = 304.5 * 5.25 * 36\,364 * 30 \text{ kWh} \quad (4.4)$$

$$= 1\,743\,971\,985 \text{ kWh}$$

4.5. INVERTER DESIGN

4.5.1. Role of inverters

Since the distribution of electric energy is done in AC current, the necessity to convert DC current from PV into AC is mostly required. The device to invert this polarity of power produced by PV is called an ‘inverter’.[52]

4.5.2. PV inverters topology

PV inverters topologies are several according to the requirements. These topologies help to determine the connection of the PV modules and the inverter[52]. We have Central inverters, string inverters, Multi string inverters, Module integrated inverters, Mini central inverters.

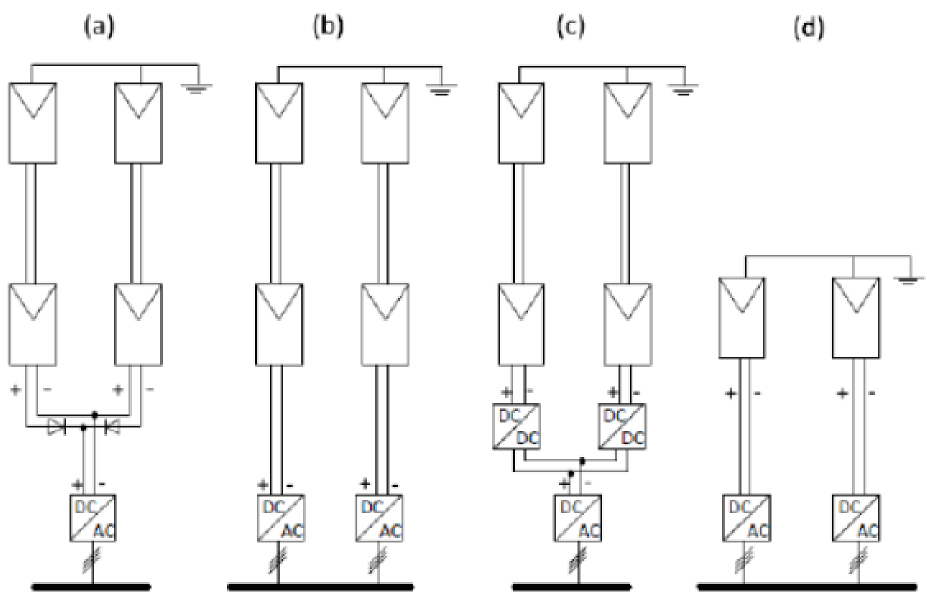


Figure 4-3: PV inverter topologies

In Figure 4-3, (a) central inverter, (b) String inverter, (c) Multi string inverter and (d) Module integrated inverter. Each topology is used depending on design requirements. The choice is depending on the preference by analyzing the advantages and drawbacks of each topology. Some of the popular PV inverter manufacturers are *SMA*, *ABB* and *Kaco*.

4.5.3. Inverter selected characteristics

The selected model inverter for this thesis is Sunny Central 2200 manufactured by SMA. The main characteristics of this inverter are shown in Table 4-3:

Table 4-3:Inverter characteristics

Technical data	**SC 2200**
Type of inverter	**Multi-String inverter**
Maximum input voltage	**1100 V**
Maximum PV input current	**3960 A at 25° and 3600 at 50°**
Nominal output power	**2200 KVA (at 25°)**
Nominal AC voltage	**385 V**
Maximum inverter output current	**3300 A**
Maximum efficiency	**98.6%**

CEC efficiency	**98.0 %**
Dimensions	**2780 x 2318 x 1588 mm**
Weight	**4000 kg**

For other technical data, consult the datasheet[53].

4.5.4. PV set calculations

The PV modules are distributed in PV sets. Many PV modules from a PV Set are connected to an inverter. The inverter output power is then injected into the grid at the point of common coupling (PCC) through an interconnection (i/c) transformer and cable, respectively. The block diagram is presented in the figure that follows; it shows the configuration of the entire power plant.

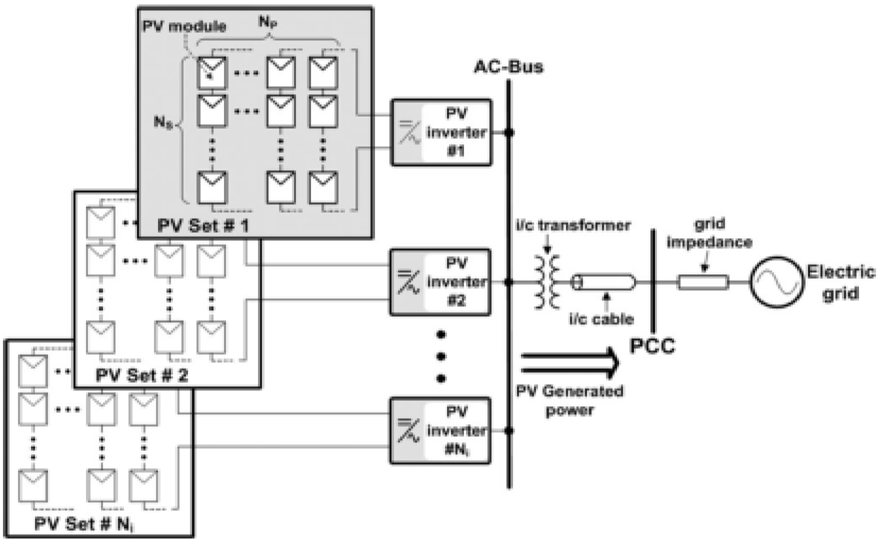


Figure 4-4:Block diagram of the Solar PV Power Plant[54]

We have 1 inverter per PV set. Each PV set consists of N_p strings ($N_p \geq 1$), while each string is composed of N_s PV modules connected in series ($N_s \geq 1$).

4.5.5. Number of solar panels in series per PV set

The numbers of PV modules to connect in series in each PV string, N_{smin} and N_{smax} , are calculated according to the PV inverter dc input maximum power point (MPP) voltage level $V_{i,max}$ (V) and the maximum permissible dc input voltage level, $V_{DC,max}$ (V) both specified by the PV inverter manufacturer [55]:

$$N_{smin} = 1 \leq N_s \leq N_{smax} = min\left[floor\left(\frac{V_{i,max}}{V_{M,max}}\right), floor\left(\frac{V_{DC,max}}{V_{oc,max}}\right)\right] \quad (4.5)$$

where $V_{oc,max}$ and $V_{M,max}$ are the maximum open-circuit voltage (V) and MPP voltage (V), respectively, which can be developed at the PV module output terminals. From the Equation (4.5), the number of solar panels in series can be obtained;

$$N_{smin} = min\left[floor\left(\frac{950\ V}{38.11V}\right), floor\left(\frac{1100\ V}{46.4\ V}\right)\right] = min[24{,}23] = 23.$$

$V_{i,max} = 950V$, $V_{M,max} = 38.11V$, $V_{DC,max} = 1100V$ and $V_{oc,max} = 46.05V$ from the technical datasheet [49][55].

4.5.6. Number of solar in parallel per PV set

The PV modules number in parallel is:

$$N_{P,max} = floor\left(\frac{I_{DC,max}}{I_{M,max}}\right) \quad (4.6)$$

Where $I_{DC,max}[A]$ is the maximum continuous current of the inverter; $I_{M,max}[A]$ is the maximum MPP current of the PV module. We have now:

$$N_{P,max} = floor\left(\frac{3960\ A}{8.77\ A}\right) = 451.53 \simeq 451$$

4.5.7. Number of inverters

The number of inverters is calculated using the following formula:

$$N_i = ceil\left(\frac{N_{PV}}{N_p * N_s}\right) \quad (4.7)$$

where it is considered $N_s = N_{s,max}$ and $N_p = N_{p,max}$. The final value is obtained by rounding the result to the greater nearest integer the value obtained in the calculation.

For stand-alone configuration, the inverter must be large enough to handle the total amount of power produced at one time. Then the inverter is designed at 25-30% bigger than total loads appliances. However, for grid-tie systems, the input rating of the inverter should be same as PV array rating to allow for safe and efficient operation. From Equation (4.7), we have:

$$N_i = ceil\left(\frac{36\ 364}{451 * 24}\right) = ceil\left(\frac{36\ 364}{10\ 824}\right) = 4$$

4.6. FINAL NUMBER OF PV MODULES

As we know the PV and the PV set number (number of the inverters), the total number of PV modules found previously must be recalculated.

$$N_{PV,final} = N_s * N_p * N_i \quad (4.8)$$

We have now:

$N_{PV,final} = 24 * 451 * 4 = 43\ 296$

4.7. FINAL INSTALLED CAPACITY

Knowing the total number of PV panels which will be used in the Solar Power plant, we can calculate the final installed capacity of the power plant:

$$P_{installed} = N_{PV} * P_{M,STC} \quad (4.9)$$

The installed capacity is now $P_{installed} = 43\ 296 * 330\ W = 14\ 287\ 680\ W = 14.28\ MW$

4.8. SOLAR PV AREA

The area occupied by the PV modules will be calculated again.

$$S_{array,final} = S_{PV} * N_{PV,final} \quad (4.10)$$

$S_{array,final} = 0.991 * \ 1.956 * 43\ 296 = 83\ 924.79\ \ m^2$

4.9. TEMPERATURE CALCULATION OF THE SOLAR PANEL ($\boldsymbol{TM}$)

The performance of the PV module can be affected by its temperature that why it is important to calculate its value. The formula helped to find the temperature of the PV module is given by the equation below[56][52]:

$$T_M = T_{amb} + \frac{G_T}{800} * (NOCT - 20) \quad (4.11)$$

Where, T_{amb} [ºC] is the ambient temperature, G_T [W/m^2] is the solar irradiance at STC and $NOCT$ [ºC] nominal operating cell temperature which is defined as the temperature reached by open-circuited cells in a module under the following conditions: Irradiance on the cell surface at 800 W/m^2, air temperature at 20°, the wind velocity at 1 m/s and the coefficient air mass (AM) at 1.5. As the average ambient temperature for the city of Goma is 19.5°[47] and at STC the solar irradiance is $1000\ W/m^2$, the nominal operating temperature of the selected Solar PV at 47° from [57] , we have:

$$T_M = 19.5° + \frac{1000}{800} * (47 - 20) = 53.25°$$

4.10. MPP POWER OF EACH PV MODULE (P_M)

The PV power generation has a close relationship with weather conditions, such as the temperature, solar irradiance, hourly solar angle, and the geographical location. Suppose the rated PV power output of a single array at the MPP is $P_{M,STC}$. Influenced by temperature and solar irradiance, we have:

$$P_M = \left[P_{M,STC} * \frac{G_T}{1000} * \left(1 - \Upsilon * (T_M - 25)\right)\right] \quad (4.12)$$

With P_M the power output of the PV array at MPP, Υ the power temperature coefficient in %/°C at MPP, T_M the temperature of the solar panel in °C. From the selected PV technical data, we have $\Upsilon = -0.41\%/°C$, that “minus” shows that the power decreases at 0.41% of its value with an increase of $1°C$ to the temperature. From the calculation, using the Equation (4.12), we have:

$$P_M = \left[330 * \frac{1000}{1000} * \left(1 - 0.0041 * (53.25 - 25)\right)\right] = 291.77\ W$$

4.11. POWER OUTPUT OF EACH PV MODULE (P_{PV})

The actual output power of each PV module on year y (1 ≤ y ≤ n), day d (1 ≤ d ≤ 365), and at time t (1 ≤ t ≤ 24), P_{PV} (y, d, t, β) (W) is calculated as follows[54]:

$$P_{PV}(y, d, t, \beta) = \left[1 - y * \frac{r(y)}{100}\right] * \left(1 - \frac{d_f}{100}\right) * \ P_{M-SH}(y, d, t, \beta) \quad (4.13)$$

where β (°) is the PV modules tilt angle (0° ≤ β ≤ 90°), r(y) (%/year) is the annual reduction coefficient of the PV module output power, (if y = 1, then r(y)=0; for 1 < y ≤ n, whose value is given by the PV manufacturer), d_f (%) is the derating factor due to the dirt deposited on the PV surface [54]. P_{M-SH}(y, d, t, β) (W) is the output power of each PV module at the MPP that is calculated by taking into account the shading conditions. In this research, y is considered equal to 1, therefore r(y) = 0. Means that the PV power output is evaluated in one year. Equation 4.13 is now written as follow:

$$P_{PV}(y,d,t,\beta) = \left(1 - \frac{d_f}{100}\right) * \ P_{M-SH}(y,d,t,\beta) \tag{4.14}$$

Although large-scale PV plants are often built such that there are no obstacles surrounding the installation field, their impact on the production is considered in this design method. The percentage of the PV module total area that is shadowed by the surrounding obstacles S_P (%) as well as the hour of the day t_1(h) that these obstacles start to shadow the PV modules and the corresponding time duration of the shadow t_2(h); all these parameters are specified by the PV designer. Then, the output power of each PV module is calculated by taking into consideration the power loss due to the shading effect which is proportional to the shaded area[54][58]:

$$P_{M-SH}(y,d,t,\beta) = \begin{cases} \left(1 - \frac{S_P}{100}\right) * P_M & if\ t_1 \le t \le t_1 + t_2 \\ P_M & else \end{cases} \tag{4.15}$$

Considering the effect of shading, we have:

$$P_{PV}(y,d,t,\beta) = \left(1 - \frac{d_f}{100}\right) * \left(1 - \frac{S_P}{100}\right) * P_M \tag{4.16}$$

Where S_P are shading effect losses, set at 3% [59], the losses due to pollution d_f are set at 6.9% for a plant built on a quite sandy site, while for the one built on a more compact ground d_f are set at 1.1%. Our Solar PV power plant is designed assumed built in a compact ground.[60]

$$P_{PV}(y,d,t,\beta) = \left[1 - \frac{3}{100}\right] * \left(1 - \frac{1.1}{100}\right) * 291.77\ W = 280.47\ W$$

The shading losses used in this model are only an assumption based on results obtained by using the literature, but for more precision, a 3D model of the plant should be modelled or the real shading losses obtained by field measurements. It is possible to calculate the lost power, the following formula is used.

$$P_{PV,\ losses} = P_M - P_{PV}(y,d,t,\beta) \tag{4.17}$$

$$P_{PV,\ losses} = 291.7775\ W - 280.47\ W = 11.3\ W$$

4.12. OUTPUT POWER PER PV SET ($P_{output\ pv\ set}$)

The PV set output is calculated as follows:

$$P_{\boldsymbol{output\ pv\ set}} = N_s * N_p * \frac{\eta_{mppt}}{100} * \left(1 - \frac{\eta_{dc}}{100}\right) * \left(1 - \frac{\eta_{mismatch}}{100}\right) * P_{PV} \tag{4.18}$$

Where, η_{mppt} (%) is the MPP efficiency of the dc/ac inverter set at 99% according to [61], η_{dc} (%) is the voltage drop of the dc cable which is 1.5% according to IFC [62]. The mismatch losses, $\eta_{mismatch}$ appear due to slight difference of PV panels when manufactured. They can also be caused by PV module different conditions in the same array. They are taken at at 2% [59]. In order to obtain realistic values and to improve the above equation respectively, shading losses are added to this equation and the cable losses can be calculated in a more accurate manner. However, since our study is a preliminary project, we consider the Equation (4.18) to have the out power of each PV set ($P_{output\ pv\ set}$).

$$P_{\boldsymbol{output\ pv\ set}} = 24 * 451 * \frac{99}{100} * \left(1 - \frac{1.5}{100}\right) * \left(1 - \frac{2}{100}\right) * 280.4 = 2\ 925\ 554{,}016\ \ W$$

4.13. INVERTER OUTPUT POWER (P_O)

Based on the block diagram of Figure 4-4, each PV set has its inverter. The output power from the inverter is given by:

1. If $P_{output\ pv\ set} \leq P_{i,na}$, then

$$P_O = \frac{\eta_{inv}}{100} * P_{\boldsymbol{output\ pv\ set}} \tag{4.19}$$

Else

$$P_O = \frac{\eta_{inv}}{100} * P_{i,na} \tag{4.20}$$

2. If $P_{output\ pv\ set} \leq P_{i,sc}$, then $P_O = 0$ (4.21)

Where, $P_{i,na}$ [W] is the inverter maximum permissible power level, η_{inv} [%] is the inverter efficiency, considered the same for all the PV sets. $P_{i,sc}$ [W] is the inverter self-power consumption.

$$P_O = \frac{98.6}{100} * 2\ 925\ 554.016\ \ W = 2\ 884\ 596.2598\ \ W$$

Where, the efficiency of the inverter $\eta_{inv} = 98.6\%$ from technical data of the chosen inverter[53].

4.14. POWER INJECTED INTO THE GRID (P_{PLANT})

The power injected into the grid is given by:

$$P_{PLANT} = \frac{\eta_T}{100} * \frac{\eta_{cable}}{100} * P_O * N_i \quad (4.22)$$

$$P_{PLANT} = \frac{99}{100} * \frac{99.5}{100} * 2\,870\,064.4\ W\ * 4 = 11\,365\,886.183\ W = 11.36\ MW$$

where ηT [%] is the transformer efficiency set at 99%[54], η_{cable} [%] is the AC cable efficiency at 99.5% according to literature[63]. For practical reasons the P_{PLANT} is considered as the power that is injected into the grid, without power and voltage grid limitations. This condition is assumed to be valid: $P_{PLANT} \leq P_{grid,\ max}$ where, $P_{grid,\ max}$ [MW] is the maximum power that can be injected[52].

4.15. ENERGY INJECTED INTO THE GRID (E_{GRID})

The formula below is used to calculate the energy that is injected into the grid.

$$E_{GRID} = \frac{EAF}{100} * P_{PLANT} * \Delta t \quad (4.23)$$

Where EAF [%] is the energy availability factor of the PV plant due to maintenance and set at 99.5% [64]. Δt [h] is the time step. From Equation (4.23), we have:

$$E_{GRID} = \frac{99.5}{100} * 11\,365\,886.183\ W * 1916.25 = 21\,670\,980\,001.18\ Wh$$

$$= 21\,670.98\ MWh$$

where $\Delta t = 365 * 5.25\ h\ (average\ sunshine\ hours) = 1916.25\ hours$

4.16. SPECIFIC ENERGY GRID (SE_{GRID})

The specific energy grid SE_{GRID} is given by the total energy output divided by its installed capacity. It also means the number of hours that the PV array would need to operate at its rated power for generating the same energy. It can be expressed in Kwh/kW_p or hours. [3][65]

$$SE_{GRID} = \frac{E_{GRID}}{PSC} \quad (4.24)$$

By using the above equation, we have:

$$SE_{GRID} = \frac{21\ 670\ 980.001\ kWh}{14\ 287.680\ kW} = 1516.75\ Kwh/kW_p\ or\ 1516.75\ hours.$$

4.17. CAPACITY FACTOR (*CF*)

It is expressed by the formula below based on [65]:

$$CF(\%) = \frac{SE_{GRID}}{OH} * 100 \tag{4.25}$$

For our case,

$$CF(\%) = \frac{1516.75\ Kwh/kW_p}{8760\ hours} * 100 = 17.31\ \%$$

Generally, the capacity factor (CF) is considered as a factor that demonstrates the performance and estimated as the ratio of the specific energy production to the time of operation typically 8760 hours in a year. However, the PV system operates only in the day time, 5.25 hours in our case study. This means that the CF seems not an appropriate parameter that defines the performance, that is why the performance ratio (PR) was introduced as a new parameter to define the PV system performance.

4.18. PERFORMANCE RATIO (*PR*)

The Performance ratio is a quality indicator due to it can be used for comparing different PV systems independently of their installed capacity. This parameter is calculated by the equation which follows. [62][65][66].

$$PR(\%) = \frac{SE_{GRID}}{RY} \tag{4.26}$$

where SE_{GRID} [MWh] is the total generated energy by the plant during one year and RY is the reference yield in hours. The reference yield RY can also be expressed by the following formula:

$$RY = \frac{H}{G_T} \tag{4.27}$$

Where H is the total plane irradiance in kWh/m^2 and G_T the PV reference irradiance in kW/m^2 (the value at STC which is $1000\ W/m^2$). From the Equation (4.28) we have:

$$RY = \frac{1778\ kWh/m^2}{1\ kW/m^2} = 1778\ hours.$$

Then the performance ratio is:

$$PR = \frac{1516.75\ Kwh/kW_p}{1778\ hours} = 0.8526$$

$$PR = 85.3\%$$

4.19. ECONOMIC ANALYSIS

4.19.1. Cost of installation

The economic analysis starts with the cost of installation calculations. This can be also called the total capital cost. It includes the solar PV price, the price of the inverter, transformers, civil works of the plant, the land, the Balance of the System components (wiring, protection devices, etc.) non-electric components and the overall system price which is estimated. This is calculated using a summary of component prices by the following table:

Table 4-4:Cost of the used components

	Values
Solar PV modules [$/kW]	600
Inverter [$/kW]	50
Transformer [$/kW]	20
BOS [$/kW]	74
Civil works [$/kW]	165
Land [$/km^2]	10 000

The prices of all components are coming from these works of literature [52][67][68][69]. The total cost can be estimated in the following table:

Table 4-5:Total cost of the components used

Components	Prices ($)
Solar PV modules	8572608
Inverter	1100000
Transformer	240 000
BOS	1057288,32
Civil works	2357467,2
Land	25 000
TOTAL	13352363,52

From Table 4-5, the total capital cost is estimated at C=13 352 363.52 $. This amount can be shown in Figure 4-5, which shows the percentage taken by each component of the total cost.

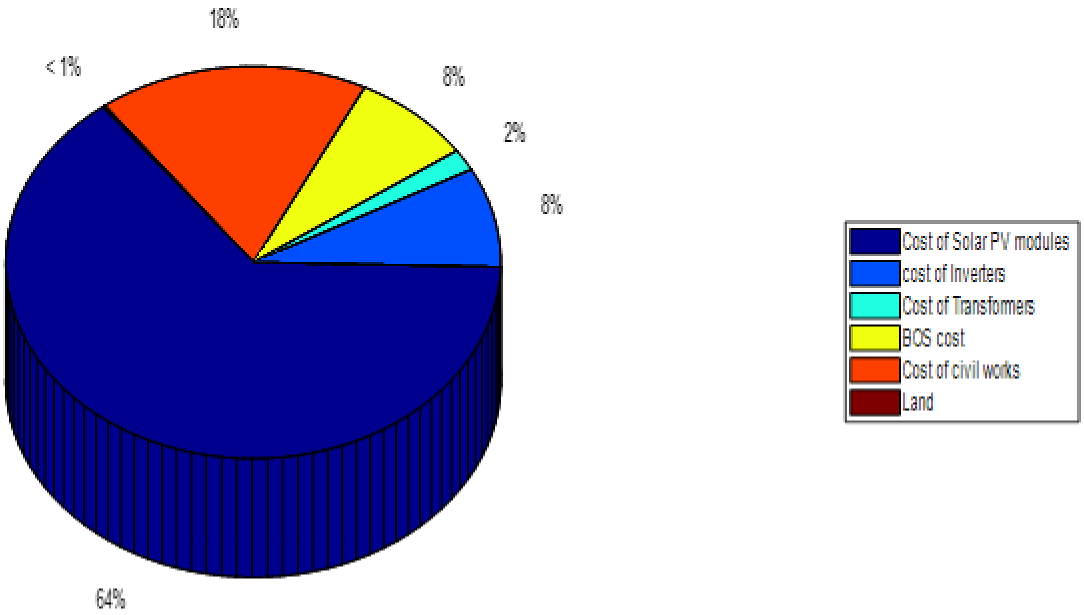


Figure 4-5: Total cost of the Solar PV installation

As it is shown on the figure Solar PV modules represent 64% of the total cost, follow then the civil works, the BOS, the inverters, transformers and at the last cost of the land which is less than 1% of the total cost.

4.19.2. Maintenance and Operations (M&O) cost

The cost of maintenance and operation during the year is calculated at 1 to 2% of the total cost of investment [70], so we have :

$$\text{M\&O} = 1\% * \text{Investment cost} \tag{4.28}$$

$$\text{M\&O cost} = 0.01 * 13\,352\,363.52\ \$ = 133\,523.6\ \$$$

4.19.3. Life Cycle Costs

The life cycle cost is concerning the initial capital cost and the long-term costs for M&O ($LTCM$). It is determined by:

$$Lcc = C + LTCM \tag{4.29}$$

In this cost calculations, the plant is assumed to operate for 25 years, at a discount rate of 10%. The large current value (present value) for the maintenance and operational costs ($LTCM$) during the project life of 25 years with a 10% discount rate is:

$$LTCM = \text{M\&O cost}\left[\frac{(1+i)^n-1}{i(1+i)^n}\right] \quad (4.30)$$

$$LTCM = 133\ 523.6\ \left[\frac{(1+0.1)^{25}-1}{0.1(1+0.1)^{25}}\right] = 1\ 211\ 994.036\ \$$$

The Lcc is then determined by

$$Lcc = 13\ 352\ 363.52\ \$\ + 1\ 211\ 994.036\ \$ = 14\ 564\ 357.556\ \$$$

4.19.4. Sale of electricity

Knowing the price of electricity for residentials in DRC at $0.05\$/\text{kWh}$ and the energy produced in the year (AEP) of the solar PV power plant at $21\ 670\ 980\ 001.18\ Wh$, we have:

$$\text{SE (25 years)} = 21\ 670\ 980.00118\ \text{kWh/year} * \frac{0.05\$}{\text{kWh}} * 25\ \text{years}\ = 27\ 088\ 725.0012\ \$.$$

4.20. CONCLUSION

As described in this chapter, the project consisted of designing a 12 MW solar PV power plant according to the electricity demand to supply electricity to Mugunga quarter in the city of Goma. The modelling of the system was developed through calculations with formula coming from specified references in the literature. Initially, we had a given capacity of the PV power plant. A 12 MW solar PV Power plant was chosen to supply the Mugunga area. With this capacity 36 364 PV modules of the manufacturer “JA Solar”, model “JAP6-72-330/3BB” were found firstly with an area of $70\ 588.235\ m^2$ for the Solar Power Plant. The calculations related to inverters led to recalculate the total number of PV at 43 296. We have found that 4 inverters manufactured by “SMA”, model “Sunny Central 2200” will be used to convert the DC electric power to AC. Each inverter is connected to its PV set which is composed of many PV modules: 24 PV modules in series forming 451 strings. This showed that each inverter consisted of 10 824 PV modules. This number of PV was designed as a « **PV set** ». From considering losses (temperature, dc and ac wiring cable, mismatch etc., we got the power injected to the grid of $11.36\ MW$. The total energy injected into the grid during a year was $21\ 670.98\ MWh$. After that we evaluated some of the PV solar power plant performance parameters as the specific yield, the capacity factor and the performance ratio and which were $1516.75\ Kwh/kW_p$ ($1516.75\ hours$), 17.31% and 0.853 respectively.

Chapter 5 : SIMULATION RESULTS AND DISCUSSIONS

5.1. INTRODUCTION

Computer simulations using PVSYST and MATLAB/SIMULINK were developed in this research work. This helped to make a comparison between the results found in the previous chapter of the design with the simulation results.[38]

5.2. PV SYST SIMULATION

This thesis aims to analyze the performance on the feasibility of operating a 12 megawatts grid-connected PV system connected to the network of Matebe hydroelectric power plant located in the city of Goma, by using a software program called PVsyst.

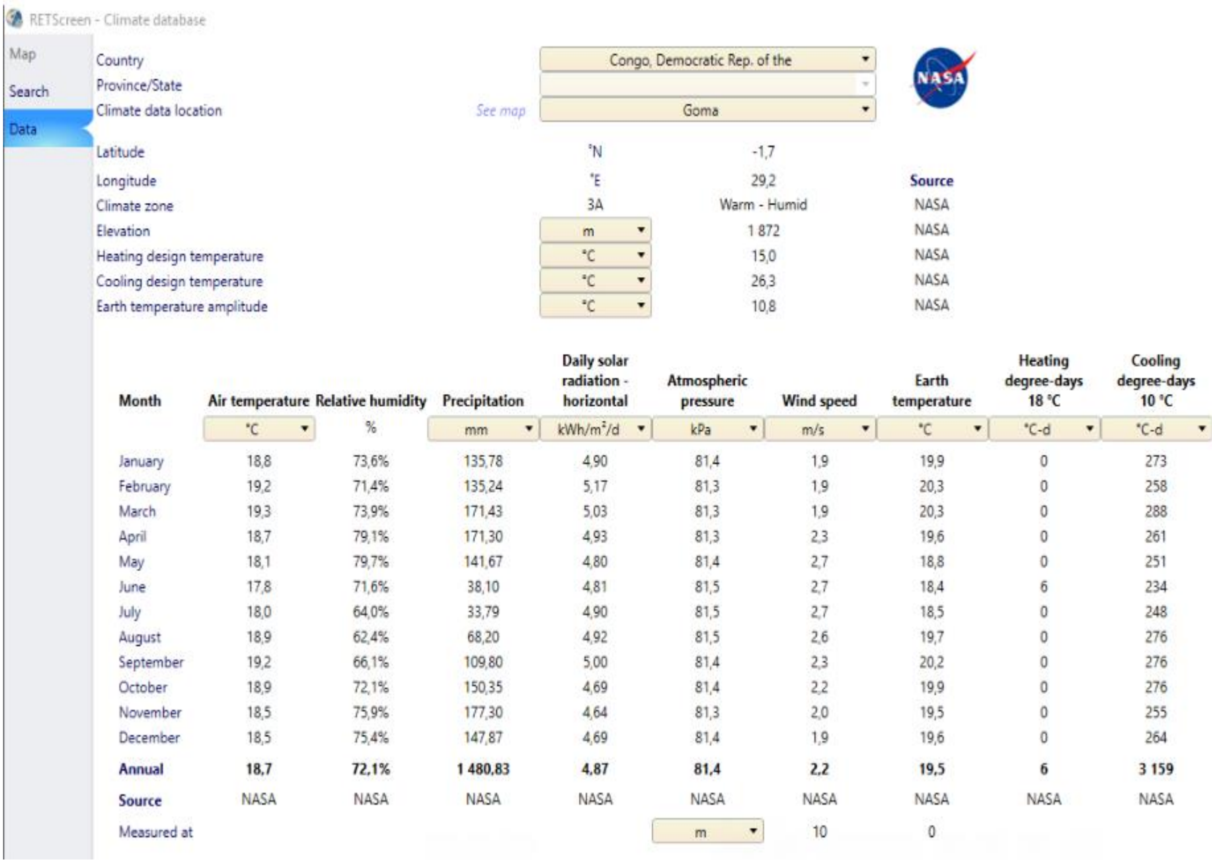
PVsyst is a dedicated PC software package for PV systems which was developed by the University of Geneva. It is a modelling tool that is used by engineers and researchers to find how much solar energy can be harnessed from a specific location. The grid-connected configuration, standalone and also pumping systems can be modelled in the PVSyst software. It includes a large meteorological statistics and other tools for studying PV systems, integrates pre-feasibility, sizing and simulation support for PV systems.[71][72]

5.2.1. Geographical and meteorological data of the selected site

The power plant is expected to be built in the city of Goma. As solar PV is an intermittent source of energy, climate and seasonal data are very important in the design and simulation of PV systems. The site selection is the first step in PVSyst software because of geographic location and meteorological data. As the chosen site is Mugunga area located in the western part of the city of Goma and we don't have its meteorological data because of the absence of the meteorological institution in the city, the entire city will be considered as the location for our simulation.

Meteorological data were obtained from Retscreen software climate database which is also based on data provided by NASA [47]. The obtained data constituted a synthetically generated hourly values of ambient temperature, daily solar radiation and the average sunshine hours of the city of Goma. These data found were saved in PVSyst for creating a new geographical site.

The city of Goma is located at latitude and longitude of -1.7° N, 29.2° E respectively and altitude of 1872 m above sea level as geographic coordinates.



RETScreen - Climate database

Map | Search | Data

Country		Congo, Democratic Rep. of the	
Province/State			
Climate data location	See map	Goma	
Latitude	°N	-1,7	
Longitude	°E	29,2	Source
Climate zone	3A	Warm - Humid	NASA
Elevation	m	1 872	NASA
Heating design temperature	°C	15,0	NASA
Cooling design temperature	°C	26,3	NASA
Earth temperature amplitude	°C	10,8	NASA

Month	Air temperature	Relative humidity	Precipitation	Daily solar radiation - horizontal	Atmospheric pressure	Wind speed	Earth temperature	Heating degree-days 18 °C	Cooling degree-days 10 °C
	°C	%	mm	kWh/m²/d	kPa	m/s	°C	°C-d	°C-d
January	18,8	73,6%	135,78	4,90	81,4	1,9	19,9	0	273
February	19,2	71,4%	135,24	5,17	81,3	1,9	20,3	0	258
March	19,3	73,9%	171,43	5,03	81,3	1,9	20,3	0	288
April	18,7	79,1%	171,30	4,93	81,3	2,3	19,6	0	261
May	18,1	79,7%	141,67	4,80	81,4	2,7	18,8	0	251
June	17,8	71,6%	38,10	4,81	81,5	2,7	18,4	6	234
July	18,0	64,0%	33,79	4,90	81,5	2,7	18,5	0	248
August	18,9	62,4%	68,20	4,92	81,5	2,6	19,7	0	276
September	19,2	66,1%	109,80	5,00	81,4	2,3	20,2	0	276
October	18,9	72,1%	150,35	4,69	81,4	2,2	19,9	0	276
November	18,5	75,9%	177,30	4,64	81,3	2,0	19,5	0	255
December	18,5	75,4%	147,87	4,69	81,4	1,9	19,6	0	264
Annual	**18,7**	**72,1%**	**1 480,83**	**4,87**	**81,4**	**2,2**	**19,5**	**6**	**3 159**
Source	NASA	NASA	NASA	NASA	NASA	NASA	NASA	NASA	NASA
Measured at					m	10	0		

Figure 5-1:Goma Climate DataBase

5.2.2. Orientation and horizon

After defining the location, the fixed tilt and azimuth are determined. A fixed tilt of 5° and zero azimuth have been considered in the simulation.

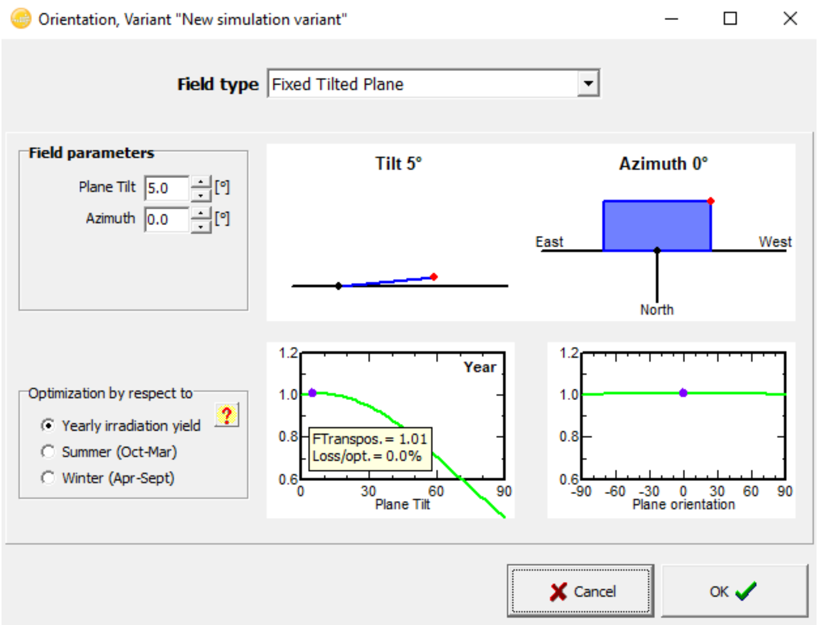


Figure 5-2: Orientation of PV panels from PVSyst

5.2.3. System configuration

In this part, we proposed a planned power of 12 000 kWp for the entire PV power plant. PVSyst gave a surface of 70 488 m^2. After that PV module (solar panel) and the inverter models are chosen in the database.

➢ **PV panels selection**

The Solar panel used in the simulation of the system is also manufactured by JA Solar, the model number JAP6-72-330/3BB. The module efficiency is 17 % with NOCT of 47°.

Table 5-1:Main characteristics of the PV module

Manufacturer	**JA Solar**
Rated power	**330 W**
Model	**JAP6-72-330/3BB**
Open circuit voltage	**46.05**
Short circuit current	9.09
Maximum voltage	38.11
Maximum current	8.6
Efficiency	17%

➢ **The inverter selection**

The chosen inverter is rated at 2200 KVA triphased working at a frequency of 50 Hz. The choice was done to the model Sunny Central 2200 of the manufacturer SMA. Its characteristics are shown on the technical datasheet [53].

Table 5-2:Main characteristics of the inverter

Manufacturer	**SMA**
Model	**Sunny Central 2200**
$V_{DC\ (max)}$	**1100 V**
$I_{DC\ (max)}$	**3960 A (at 25°) and 3600 A (at 50°)**
$V_{DC\ (MPP)}$ range	**570 V to 950 (at 25°) and 850 V (at 50°)**

$I_{AC\ (max)}$	**3300 A**
Nominal AC Power	**2200 kVA**

After the inverter and PV module selection, the program will choose the required number of inverters, according to a pre-defined nominal power array/inverter ratio of 1.25. It will then propose some modules in series, and some strings to approach the desired power or available area. The acceptable choices for the number of modules in series/parallel are mentioned in the dialogue. They should meet the following requirements [47]:

- The minimum array voltage in worst temperature conditions (60°C) should not be under the inverter’s voltage range for MPPT

- The maximum array voltage in worst temperature conditions (20°C) should not be above the inverter's voltage range for MPPT,

- The maximum array voltage in open circuit (V_{OC} at -10°C in Europe) should not exceed the absolute maximum voltage at the input of the inverter,

- The maximum array voltage in open circuit (V_{OC} at -10°C in Europe) should not exceed the allowed system voltage specified for the PV module.

If these above requirements are not satisfied, a warning message will be displayed, means there are some incompatibilities between the chosen parameters. Red warnings are not acceptable (simulation cannot be performed) and orange warnings are indicative. These colours will be thrown back on the "*System*" LED's button. The general overview of the system configuration is presented as shown below on the figure:

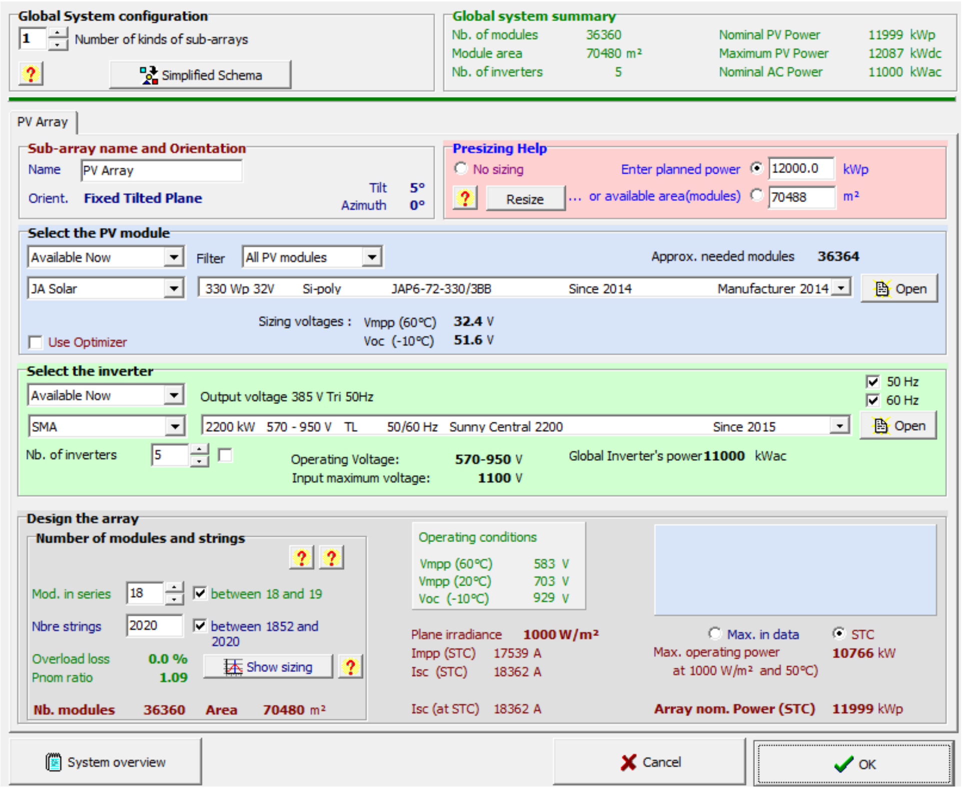


Figure 5-3:Global system configuration

There are total 36 360 panels with a maximum number of 2020 strings composed of 18 PV panels in series per string. The system is distributed in 4 parallel string inverters.

5.2.4. SIMULATION RESULTS

The simulation process involves several dozens of variables, which are stored in monthly values in the results file, and will be available as monthly tables and graphs.[47] The overall simulation has been carried out on PVSyst 6.8.1. Simulation results obtained for a proposed 12 MW PV with *PVsyst* are detailed and analyzed. From PVSyst we get these detailed results:

PVSYST V6.81		02/10/20	Page 1/4

Grid-Connected System: Simulation parameters

Project : **12 MW SOLAR POWER PLANT**

Geographical Site	**Goma**		Country	**Democratic Republic Of The**
Situation	Latitude	-1.70° S	Longitude	29.20° E
Time defined as	Legal Time	Time zone UT+2	Altitude	1872 m
	Albedo	0.20		
Meteo data:	**Goma**	NASA - Synthetic		

Simulation variant : **New simulation variant**

Simulation date 02/10/20 20h32

Simulation parameters	System type	**No 3D scene defined, no shadings**		
Collector Plane Orientation	Tilt	5°	Azimuth	0°
Models used	Transposition	Perez	Diffuse	Perez, Meteonorm
Horizon	Free Horizon			
Near Shadings	No Shadings			
User's needs :	Unlimited load (grid)			

PV Array Characteristics

PV module	Si-poly	Model	**JAP6-72-330/3BB**		
Original PVsyst database		Manufacturer	JA Solar		
Number of PV modules		In series	18 modules	In parallel	2020 strings
Total number of PV modules		Nb. modules	36360	Unit Nom. Power	330 Wp
Array global power		Nominal (STC)	**11999 kWp**	At operating cond.	10766 kWp (50°C)
Array operating characteristics (50°C)		U mpp	614 V	I mpp	17539 A
Total area		Module area	**70480 m²**	Cell area	63710 m²
Inverter		Model	**Sunny Central 2200**		
Original PVsyst database		Manufacturer	SMA		
Characteristics		Operating Voltage	570-950 V	Unit Nom. Power	2200 kWac
Inverter pack		Nb. of inverters	5 units	Total Power	11000 kWac
				Pnom ratio	1.09

PV Array loss factors

Thermal Loss factor	Uc (const)	20.0 W/m²K	Uv (wind)	0.0 W/m²K / m/s
Wiring Ohmic Loss	Global array res.	0.59 mOhm	Loss Fraction	1.5 % at STC
Module Quality Loss			Loss Fraction	-0.8 %
Module Mismatch Losses			Loss Fraction	1.0 % at MPP
Strings Mismatch loss			Loss Fraction	0.10 %
Incidence effect, ASHRAE parametrization	IAM =	1 - bo (1/cos i - 1)	bo Param.	0.05

Figure 5-4:Simulation parameters from the PVSyst software

PVSYST V6.81		02/10/20	Page 2/4

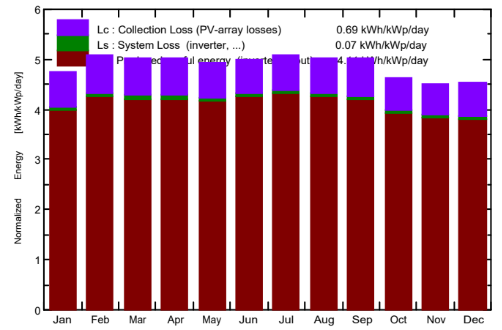
Grid-Connected System: Main results

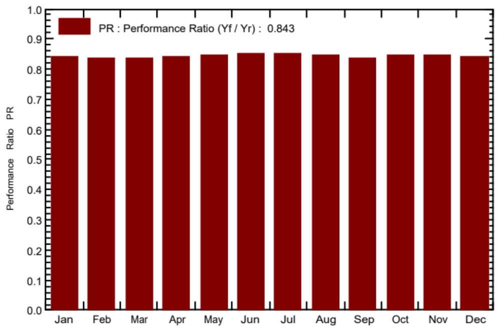
Project : **12 MW SOLAR POWER PLANT**

Simulation variant : **New simulation variant**

Main system parameters	System type	**No 3D scene defined, no shadings**		
PV Field Orientation	tilt	5°	azimuth	0°
PV modules	Model	JAP6-72-330/3BB	Pnom	330 Wp
PV Array	Nb. of modules	36360	Pnom total	**11999 kWp**
Inverter	Model	Sunny Central 2200	Pnom	2200 kW ac
Inverter pack	Nb. of units	5.0	Pnom total	**11000 kW ac**
User's needs	Unlimited load (grid)			

Main simulation results				
System Production	**Produced Energy**	**18016 MWh/year**	Specific prod.	1501 kWh/kWp/year
	Performance Ratio PR	84.30 %		





New simulation variant

Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_Grid MWh	PR
January	151.9	65.79	18.80	147.2	141.9	1509	1483	0.839
February	144.8	68.95	19.20	142.3	137.5	1453	1428	0.836
March	155.9	78.03	19.30	155.7	150.5	1592	1564	0.837
April	147.9	69.65	18.70	150.1	145.1	1540	1513	0.841
May	148.8	65.37	18.10	152.8	148.1	1577	1549	0.845
June	144.3	63.20	17.80	149.6	144.7	1558	1531	0.853
July	151.9	63.96	18.00	157.4	152.3	1634	1606	0.850
August	152.5	69.91	18.90	155.9	150.7	1612	1584	0.847
September	150.0	62.69	19.20	150.6	145.8	1536	1509	0.835
October	145.4	77.13	18.90	143.7	138.6	1486	1460	0.847
November	139.2	68.05	18.50	135.5	130.5	1400	1375	0.846
December	145.4	63.50	18.49	140.2	134.8	1440	1414	0.841
Year	1778.0	816.22	18.65	1781.1	1720.5	18336	18016	0.843

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

Figure 5-5:The main results from PVSyst

PVSYST V6.81		02/10/20	Page 3/4

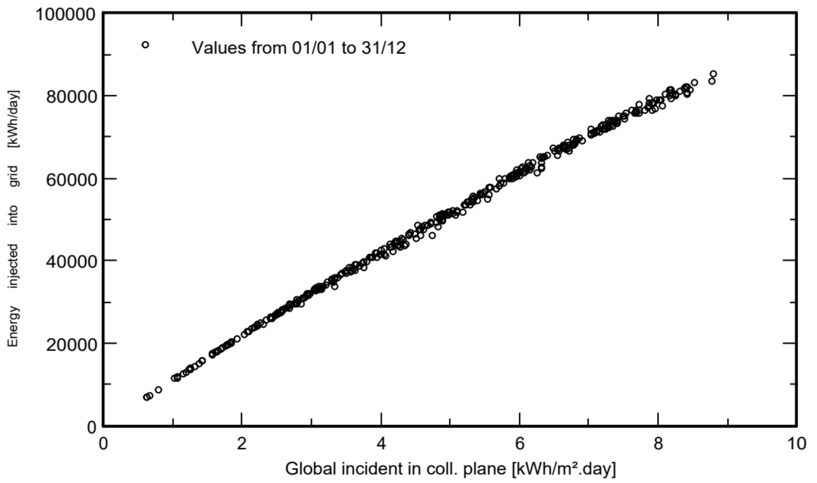
Grid-Connected System: Special graphs

Project : **12 MW SOLAR POWER PLANT**

Simulation variant : **New simulation variant**

Main system parameters	System type	**No 3D scene defined, no shadings**		
PV Field Orientation	tilt	5°	azimuth	0°
PV modules	Model	JAP6-72-330/3BB	Pnom	330 Wp
PV Array	Nb. of modules	36360	Pnom total	**11999 kWp**
Inverter	Model	Sunny Central 2200	Pnom	2200 kW ac
Inverter pack	Nb. of units	5.0	Pnom total	**11000 kW ac**
User's needs	Unlimited load (grid)			

Daily Input/Output diagram



System Output Power Distribution

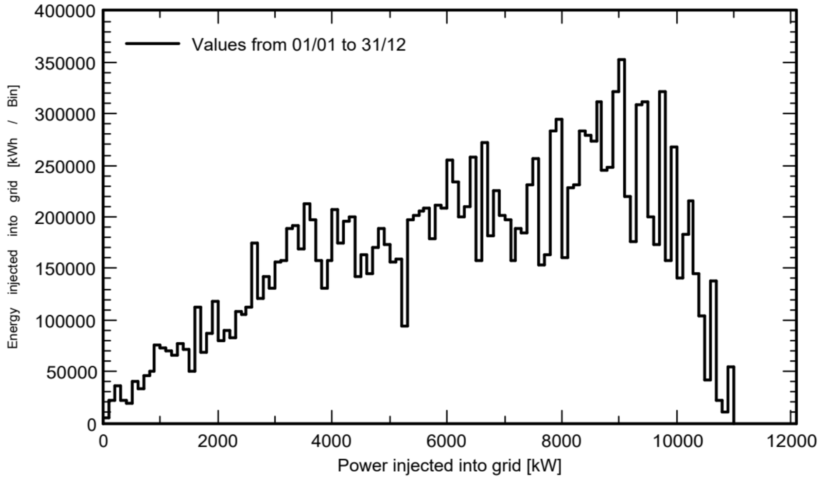


Figure 5-6: Special graphs of the Grid-connected

PVSYST V6.81		02/10/20	Page 4/4

Grid-Connected System: Loss diagram

Project : **12 MW SOLAR POWER PLANT**

Simulation variant : **New simulation variant**

Main system parameters	System type	**No 3D scene defined, no shadings**		
PV Field Orientation	tilt	5°	azimuth	0°
PV modules	Model	JAP6-72-330/3BB	Pnom	330 Wp
PV Array	Nb. of modules	36360	Pnom total	**11999 kWp**
Inverter	Model	Sunny Central 2200	Pnom	2200 kW ac
Inverter pack	Nb. of units	5.0	Pnom total	**11000 kW ac**
User's needs	Unlimited load (grid)			

Loss diagram over the whole year

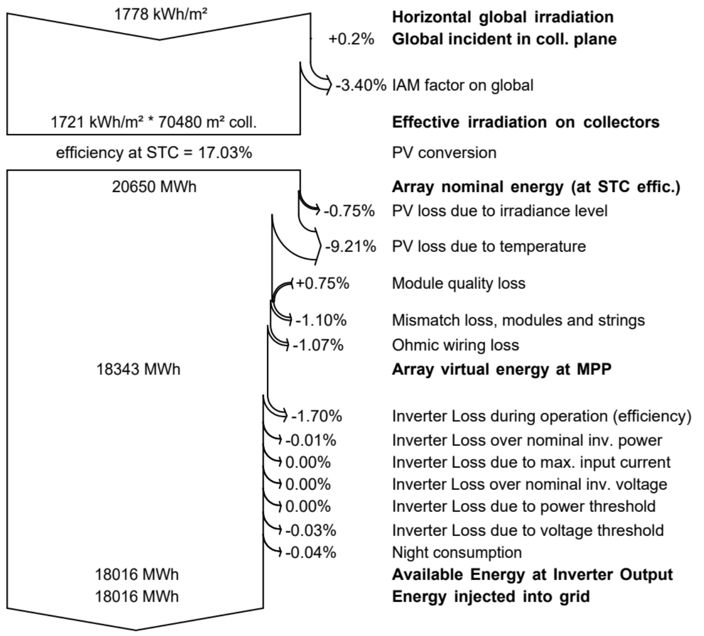


Figure 5-7:Loss diagram of the Solar PV grid-connected

5.3. RESULTS INTERPRETATION

This part consists of a comparison between the simulation results from PVSyst and the one found in the calculation method.

Table 5-3:Results comparison from PVSyst and calculations

	PVsyst	Calculations
Number of PV modules in series	**19**	**24**
Number of PV modules	**36 360**	**43 296**
AC Output power (kW ac)	**11000**	**11 365.886**
Number of inverters	**5**	**4**
AEP [MWh/year]	**18016**	**21 670.98**
PR [%]	**0.843**	**0.853**
Specific yield [kWh/kWp]	**1501**	**1516.75**

The difference of results between simulation and calculations related to the number of PV and inverted to be used, the AC output value, the surface of the PV power plant, etc., are caused by the following reasons:

- The applied formula and methodology are not the same
- PVSyst is based on a combination of the experimental and manufacturer data, while the technical data considered in the calculation method is entirely based on the information got from the manufacturer.
- The meteorological data used in the city of Goma is not coming from the same sources, this can affect the found results.

From the comparison of different values, we have found that the AC output power obtained in PVsyst simulation is around 3.21 % less than the AC output from calculations. This is due to the reasons specified above. The values of output power were $11000\ kW$ and 11365.886 kW from the PVSyst simulation and calculations, respectively.

5.4. MATLAB/SIMULINK SIMULATION

The Matlab simulation was carried out by showing the graph of the power, current and voltage at every point of the system. This enabled us to have a look at how the signal is varying depending on the input parameters which are the irradiance and the temperature of the PV module.

5.4.1. Block diagram of the system

In this part, the overall system block is shown. As our system is composed of 4 inverters to produce the 11.3 MW, let first design the PV set means the topology per inverter. This is shown in Figure 5-8, which represents a block diagram for the PV set.

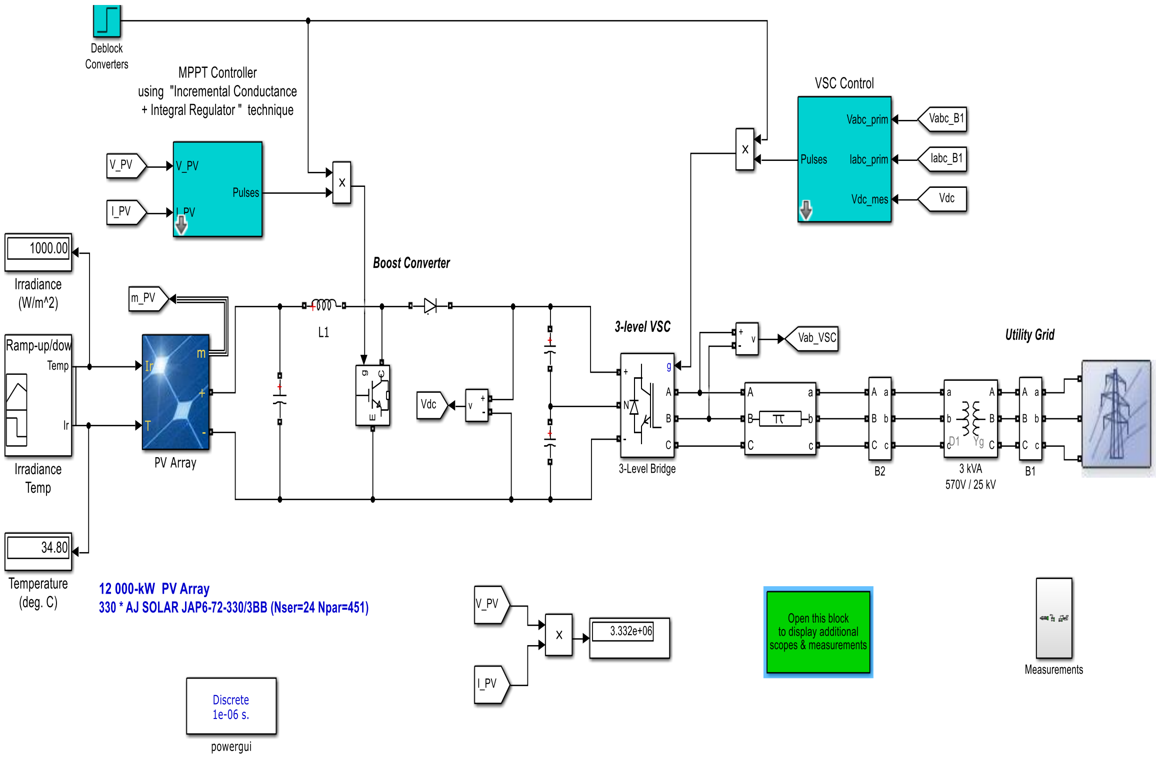


Figure 5-8: PV Set Block diagram of the system

The PV array used in Matlab is edited to parameters of the modules chosen to supply electric power. As the PV module is chosen was not in the NREL database of Matlab/SIMULINK, which includes manufacturer datasheets measured under standard test conditions, the user-defined option was selected and the values of its parameters edited (Figure 5-9).

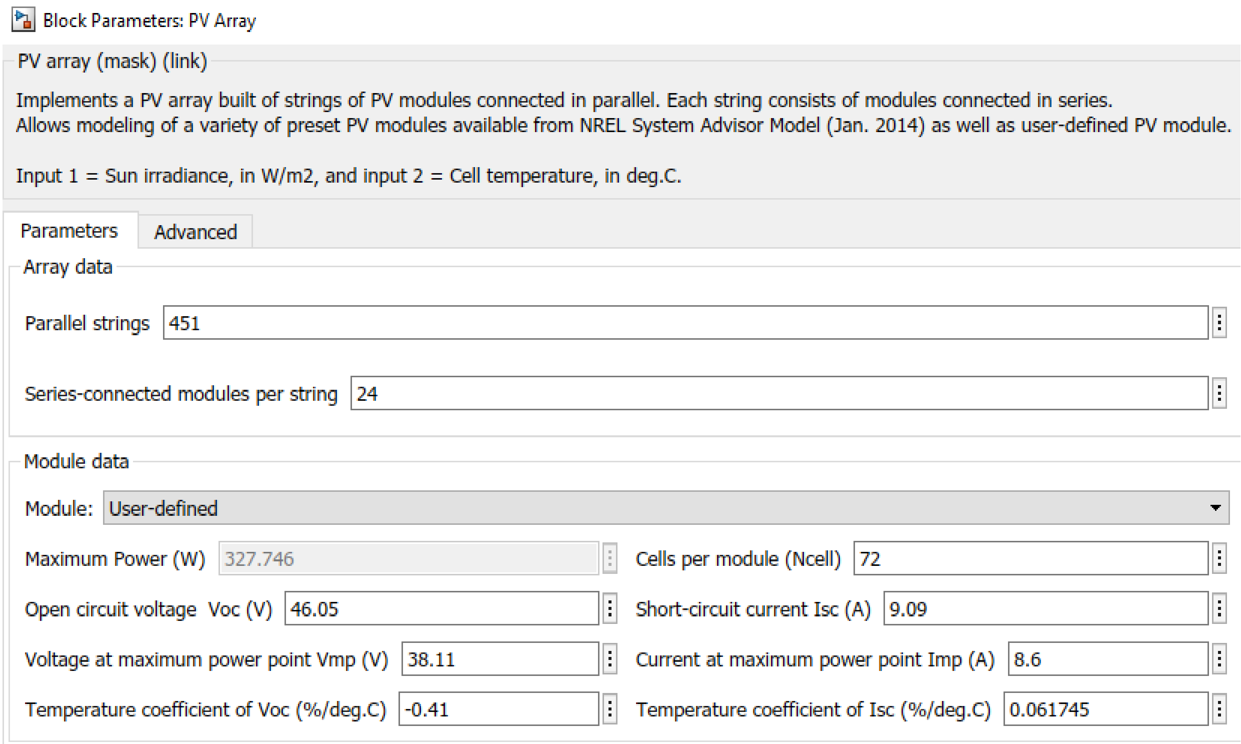


Figure 5-9: PV configuration

After the configuration of all the components used, the results are shown in the following graph. The signal of these graphs is varying according to the total amount of sunlight means the irradiance and the temperature of the PV array.

5.4.2. Simulation results

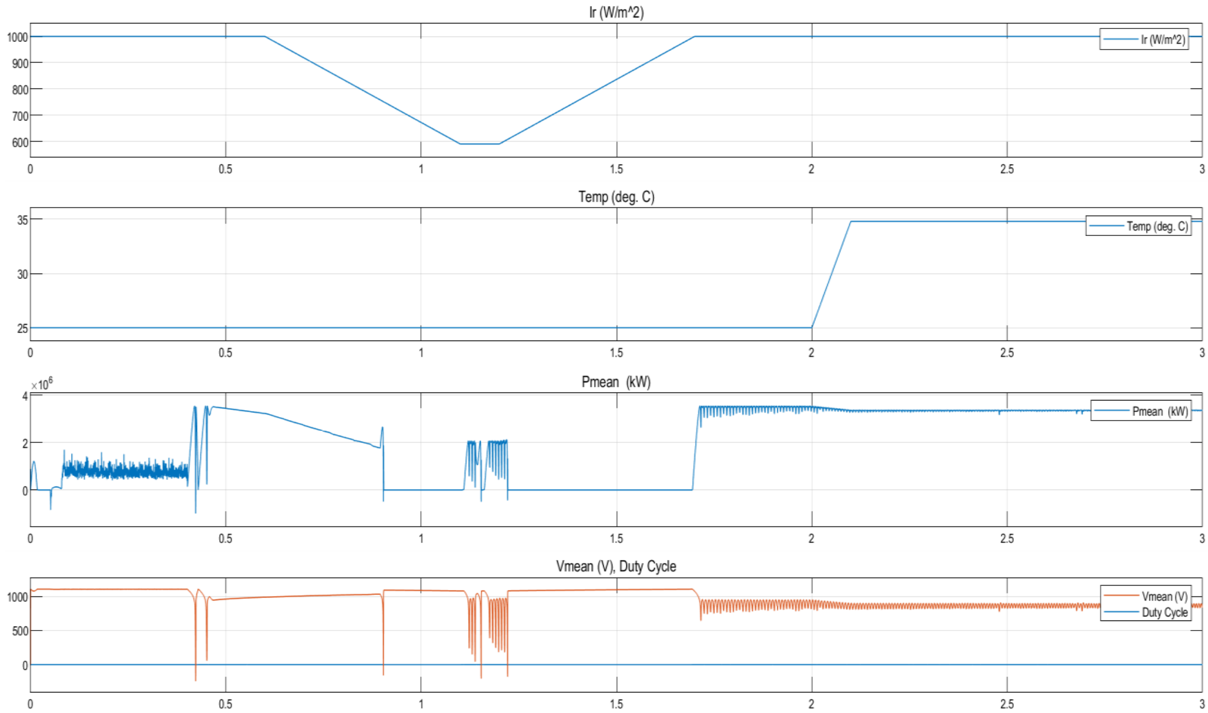


Figure 5-10:Graph of power, the voltage of the PV array

The output power from the PV Set is changing depending on temperature and the irradiation. As it is shown in the Figure 5-10, at the point of minimum value of temperature(25°C) and the irradiance of 600 W/m^2, the output power is less than the other points of the graph. This shows that the temperature and the irradiance of the selected site play an important role.

5.5. PARTIAL CONCLUSION

The fifth chapter consisted of simulation using PVSyst and Matlab software. The simulation results led to approximate values from those found in the calculation method. It was also showed that the annual energy production of the designed grid was found at 18016 MWh/year from PVSyst while we have found 21 670.98 MWh/year in the calculus. The simulation of the PV power plant demonstrated that the system will be performant because of its acceptable performance parameter. The Matlab simulation has been carried out and showed the evolution of the PV output related to some changing variables of the irradiance and temperature.

GENERAL CONCLUSION AND RECOMMENDATIONS

By the end of this research, it is shown that the objectives were attained. The study consisted of the integration of a solar PV power plant through its design using calculation and simulation method. We calculated electrical parameters from the installed PV modules up to the grid side with the total energy injected to the grid. Both methods led to approximate values instead of using different sources.

The meteorological data or climate data for the city of Goma were considered in the modelling because of the lack of data related to Mugunga quarter, where the PV will be implanted, which is located in the city of Goma. The load calculation of the Mugunga quarter was found at 10.9 MW of electric power needed. A 12 MW grid-connected solar PV was proposed to increase the electricity access rate of this area. The results obtained proved that the project is feasible because of the following facts:

- As there are no hydroelectric resources near the city of Goma, solar energy is the one to use for getting electricity. It is the available resource of electrical energy.
- The city of Goma is located in the region with a medium level of irradiance in the DRC
- During sunshine hours, the energy injected to the grid can be used to supply the loads and in the night time, these will be supplied by the grid.
- Mugunga has some unoccupied vast areas that can be used to produce electrical energy. It is a suited place to implement a Solar PV System to reach a high amount of energy. The shading is less than in the other places in the city of Goma.

In future we expect the Government of the DRC and some investors to focus and invest on solar energy in the city of Goma by building some large-scale PV solar power plant as this energy is the available resources of the city of Goma. It is also the energy for future generations. Such kind of projects can increase the electricity access rate and contribute to the sustainable development of the entire nation while becoming a business for potential investors.

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