School of Information Technology and Engineeri
the ADA University

School of Engineering and Applied Science
at the George Washington University

INTEGRATION OF RENEWABLE ENERGY SOURCES INTO THE ENERGY SYSTEM

A Thesis
Presented to the Graduate Program of Electrical and Power Engineering
of the School of Information Technology and Engineering
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By
(Mammad Mammadli)

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THESIS ACCEPTANCE

This Thesis by: [Mammad Mammadli]
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ABSTRACT

This thesis discusses the integration of renewable energy sources into electrical power systems, with a focus on the design, simulation, and optimization of a 445 MW solar power plant located in Bilasuvar, Azerbaijan. Using highly specialized software like PVsyst and PowerFactory, the study evaluates the prospect of energy production, grid stability, environmental benefits, and economic feasibility. Establishing the solar park will not only lower greenhouse gas emissions, in line with Azerbaijan's sustainability objectives and the global push to adapt clean and efficient systems, but also satisfy the rising energy demands of Azerbaijan at the same time. Analysis results presented a high level of system efficiency and operational reliability, providing evidence of its annual yield of 684 GWh and an 87.7% Performance Ratio.

The study analyzes the power system's stability at different states of solar irradiance, demonstrating the efficient integration of solar power in Azerbaijan's electrical grid. Simulation results under PowerFactory underline the importance of dynamic stability in terms of guaranteeing a non-interrupted supply of energy even under changes in solar production. Furthermore, the environmental assessment presents a huge impact: more than 3 gigatons of CO_2 emissions avoided over the whole 30-year lifetime of the plant, underscoring the importance of this project for fighting climate change. The financial analyses confirm economic viability through a payback period of 10.9 years and an investment return of 129.6%, hence very attractive to stakeholders and investors.

The Bilasuvar Solar Park epitomizes Azerbaijan's potential in harnessing solar energy using its geographical advantages of high solar irradiance and favorable climatic conditions. This is further enabled by the incorporation of advanced technologies like monocrystalline photovoltaic modules and central inverters with Maximum Power Point Tracking (MPPT) to improve energy yield and system reliability. The thesis provides pragmatic recommendations for improving the efficiency of a solar plant, dealing with losses in the system, and optimizing design parameters in large-scale solar projects.

This will improve the integration of renewable energy in existing power grid infrastructures as a whole through advanced simulation. It puts forward flexible solutions applicable in various contexts and underlines innovative methodologies needed for the deployment of renewable energies. This, in fact, gives the greatest importance to proper planning and highly complex simulation methods involving collaboration between energy planners, policymakers, and industry actors. The results from this research are supposed to lead future initiatives on renewable energy, helping Azerbaijan transform towards a sustainable energy future and providing a framework for addressing global energy and environmental challenges.

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LIST OF ABBREVIATIONS

Abbreviation	Explanation
AC	Alternating Current
CAPEX	Capital Expenditure
CO_2	Carbon Dioxide
DC	Direct Current
CAPEX	Capital Expenditure
DIgSILENT	Digital Simulation and Electrical Network Tool
GHG	Greenhouse gas
GWh	Gigawatt-hour
HV	High voltage
LCOE	Levelized Cost of Energy
MPPT	Maximum Power Point Tracking
NPV	Net present value
OPEX	Operating Expenditure
P/O	Perturb Observe
PR	Performance Ratio
PV	Photovoltaic
ROI	Return on investment
STC	Standart Test Condition
VOC	Open circuit voltage
PSH	Peak Sun Hours

CHAPTER ONE

INTRODUCTION

Modern electric power industry requires the design and operation of electric power systems in an economic manner. With the fast depleting state of natural resources, efficient use of existing energy sources is very necessary to lower operating costs and to meet stringent environmental regulations. At the same time, many planning and operational strategies are including a power system reliability analysis. In addition, there has been a high interest in renewable energy sources over the past years. In some aspects, they are much more advantageous compared to traditional fossil fuels. For instance, they do not consume the limited fuel reserves and are environmentally friendly. Some of these renewable energy technologies, like solar panels, are time-dependent.

In the middle of the reducing availability of fossil fuels, the world is getting off with renewable sources of energy motivated by both ecological concerns and strategic imperatives of providing security for energy. Accordingly, in view of mounting pressure to meet demand, taking into consideration the urge to minimize the increase in greenhouse gas emissions, sustainable energy projects have obtained priority worldwide, including in Azerbaijan. Azerbaijan is well-placed to exploit solar energy for achieving energy security in the country and the region since it is located at an advantageous geographic position and is rich in solar resources.

The traditional electrical infrastructure of fossil fuels in Azerbaijan has been very carbon-intensive. The government has hence set aggressive goals on renewable energy to further push for diversification of its energy system toward sustainability. One of the big steps towards this conversion by Azerbaijan is the integration of the 445 MW solar power plant in the Bilasuvar region, on which this thesis is based.

The Bilasuvar region has been selected based on favorable climatic conditions, such as high solar irradiance, minimal cloud cover, and available land resources. The project utilizes advanced technologies and sophisticated simulation tools for increasing energy production while keeping the grid stable and investigating environmental and economic benefits. This study provides very meaningful insights into the potential challenges and solutions of large-scale solar integration in Azerbaijan under various operational scenarios simulated.

To achieve these objectives, two of the most well-known software programs, PVsyst and PowerFactory, have been used [25]. PVsyst allowed the modeling of energy production and performance characteristics of the solar plant by providing detailed analyses of system losses, shading effects, and module efficiency. The use of PowerFactory enabled the reproduction of the dynamic behavior of the electrical grid in order to assess its ability to integrate large renewable energy sources while remaining stable. The combination of these tools allows for a thorough assessment of the technical and financial viability of the solar park.

Results from such a study will, therefore, help the industrialist, energy planner, and lawmaker to realize the existing dynamics relating to the realistic integration of renewable sources of energy. The findings demonstrate how advanced modeling and simulation approaches can support the successful implementation of solar energy initiatives to offer scalable solutions for different regions in Azerbaijan and beyond.

The present research aims at contributing to the increasing literature dealing with the integration of renewable energies, underlining the crucial importance of thorough planning, sophisticated simulation techniques, and cutting-edge technologies.Effective execution of the Bilasuvar Solar Park provides one example for future projects within this domain, and an effective potential of solar power to supply energy demands along with challenging environmental issues altogether.

PROBLEM STATEMENT

The main purpose of the thesis project is the design of a new solar park for installation in Bilasuvar and detailed analysis of all processes. The initial input parameters, such as the general installed capacity of the solar park, the geographical location coordinates, as well as initial parameters necessary to start the process of integration, were provided by Azerenergy OJSC. To fully realize all the benefits of solar energy, it becomes important to address the many challenges related to network stability, energy losses, and system efficiency. In the process of designing and simulating the 445 MW solar park located in Bilasuvar, this research will analyze important aspects such as the reduction of losses of the solar park under development with minimum losses, the financial feasibility considered acceptable, and the reduction in carbon dioxide emissions released into the atmosphere. All the findings will be explained in detail within the thesis.

DEFINITION OF TERMS

1. Array Characteristics: PVsyst provides advanced analysis of your photovoltaic system

2. Losses of Solar Park: The analysis of losses in PVsyst thus creates a premise where, based on that premise, one can pursue overcoming shortcomings in energy production while proposing a sure and efficient installation.
3. Grid Integration: The ability of an electrical grid to integrate full of solar energy into the energy system
4. Performance Ratio (PR): A measure of effectiveness of a photovoltaic system, comparing the output power to the theoretically possible energy production, given ideal conditions.
5. Financial Analysis of Solar Park: That means the approach to determining the ROI for solar energy systems should have a fiscal estimate of the benefits as well as the costs incurred in installing and operating solar panels.

SIGNIFICANCE OF THE STUDY

This study carries importance on manifold dimensions:

1. Solar Park design: The paper discusses the integration of large-scale solar power plants within the electrical grid, addressing issues such as stability, efficiency, and energy loss.
2. CO_2 Emission balance: Helps to explain how renewable energy can significantly reduce CO_2 emissions and combat climate change.
3. Financial Analysis: Assesses the financial sustainability of solar energy initiatives, providing analysis regarding cost-effectiveness and return on investment.

LIMITATIONS OF THE STUDY

This study has a few limitations:

1. Analytical Scope: This discussion is solely about solar power and does not embrace any consideration of other kinds of alternative energy, including wind or hydropower sources.
2. Geographic Specificity: The results are specific to the Bilasuvar area and may not be usable directly for areas with a different set of climatic conditions or grid parameters.
3. Economic Variables: Changes in the global prices of solar panels, currency conversion rates, and inflationary trends may impact the economic appraisal.

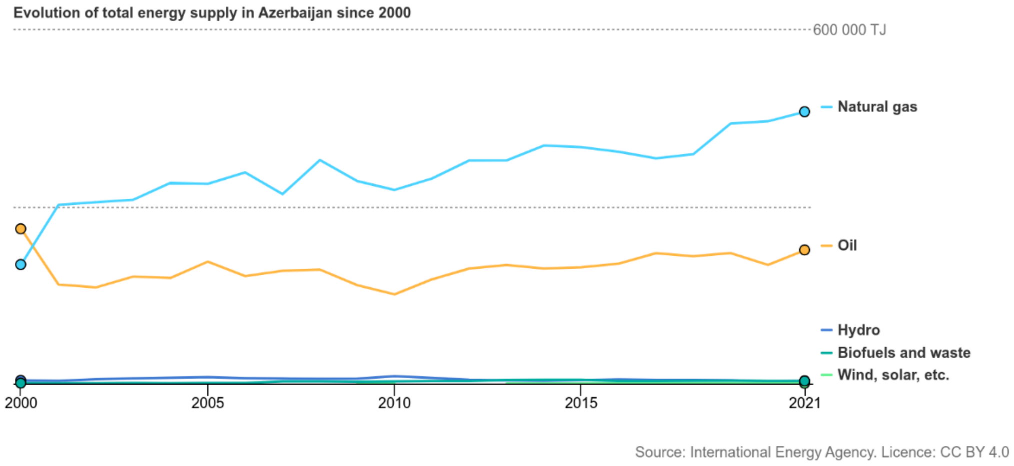
CHAPTER TWO

REVIEW OF THE LITERATURE

Over the last two decades, more than 85 tools have been proven as a result of increasing trends in the development of new models in energy planning [1], [2]. Most of them were great contributors to the strategic formation of integrating renewable energies in national energy systems [2]. Many of these models are exploited in Latin America [1], [3]. Three possible long-term simulation models on integrating renewable energy in South America were done using the Open Source Energy Modeling System [4].

2.1. Azerbaijan's Renewable Energy Potential.

Oil and natural gas are currently the most essential and used energy sources. However, growing concern about environmental sustainability and the depletion of fuels forces humanity to shift toward cleaner renewable energy sources. This is a review paper on information concerning wind and solar power potential in Azerbaijan, alongside some barriers to integration that are leading experts to implement new models to integrate those sources of energy into an electric grid to have secure and stable delivery.



Source: International Energy Agency. Licence: CC BY 4.0

Figure 2.1. Evolution of total energy supply in Azerbaijan since 2000

2.1.1. Current Energy System

Several studies have analyzed Azerbaijan's energy sources and highlighted its dependence on fossil fuels [5, 6].

Natural gas accounts for more than 90% of electricity production in Azerbaijan, and the share of hydropower resources playing a minimal role [6].

Also, the system has the ability to be self-sufficient due to the high electrical energy it produces and can significantly exceed its internal demand [7].

2.1.2. Solar Energy

Azerbaijan possesses significant potential for solar energy integration due to its favorable climatic conditions, characterized by abundant sunshine. Statistical data suggests that the technical potential of solar energy in Azerbaijan is estimated to be near 23,000 MW. Notably, the regions with the most promising solar resources are concentrated in the central river valleys, along with the northern and northwestern parts of the country [8].

2.1.3. Wind Energy

Azerbaijan boasts significant wind energy potential, particularly along its Caspian Sea coastline. Studies estimate the technical potential to be around 3,000 MW, while the economic potential is estimated at 800 MW [8]. This economic potential translates to an environmentally friendly energy generation capacity of approximately 2.4 TWh/h. Notably, exploiting this potential would lead to a reduction in CO2 emissions and a potential savings of 1 metric ton of conventional fuel.

A collaborative study by the Azerbaijan Scientific Research and Project Energy Institute and the Japanese company "Tomen" revealed an average annual wind speed of 7.9–8.1 meters per second (m/s) in the Absheron region. This finding, coupled with the country's overall average wind speed of 6 m/s, provides strong evidence for the technical and economic viability of wind energy in Azerbaijan [8].

2.2. State-of-the Art Solar Integration

First, the Maximum Power Point Tracking algorithm is necessary in integrating the solar energy for maximum efficiency of the solar panel. The days with solar irradiance of about 1000 W/m2 and above give higher productions of electricity. Thus, this proves the efficiency of the solar panel to be 10% [9]. In a photovoltaic panel, there is an important point in both P-V and I-V curves; it is known as MPP. At this point, monitoring of the PV system is important, to be operated continuously and to provide as much electricity as the PV panel can transmit to the load for increasing the efficiency of the system [10]. MPPT thus enables a responsive adjustment of the irradiance and temperature profiles that are coupled to MPP in a PV system. This approach aids in improving the operational efficiency of solar module technology [11].

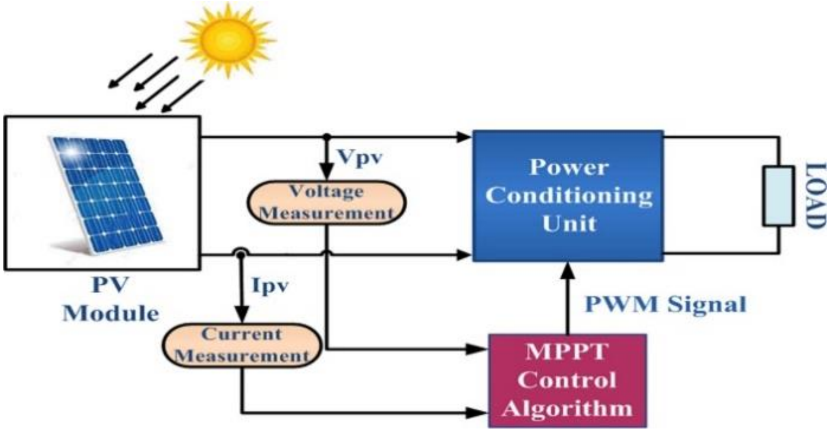


Figure 2.2. PV module using MPPT Control Algorithm

MPPT utilizes a variety of algorithms in order to further improve the electric output of PV systems. This section delves into a review of studies examining the performance and characteristics of various MPPT algorithms.

Conventional Techniques

- Fractional Short-circuit current
- Perturbation and Observation (P&O)

Soft Computing Techniques

- Fuzzy Logic Control

2.2.1. Conventional Fractional Short-circuit current

In the fractional short-circuit approach, the photovoltaic module operates under constant current conditions. This method is based on the fact that the MPP appears when the operating current of the PV array is within the range 78% to 92% of the ISC [12]. From the above, it can be noticed that the FSCC algorithm needs to short-circuit the PV panel each time in order to acquire the short-circuit current. The result of this process is power loss at the end, and an approximate tracking of MPP will be achieved [13], [14].

$I_{MPP}=K_i*I_{SC}$ (K_i is a constant of compliance)

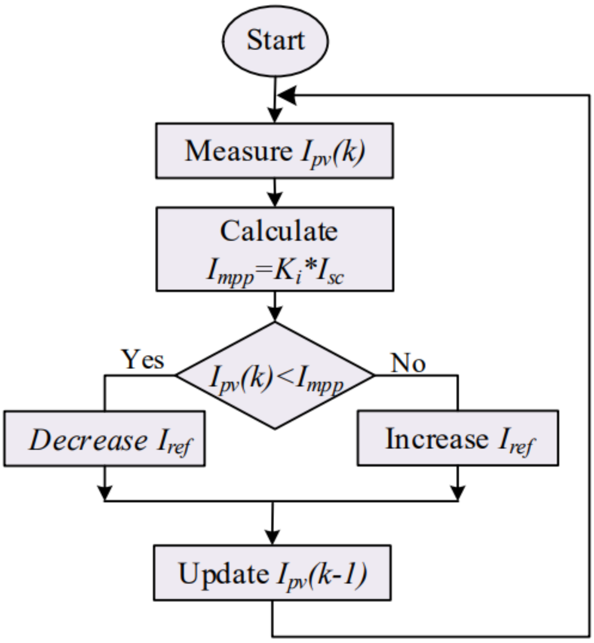


Figure 2.3. Flowchart of the FSCC algorithm

2.2.2. Perturbation and Observation (P&O)

The approach enables the solar panel to provide the maximum available electricity consistent with the dynamic changes in solar radiation during operating periods of the inverters. The power conditioning unit of the photovoltaic solar system has, in this regard, the MPPT controller whose duty cycle is varied according to changes in both of irradiance and temperature [15-17]. You can find huge amount of details on Research Methodology chapter related to P&O.

2.2.3. Fuzzy Logic Control

The fuzzy logic-based Maximum Power Point Tracking system for solar panels has 2 inputs and 1 output. These inputs are representative of the percentage of error and the variation (rate of change) of this error, both obtained from real-time energy monitoring [18]. The fuzzy logic controller subsequently processes these inputs to ascertain the suitable output, which adjusts the switching frequency employed in the regulation of the Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs) present within the system [19]. At the Maximum Power Point (MPP), the error value nears zero. Nonetheless, the fluctuation of the error offers supplementary insights regarding the power trajectory. This would allow the controller, once the operating point moves away from the MPP, to make a bigger change in the switching frequency in order to bring it towards the MPP [20]. The relationship between the inputs and the output is determined by some sort of correlation function, whereas the output range depends on specific design considerations [20]. This dynamic adjustment of the switching frequency is based on the system's observed response to such changes. As evidenced by Table [21] (not shown here), numerous researchers have investigated various MPPT techniques, and the table summarizes their key findings.

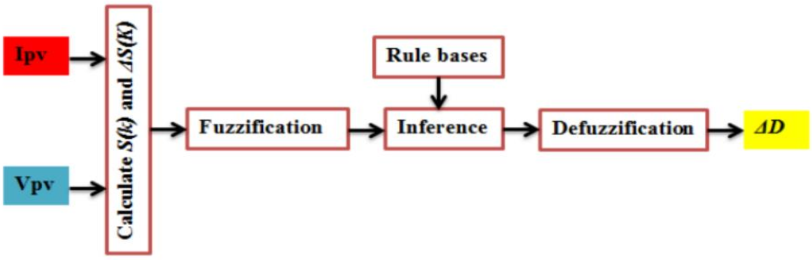


Figure 2.4. Structure of FLC

Table 2.1. Summary of related works for different MPPT methods [21].

MPPT Method	Reference	Year	Observations
FLC	[22]	2014	They compared the FLC technique with the P7O technique and concluded that the FLC technique was the superior technique regardless of different weather conditions.
P&O	[23]	2018	After presenting the P&O algorithm based on voltage sensors, the simulation and experiment results showed that the proposed method successfully improves the dynamic and steady-state tracking performance of the PV system with less material cost.
SCC	[24]	2021	They implemented a further improved MPPT using the SCC technique and obtained minimal energy loss and more perfect accuracy compared to the classical fractional SCC algorithm.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1. Solar Park Area Details

The methodology section presented herein will henceforth discuss site selection in the Predisposing conditions for the development of solar energy projects are available in the Bilasuvar district, which is located in a semiarid zone. The Bilasuvar region of Azerbaijan is promising due to high levels of solar irradiation and clear skies, which are essential for maximizing PV output. The site selection can be justified on the basis that this region receives substantial annual solar radiation, minimal cloud cover, and adequate land availability, all positively contributing to PV system efficiency [45]. The exact nature of the regional climate needs to be understood, including such things as solar irradiance, variation in temperature, seasonal patterns, and wind condition, before any proper assessment of the solar potentials can be made along with the estimation of energy production. In Fig. 1, the Global Solar Atlas published by the World Bank is illustrated. In this region, high levels of solar irradiance are observed. Therefore, Bilasuvar can be an ideal location for big-scale solar installations [26] due to following reasons:

Solar Irradiance: The Bilasuvar region receives high levels of solar irradiance, with annual averages ranging from 4.5 to 5.0 kWh/m^2 per day, making it one of the most suitable areas in Azerbaijan for solar energy generation. This level of irradiance contributes to a high annual energy yield, even during winter, maximizing the viability of large-scale solar installations [2].

Geographical Location: Positioned in southern Azerbaijan, Bilasuvar benefits from a semi-arid climate, which minimizes the likelihood of prolonged cloud cover and precipitation, ensuring that solar panels receive consistent sunlight and reducing system downtime [27].

Moderate Seasonal Temperature: With average summer temperatures around 30°C, Bilasuvar's warm climate can lead to minor efficiency losses in PV systems; however, its natural breeziness helps passively cool PV modules, improving performance. During winter, the mild temperatures minimize thermal stress on equipment, potentially extending its lifespan. Such climate advantages improve system performance and reliability [28].

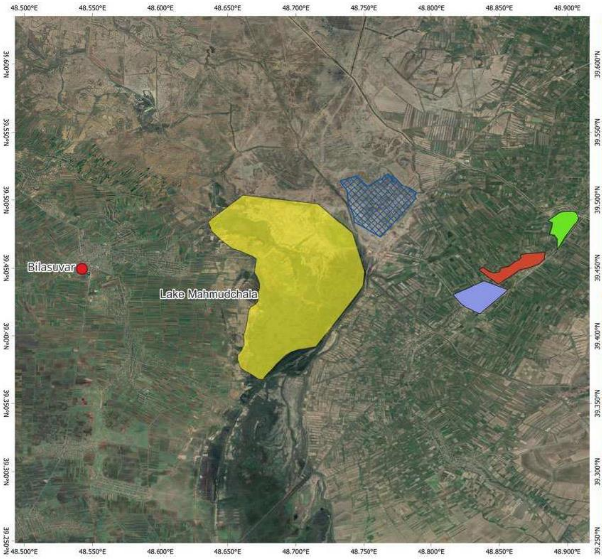


Figure 3.1. Area of Bilasuvar Solar Park

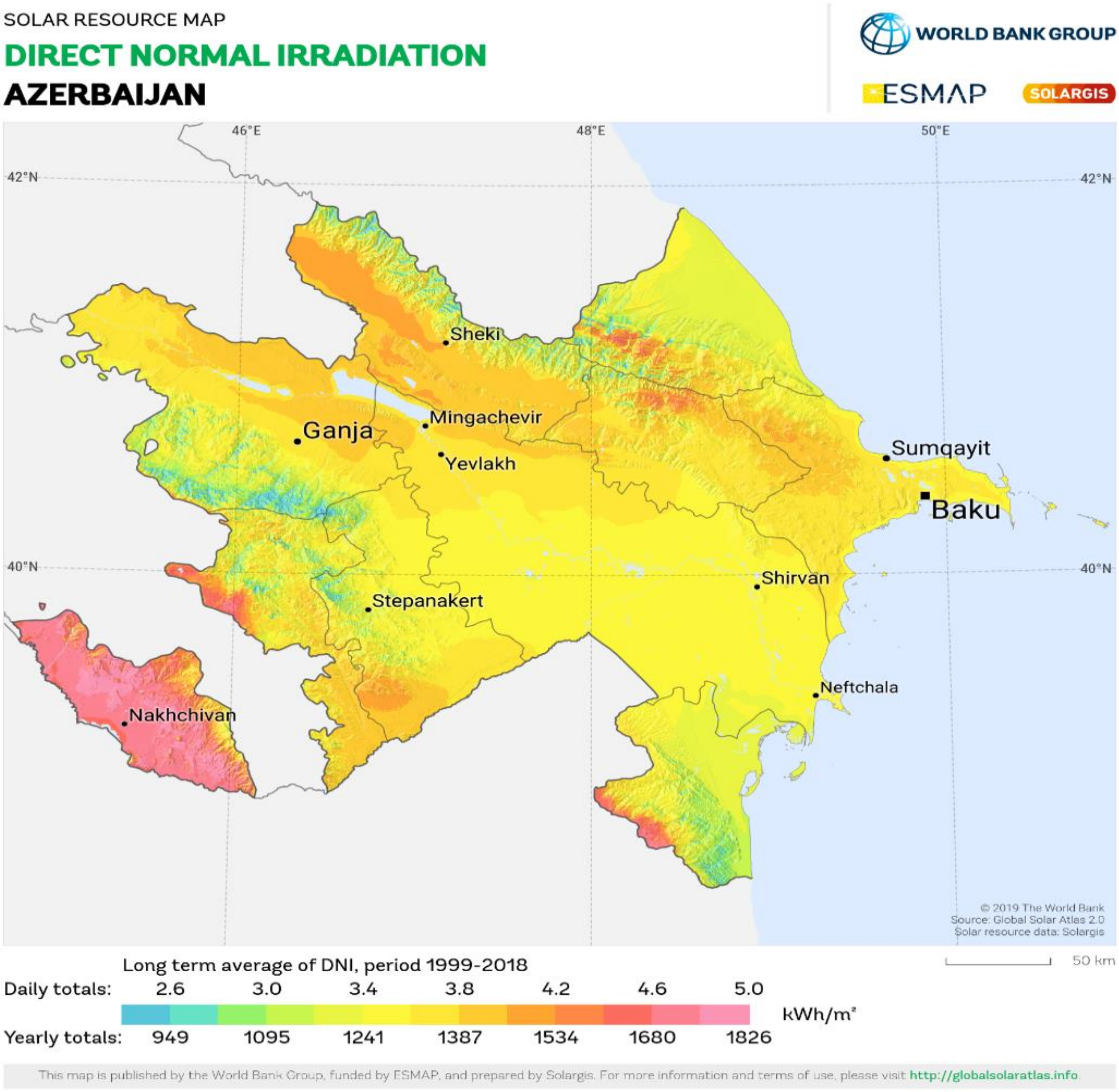
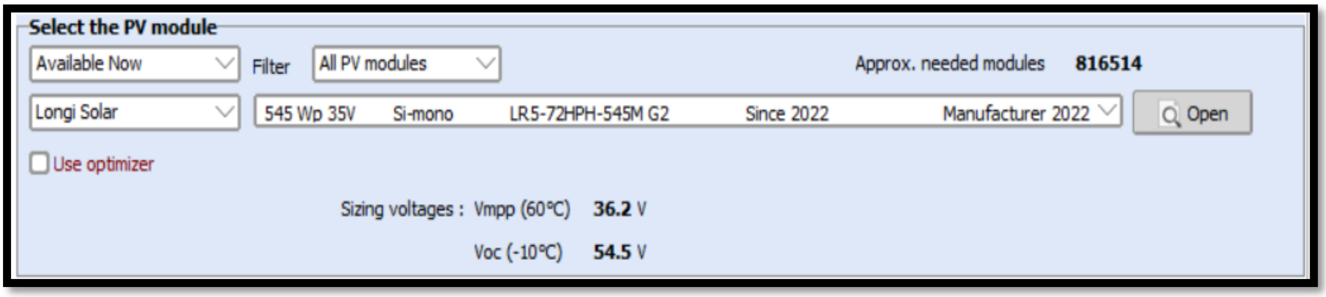


Figure 3.2. Azerbaijan Irradiance Map [44].

3.2. PVsyst Simulation Details

Considering this study, PVsyst was identified as the main simulation tool based on its popularity in the world of interdisciplinary PV system design, simulation and analysis. PVsyst provides a detailed modeling of all the advanced components such as inverters, PV modules, losses, and other crucial elements. For these reasons, it is primarily used in the analysis of vast solar parks. Moreover, PVsyst allows precise performance predictions based on the operational conditions that the designer has specified for the site, which again complies with the requirement for feasibility studies of renewable energy technologies in the energy grid [25].

The following flowchart illustrates the sequence within the simulation program: it provides clear representation of the steps involving solar park power output, type selection of the photovoltaic modules, and type specifications of inverters, among others defined in the simulation.



Select the PV module

Available Now

Filter: All PV modules

Approx. needed modules **816514**

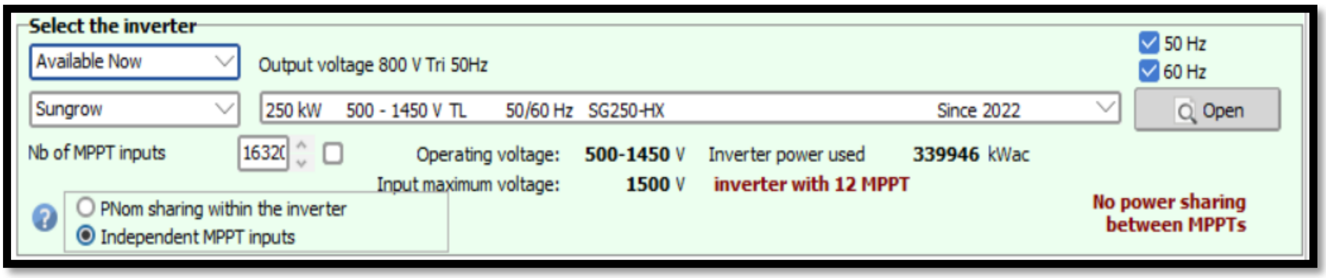
Longi Solar

545 Wp 35V Si-mono LR5-72HPH-545M G2 Since 2022 Manufacturer 2022

☐ Use optimizer

Sizing voltages : Vmpp (60°C) **36.2** V

Voc (-10°C) **54.5** V



Select the inverter

Available Now

Output voltage 800 V Tri 50Hz

☑ 50 Hz
☑ 60 Hz

Sungrow

250 kW 500 - 1450 V TL 50/60 Hz SG250-HX Since 2022

Nb of MPPT inputs 1632(☐

Operating voltage: **500-1450** V

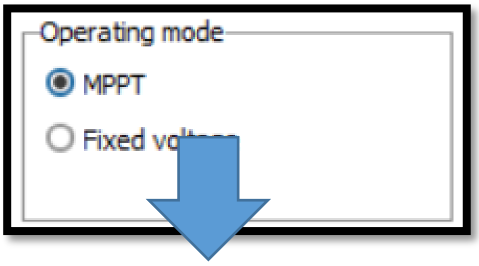
Input maximum voltage: **1500** V

Inverter power used **339946** kWac

inverter with 12 MPPT

○ PNom sharing within the inverter
● Independent MPPT inputs

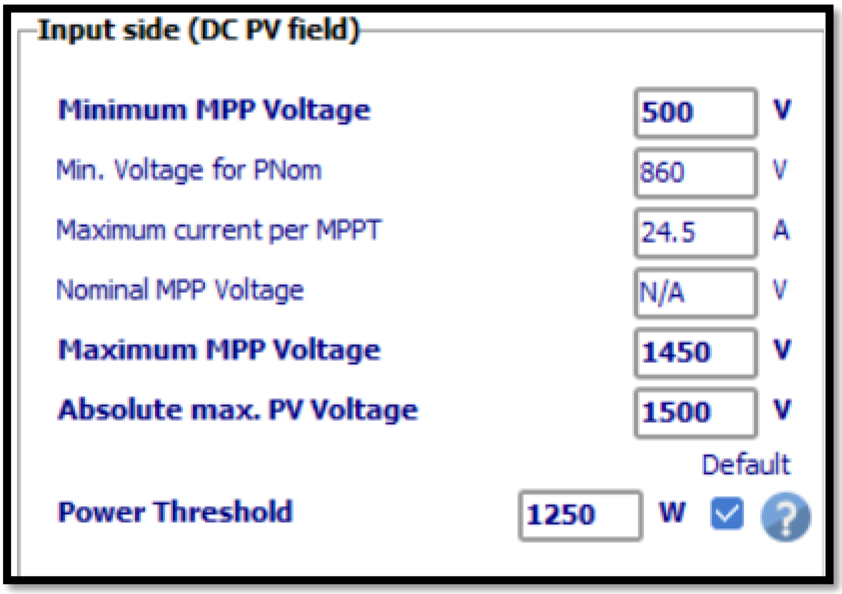
No power sharing between MPPTs



Operating mode

● MPPT
○ Fixed vo

Flowchart illustrated input parameters of MPPT



Input side (DC PV field)

Minimum MPP Voltage 500 V

Min. Voltage for PNom 860 V

Maximum current per MPPT 24.5 A

Nominal MPP Voltage N/A V

Maximum MPP Voltage 1450 V

Absolute max. PV Voltage 1500 V

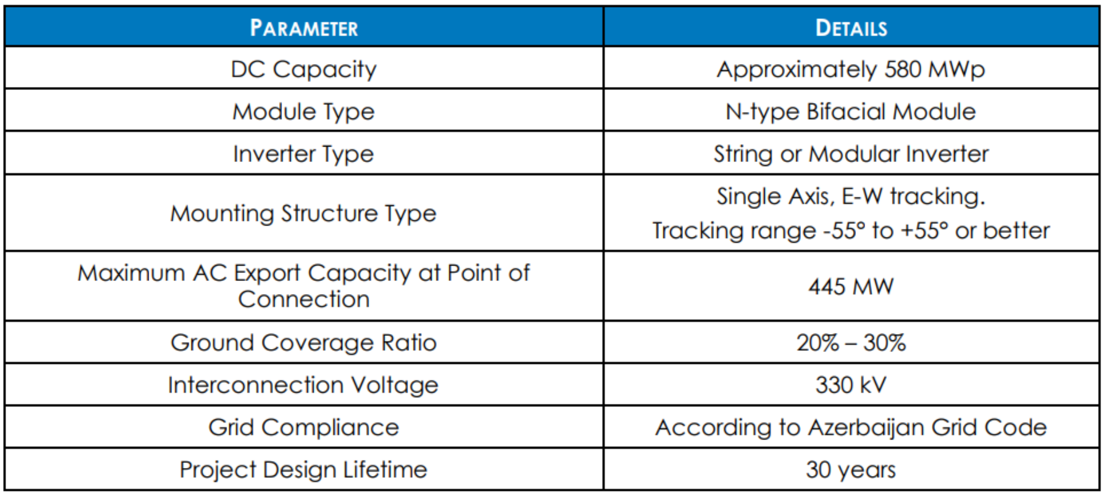
Default

Power Threshold 1250 W ☑

3.2.1. Solar Park Capacity

The solar park's 445 MW capacity was chosen to address the growing demand for renewable energy in Azerbaijan and to make a substantial contribution to the national grid [46]. By simulating a 445 MW solar park, this study aims to evaluate its potential impact on grid stability, energy supply reliability, and overall system efficiency in Azerbaijan’s power network [27].

Table 3.1. Project parameters.



PARAMETER	DETAILS
DC Capacity	Approximately 580 MWp
Module Type	N-type Bifacial Module
Inverter Type	String or Modular Inverter
Mounting Structure Type	Single Axis, E-W tracking. Tracking range -55° to +55° or better
Maximum AC Export Capacity at Point of Connection	445 MW
Ground Coverage Ratio	20% – 30%
Interconnection Voltage	330 kV
Grid Compliance	According to Azerbaijan Grid Code
Project Design Lifetime	30 years

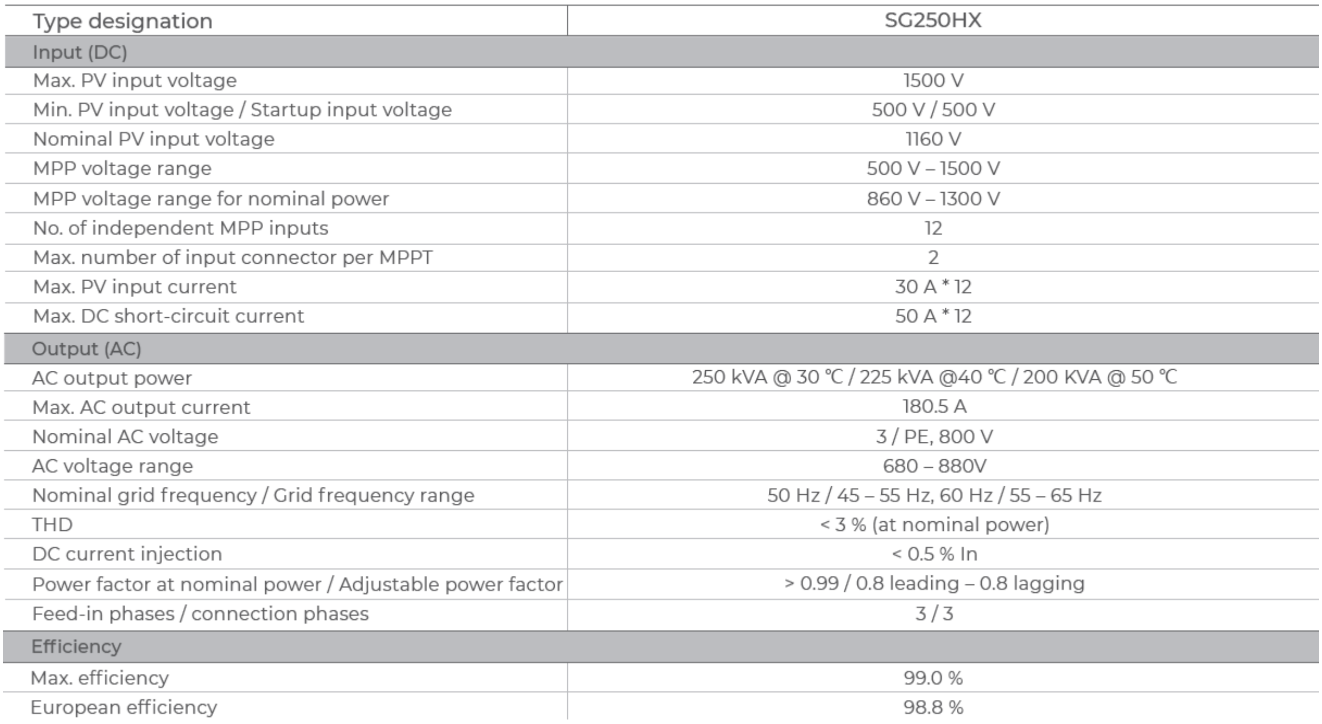
The capacities shall be selected as 445 MW based on the prevailing electricity demand on the site area, coupled with pressing need for diversification of the energy portfolio. Such a size of the system is considered suitable to contribute a substantial amount towards the energy grid, while still exhibiting the highest level of efficiency.

3.2.2. Selection of Inverter

The simulation presented here would have central inverters, which are more suitable for large-scale solar parks. Central inverters have high efficiency while handling high power and are quite economical for utility-scale projects like the Bilasuvar one. More importantly, central inverters allow for easier maintenance and better integration with the MPPT system chosen.

There are a few serious reasons to choose the Sungrow SG250HX as the inverter for the proposed solar park in tune with this project's goals. The SG250HX has been designed for a high-power string inverter targeted at modern PV systems' demands. One of its standout features is the compatibility with high-power bifacial solar modules, which can help to raise energy yield significantly by capturing sunlight on both sides of the panel. This feature is particularly good at enhancing energy production under all kinds of environmental conditions, which is very critical in maximizing the efficiency of a large-scale solar park [29].

Table 3.2. Technical specification of SG250HX [29].



Type designation	SG250HX
Input (DC)	
Max. PV input voltage	1500 V
Min. PV input voltage / Startup input voltage	500 V / 500 V
Nominal PV input voltage	1160 V
MPP voltage range	500 V – 1500 V
MPP voltage range for nominal power	860 V – 1300 V
No. of independent MPP inputs	12
Max. number of input connector per MPPT	2
Max. PV input current	30 A * 12
Max. DC short-circuit current	50 A * 12
Output (AC)	
AC output power	250 kVA @ 30 ℃ / 225 kVA @40 ℃ / 200 KVA @ 50 ℃
Max. AC output current	180.5 A
Nominal AC voltage	3 / PE, 800 V
AC voltage range	680 – 880V
Nominal grid frequency / Grid frequency range	50 Hz / 45 – 55 Hz, 60 Hz / 55 – 65 Hz
THD	< 3 % (at nominal power)
DC current injection	< 0.5 % In
Power factor at nominal power / Adjustable power factor	> 0.99 / 0.8 leading – 0.8 lagging
Feed-in phases / connection phases	3 / 3
Efficiency	
Max. efficiency	99.0 %
European efficiency	98.8 %

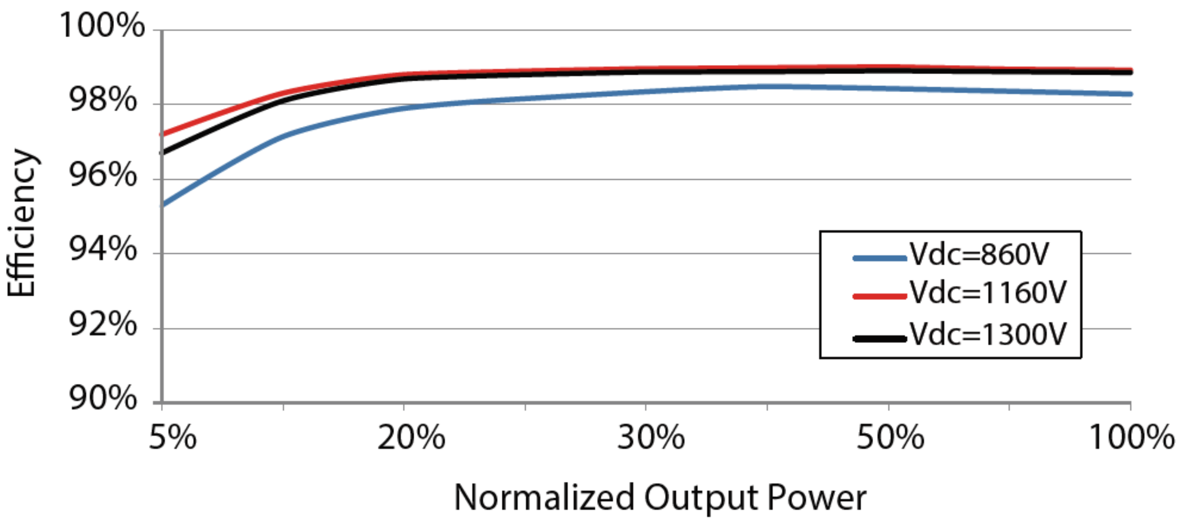


Figure 3.3. Efficiency Curve [29]

Moreover, the strong Inverter design includes industry-leading protection features, such as IP66 rating, which provides durability against harsh weather conditions of high humidity and corrosion. Chef Build—Just another WordPress site. These are critical aspects for the long-term reliability of solar installations, mostly in regions prone to extreme weather conditions. In addition, the SG250HX is optimized in converting energy with efficiency, meaning lower operation costs and increasing return on investment Slocable [30].

Additionally, we calculate the DC input and AC output power of inverter with formula given below. We have an information that the apparent power of an inverter is P_{AC}=250 kW. Let's look the formula is given below

$$P_{DC}=\frac{P_{AC}}{\eta}$$

where: P_{DC} – DC input for inverter; P_{AC} – AC power for inverter and η – Efficiency of inverter;

3.2.3. Maximum Power Point Tracking techniques

MPPT is the technology by which the maximum power point of the solar park will be tracked to maximize the energy yield [42]. Using MPPT, the inverter is enabled to constantly adjust the operating point of the solar modules for maximum power output, even in varying irradiance conditions. This is very crucial for Bilasuvar, where changes in solar intensity may occur throughout day the day. MPPT enhances the system's overall efficiency and increases its potential for being integrated into the grid by making sure that energy output becomes more stable and predictable.

Over the last two decades, more than 85 tools have been proven as a result of increasing trends in the development of new models in energy planning [36], [37]. A considerable amount of these models are used during the strategic development of renewable energy inclusions within the national energy frameworks [37]. Major among these models find their implementation in Latin America [36], [38]. South America, using the Open-Source Energy Modeling System - OSeMOSYS - has done three long-term prospective simulation models towards renewable energy inclusions [39].

3.2.4. Perturb and Observe

Since it uses only one voltage sensor to sense the PV array voltage, the implementation of the P&O approach is cheaper. The operating voltage of the DC-link connecting the PV array and the power converter is perturbed by this algorithm, that is, the duty cycle of the power converter. The next perturbation is set according to the direction of the previous perturbation and to the path of the latest power rise and by changing the voltage of the DC-link between the photovoltaic array and the power converter and thus the duty cycle of the power converter. Fig. 4, power increases when voltage is increased on the left of the MPP and it decreases when voltage is decreased on the right. The following perturbation has to be in the opposite direction if power decreases and it has to remain in the same direction if power increases. The algorithm is implemented using the flowchart in Fig. 5 based on these data, and the process is iterated until the MPP is reached. Around the MPP the operating point oscillates [40].

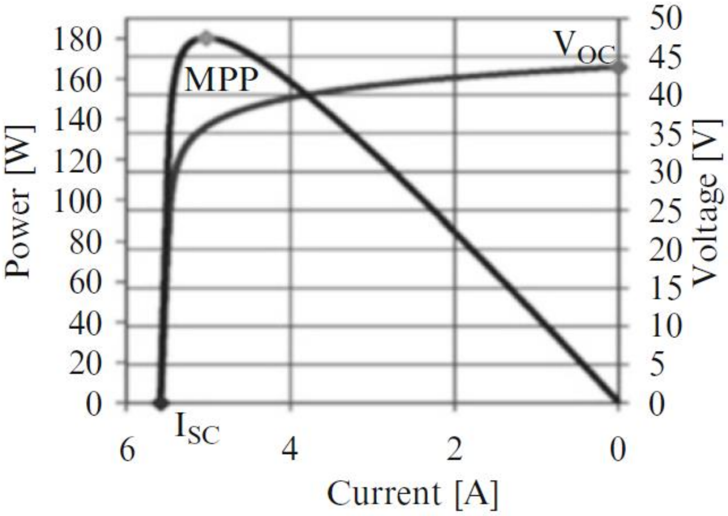


Figure 3.4. Power and current characteristic curves [40].

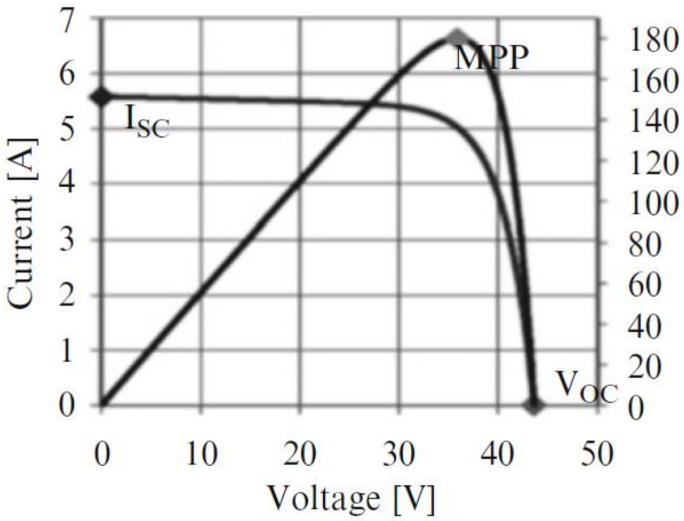


Figure 3.5. PV panel current and voltage characteristic curves [40].

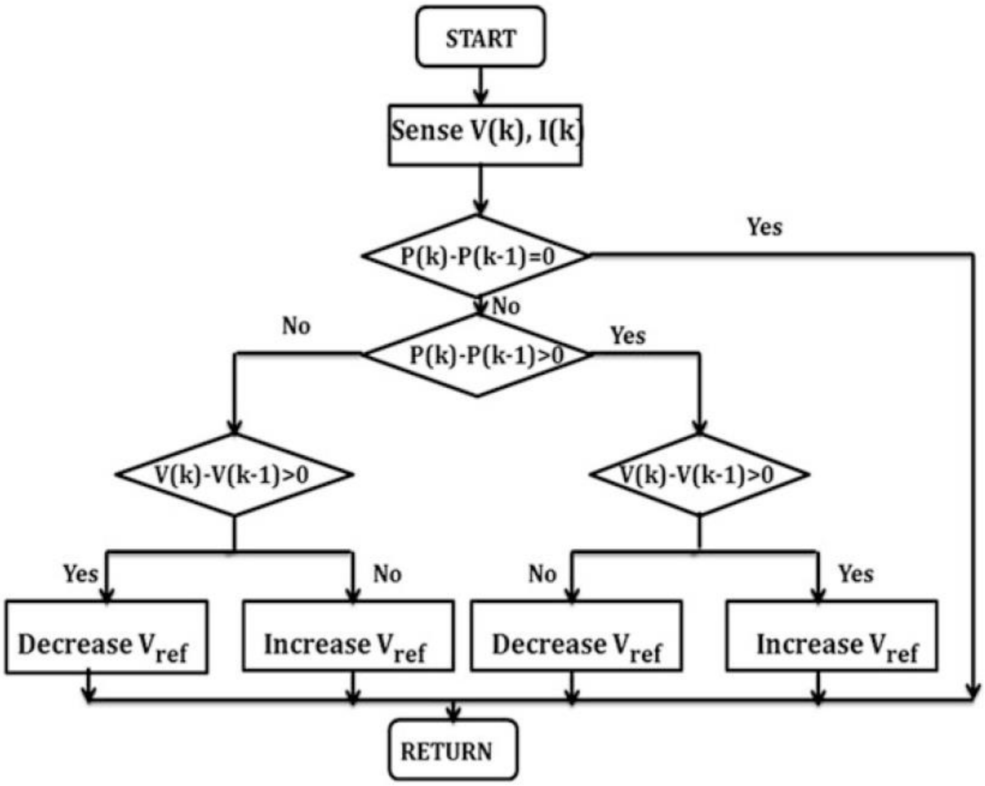
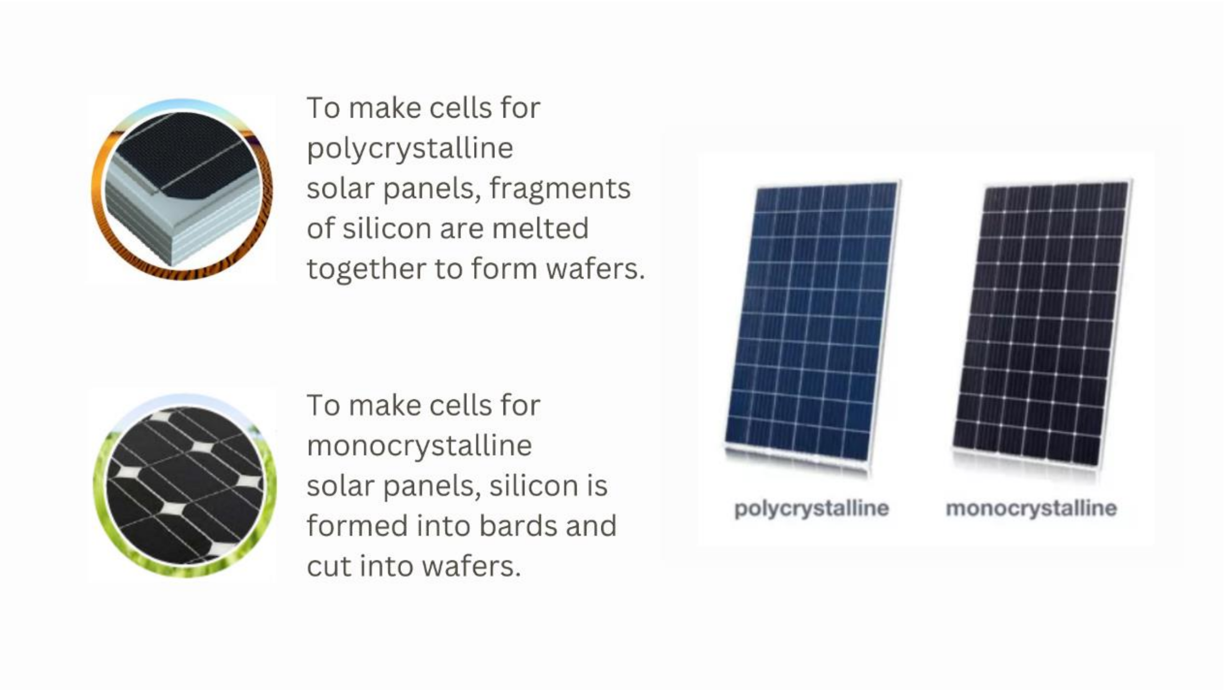


Fig 3.6. Flowchart of the perturb and observe algorithm [40].

This was followed by the presentation of the P&O algorithm using voltage sensors, simulation, and experimental results; the proposed method was therefore effective in improving the dynamic and steady-state tracking efficiency of the photovoltaic system, while the material cost was kept lower, as presented in (2018) [41].

3.2.5. Selection of PV Module

Monocrystalline photovoltaic modules are fabricated from single-crystal silicon, hence allowing better mobility of electrons, hence higher efficiency and compactness. This is contrary to the polycrystalline modules, which are fabricated from many silicon crystals, making them cheap but less efficient due to increased electron scattering. The decision between these two technologies depends on various considerations, including available installation space, budget limitations, and specific energy requirements, underscoring the importance of a detailed analysis of their performance characteristics for effective selection [31].



To make cells for polycrystalline solar panels, fragments of silicon are melted together to form wafers.

To make cells for monocrystalline solar panels, silicon is formed into bards and cut into wafers.

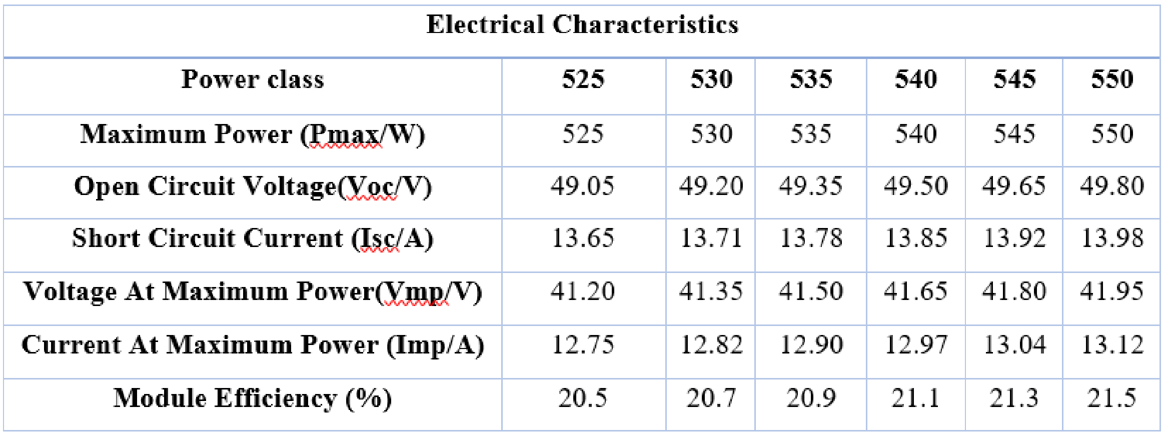
Figure 3.7. Monocrystalline and polycrystalline solar panels [32].

Table 3.3. Technical properties of monocrystalline and polycrystalline panels.

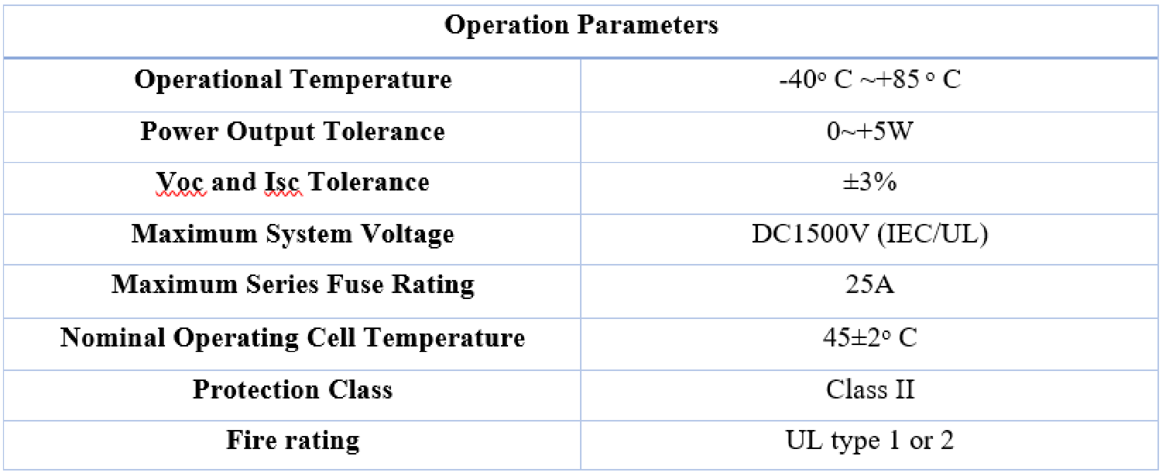
Aspects	**Monocrystalline Panels**	**Polycrystalline Panels**
Solar panel efficiency	High-efficiency rate- 16% to 23%	Low-efficiency rate- 13% to 16%
Appearance	Black	Blue
Cost	More expensive	Less expensive
Life span	lifespan of 25-35 years	lifespan of 25-35 years
Temperature coefficient	Lower temperature coefficient, more efficient in heat	Higher temperature coefficient, less efficient in heat
Durability	Highly durable	Less durable
Roof Space	Works on roofs with limited space	Requires more roof space for installations

Longi Solar LR5 is ideal for large solar installations due to its high power, which can go up to 550W per module. This large capacity can give way to more energy production and consequently is favorable in utility-scale projects where maximum power output is desired. The advanced monocrystalline PERC (Passivated Emitter and Rear Cell) technology used by this module contributes to high efficiency, nearing 21.3% in this case. This high efficiency ensures that the system has a larger possibility of converting available sunlight into usable electricity under suboptimal conditions, therefore increasing the overall energy yield from such installations [33,34].

Table 3.4. Technical specification of LR5-72HPH-525~550M



Electrical Characteristics						
Power class	**525**	**530**	**535**	**540**	**545**	**550**
Maximum Power (Pmax/W)	525	530	535	540	545	550
Open Circuit Voltage(Voc/V)	49.05	49.20	49.35	49.50	49.65	49.80
Short Circuit Current (Isc/A)	13.65	13.71	13.78	13.85	13.92	13.98
Voltage At Maximum Power(Vmp/V)	41.20	41.35	41.50	41.65	41.80	41.95
Current At Maximum Power (Imp/A)	12.75	12.82	12.90	12.97	13.04	13.12
Module Efficiency (%)	20.5	20.7	20.9	21.1	21.3	21.5



Operation Parameters	
Operational Temperature	-40° C ~+85 ° C
Power Output Tolerance	0~+5W
Voc and Isc Tolerance	±3%
Maximum System Voltage	DC1500V (IEC/UL)
Maximum Series Fuse Rating	25A
Nominal Operating Cell Temperature	45±2° C
Protection Class	Class II
Fire rating	UL type 1 or 2

As it is, the performance is not only impressive but also the Longi LR5-72HPH module was designed with a lot of durability and long-term reliability. It is of a solid construction on a gallium-doped silicon substrate, which reduces light-induced degradation and enhances power retention over time. The panels are further backed by a 12-year product warranty for the modules and a 25-year performance guarantee, which covers at least a minimum of 84% of the rated output after a period of 25 years. A combination of high output, efficiency, and reliability makes the LR5-72HPH module not only cost-effective but also a strategic investment for solar park projects in the reduction of LCOE while maximizing energy production [33,35].

3.3. Validation of Simulation

Simulation results are validated using analytical calculations using the following equations:

- DC input and AC output power of Inverter

We have an information that the apparent power of an inverter is P_{AC}=250 kW. Let's look the formula is given below

$$P_{DC}=\frac{P_{AC}}{\eta}$$

P_{DC} – DC input for inverter
P_{AC} – AC power for inverter
η – Efficiency of inverter

$$P_{DC}=\frac{P_{AC}}{\eta}=\frac{250\ kW}{0.99}=\mathbf{252{,}52\ kW}$$

- Nominal Power Ratio

This is the ratio that determines the relationship between the direct current power of the PV array and the inverter. Since the inverter works best at a certain amount of absorbed power and drops below normal, you should not oversize the inverter.

NPR – nominal power ratio

$$NPR=\frac{Total\ PV\ power}{Total\ inverter\ power}=\frac{444995\ kW}{333771\ kW}=\mathbf{1.33}$$

- Annual Energy Production of Solar Park

Let's figure out how much DC energy our system produces annually.

$$E_{DC}=P_{DC}\times(PSH)\times\ \eta_{inv}\times PR$$

Where, PDC – inverters DC power , (PSH) – number of hours when solar irradiance is average 1000 W/m2 , η_{inv} – number of inverters, PR- Power ratio

Let's compute PSH first.

$$\text{PSH}=\frac{Yearly\ irradiation\frac{kWh}{m^2}}{1000\,\frac{W}{m^2}}=\frac{1500.7}{1000}=1500{,}7\text{ h}$$

DC energy production will be:

Number of inverter – 1336 units

$E_{DC}=P_{DC}\times(PSH)\times\ \eta_{inv}$= 252,52 kW×1500,7 h×1336×1,33= 674360 MWh/year

Validation results are given on the table.

Table 3.5. Validation of simulation

	Result of simulation	**Result of analytical equation**
Power Ratio (PR)	1.31	1.33
Annual energy production of Solar Park	674 GWh/year	684 GWh/year

3.4. PowerFactory (DIgSILENT)

PowerFactory is a comprehensive program developed by DIgSILENT for power system analysis, and it is used quite broadly for the modeling, analyzing, and optimizing of power networks. These networks include distribution, transmission, and generation systems, and they model the integration, particularly in contemporary contexts, of renewable energy sources. This integration poses a number of challenges that PowerFactory addresses, and that makes it an excellent candidate for the kind of research we're pursuing with solar energy in Azerbaijan. Unlike many programs in use today, PowerFactory has features that respond directly to the kinds of problems that high-penetration solar energy can cause in a power network. Powerfactory simulates a number of what's called "dynamic behavior" tests. These tests determine how well the power network maintains performance and stability in the presence of large-scale, high-penetration solar energy generation [43].

3.4.1. Integration of Bilasuvar Solar Park into the Azerbaijan's Energy System

The work has simulated the integration impact of the Bilasuvar Solar Park on the national Azerbaijan electricity grid by means of the simulation tool called PowerFactory. The Bilasuvar Solar Park, with a generating capacity of 445 MW, is connected to the NEVAI substation via two 330 kV high-voltage power transmission lines. This dual arrangement ensures the reliability of the system. If one of the 330 kV lines requires maintenance or an unexpected failure occurs, the other line can be taken out of service without interrupting the transmission of solar energy, since it can operate at full capacity most of the time. The connection scheme of these high-voltage power transmission lines is shown in the next chapter. The scheme reflects the load percentages of the lines and the maximum load percentage of the other line when it is down for maintenance. A table was prepared by the national provider of energy of Azerbaijan called "Azerenergy" reflecting the forecasted types of energy output per day from the solar facility for the purpose of maximizing the generation of energy at the solar park.

Table 3.6. Daily load schedule obtained from Azerenergy OJSC

Time	Estimated load (MW)
09^{00}	18,19
10^{00}	55,97
11^{00}	99,82
12^{00}	148,33
13^{00}	179,12
14^{00}	199,64

15^{00}	243,49
16^{00}	222,03
17^{00}	167,46

3.5. CO_2 emission balance

These are renewable sources of energy that drastically reduce the amount of CO_2 and other greenhouse gases emitted into the atmosphere. Solar is among the major examples of such processes. It is a renewable energy source that may generate power without causing environmental degradation [47]. It is crucial to obtain precise figures on CO_2 reductions if we are to understand the ways in which solar parks and other renewable installations affect the environment.

The amount of CO_2 saved by it gives an estimation of the environmental impact of the Solar Park alone. After all, the park is producing renewable energy, which if it were not there might well be coming from fossil energy sources. Even the coal plants that have been cleaned up may still be putting out around a kilogram of CO_2 for every kilowatt-hour of electricity they produce. And CO_2 is a big part of the problem. So, to measure up how much good the solar park is doing, we can start by calculating the park's total lost CO_2 emissions, working from the amount of kilowatt-hours of energy the park produces back to the amount of CO_2 that would have been emitted if those same kilowatt-hours of energy had been produced by fossil fuel plants instead. [47] [48].

For purposes of full analysis, we will calculate the carbon dioxide emissions given off to the atmosphere in one single day, using the total daily load data provided by Azerenergy. This calculation will realize the quantification of CO_2 emissions directly linked with daily energy demand and generation practices, hence showing the environmental impact attached to energy production.

The following formula is used to estimate the amount of carbon dioxide emissions related to daily electricity generation.

$$CO_2 \text{ Emission(kg)} = \text{Energy Produced (kWh)} \times \text{Emission factor } (gCO_2/kWh)$$

We have an information about the emission factor on Bilasuvar Solar Park. The value of emission factor 491 gCO_2/kWh. Azerenergy provides daily load data, which we utilize in the table above.

Table 3.7.

Daily calculation of CO_2 emission(kg)

Time	Estimated load (MW)	CO_2 Emission(kg)
09^{00}	18,19	8931,290
10^{00}	55,97	27481,270
11^{00}	99,82	49011,620
12^{00}	148,33	72830,030
13^{00}	179,12	87947,920
14^{00}	199,64	98023,240
15^{00}	243,49	119553,590
16^{00}	222,03	109016,730
17^{00}	167,46	82222,860
Total daily	**1334,05 MW**	**655018,55 kg**

CHAPTER FOUR

SIMULATION RESULTS

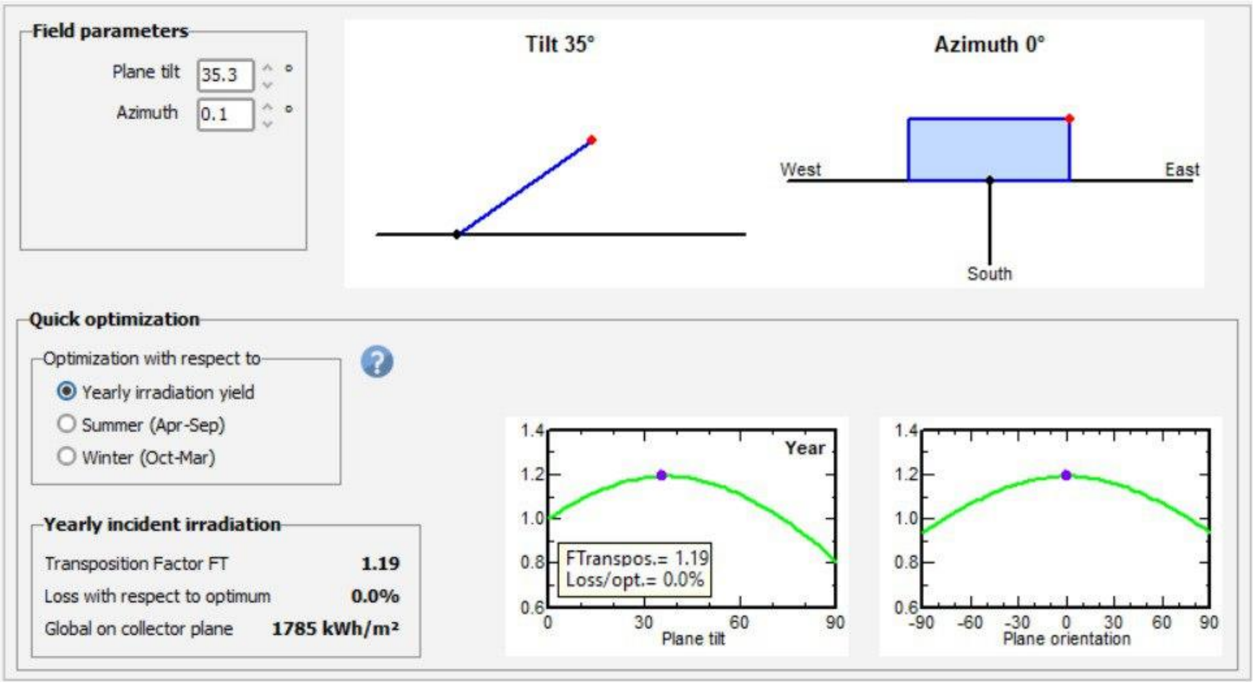
4.1 Simulation Tool

This chapter highlights the results from the simulation of the integration of the Bilasuvar Solar Park into the national energy grid of Azerbaijan. Two industrial-scale state-of-the-art tools, PVsyst and PowerFactory, were employed to simulate and model the renewable energy system. The simulations assess the actual energy production potential, system performance, and environmental benefits that a 445 MW solar park can achieve under real field operating conditions. The results are analyzed to evaluate system feasibility, performance ratio, and load analysis.

The modelling of energy output from the photovoltaic system and determination of systemic losses are done by PVsyst. The tool provides detailed outputs on performance ratios, energy production, and loss distribution. Monocrystalline panels, Longi LR5-72HPH 545W, were used for modeling the PV modules, while Sungrow SG250HX inverters were chosen based on their high efficiencies for utility-scale projects.

PowerFactory was used to analyze the grid's response to the solar park integration, simulating the dynamic behavior of the electrical network, particularly regarding load-sharing dynamics under conditions of variable solar irradiance, and performing load analysis on an annual basis.

In order to minimize losses and attain an ideal result with zero percent variation, it is crucial to adjust the solar cell's plane tilt and azimuth.



Field parameters

Plane tilt 35.3 °

Azimuth 0.1 °

Quick optimization

Optimization with respect to

● Yearly irradiation yield

○ Summer (Apr-Sep)

○ Winter (Oct-Mar)

Yearly incident irradiation

Transposition Factor FT	**1.19**
Loss with respect to optimum	**0.0%**
Global on collector plane	**1785 kWh/m²**

FTranspos.= 1.19
Loss/opt.= 0.0%

Figure 4.1. Adjustment of orientation on solar cell

This is where the configuration of the solar energy system uses simulation software at a very vital stage of the project: choosing the suitable type of solar module and inverter. This is directly followed by the desired input of the designed capacity of the solar park, upon which the software automatically calculates and shows the output voltage, the number of panels, a number of strings, and the total area that is required for installation.

Considering the option selected solar panels discussed in the methodology section, the current-voltage characteristics and maximum power efficiency under different temperature circumstances can be analyzed within the framework of photovoltaic (PV) system modeling tools. These features show that the suggested solar park arrangement is the best option with the fewest energy losses. A simulation method was carried out by assessing different kinds of inverters and solar panels in order to create a solar park with such ideal qualities. This part presents the analysis's findings, emphasizing the optimal configurations found during the simulation.

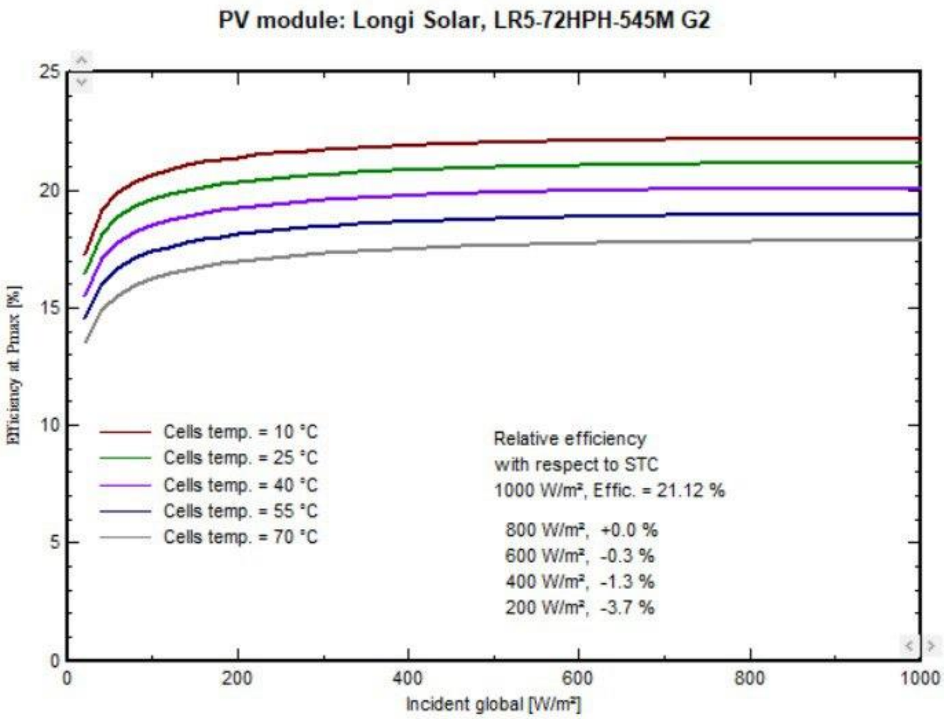


Figure 4.2. Maximum power characteristic of Longi solar cell

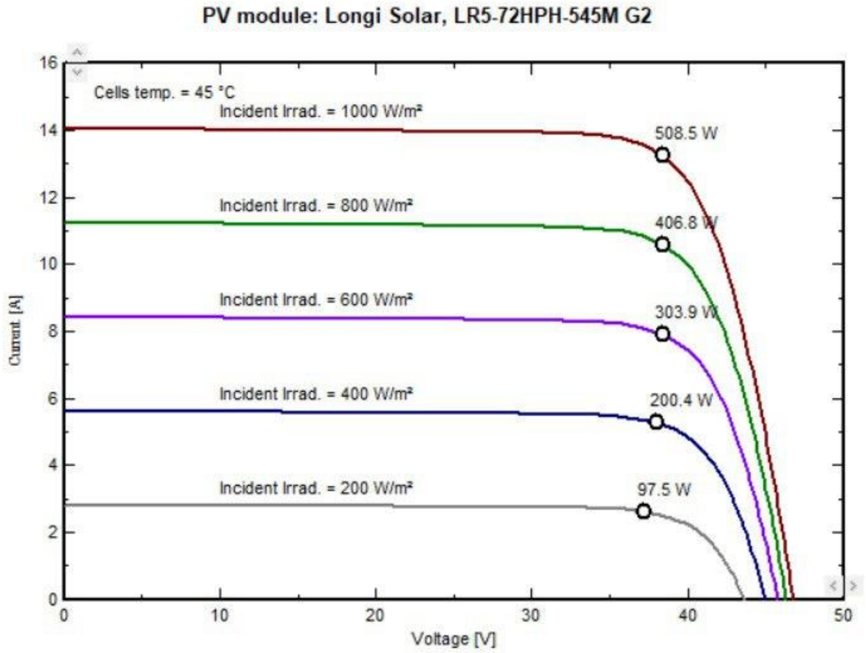


Figure 4.3. The Longi solar cell's voltage and current characteristics

4.2. Simulation results of PV plant

PV syst provides an in-depth analysis of your photovoltaic system's configuration. The main PV array's characteristics and the inverter's general parameters are displayed in the table. Here, you can view the array's electrical parameters, the total number of PV modules per string, tilt, and azimuth, as well as the near-field shading at STC and MPP.

Table 4.1. PV Array Characteristics

PV Array Characteristics	
PV module	
Manufacturer	Generic
Model	LR5-72HPH-54M G2
Unit Nominal Power	545 Wp
Number of PV modules	816504 units
Nominal (STC)	445.0 MWp
Modules	34021 string x 24 in series
At operation condition (50° C)	
P mpp	407.5 MWp

U mpp	903 V
I mpp	451076 A
Total PV Power	
Nominal (STC)	444995 kWp
Total	816504 modules
Module area	2109236 m^2
Cell area	1958003 m^2
Inverter	
Manufacturer	Generic
Model	SG250-HX
Unit Nominal Power	250 kWac
Number of inverters	16320 x MPPT 8% 1360 units
Total power	340000 kWac
Operation voltage	500-1450 V
Pnom ratio (DC:AC)	1.31
Total Inverter Power	
Total Power	340000 kWac
Number of inverters	1360 units
P nom ratio	1.31

PVsyst performs an advanced analysis of your PV system's energy output. It covers in-depth output estimations of the day-ahead production, as well as on a monthly and yearly basis. Many different parameters come into consideration, like on-site solar radiation, ambient temperature, and module temperature, when doing the estimation.

One dominant indicator of your PV system's efficiency is PR. It is the terminology used to relate real energy output to what would have been ideally produced under ideal conditions. While calculating PR, PVsyst considers a number of causes that lead to energy losses due to module mismatch, inhomogeneous irradiance distribution due to shading, pollution, and other environmental conditions.

Table 4.2. Main simulation result of PV plant

System production	
Produced Energy	**684 GWh/year**
Performance ratio	**87,7%**
Collection loss	**0,53 kWh/day**
System loss (inverter…,)	**0.06 kWh/day**
Produced useful energy (inverter output)	**4,24 kWh/day**

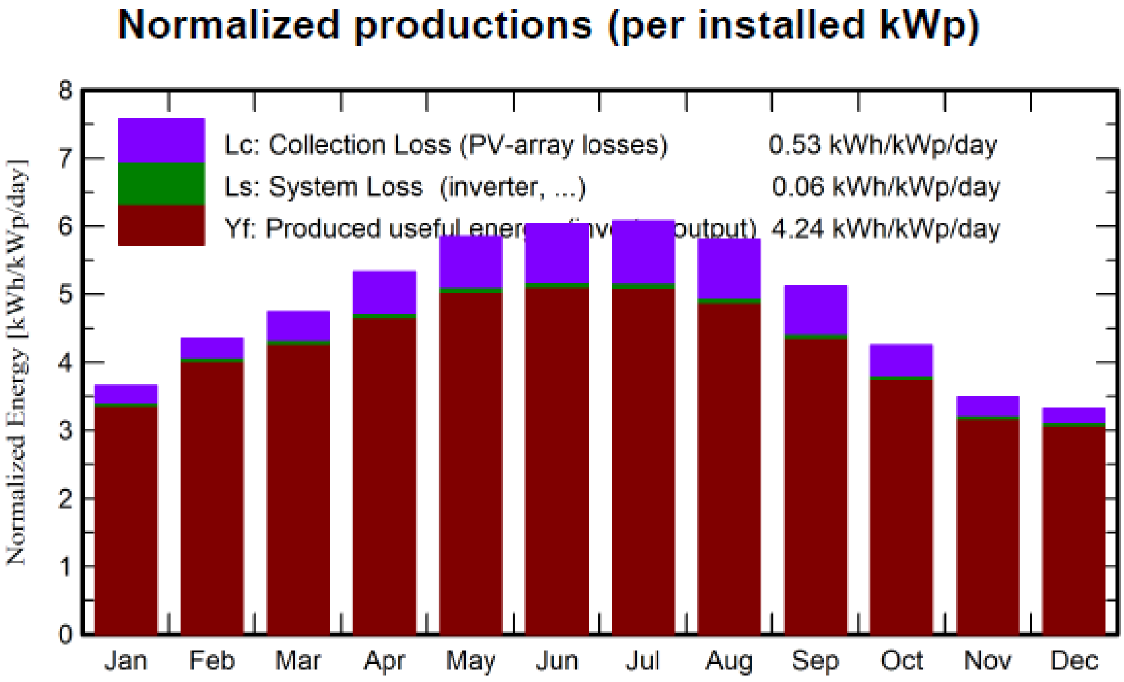


Figure 4.4. Normalized production (per installed kWp) on the solar park

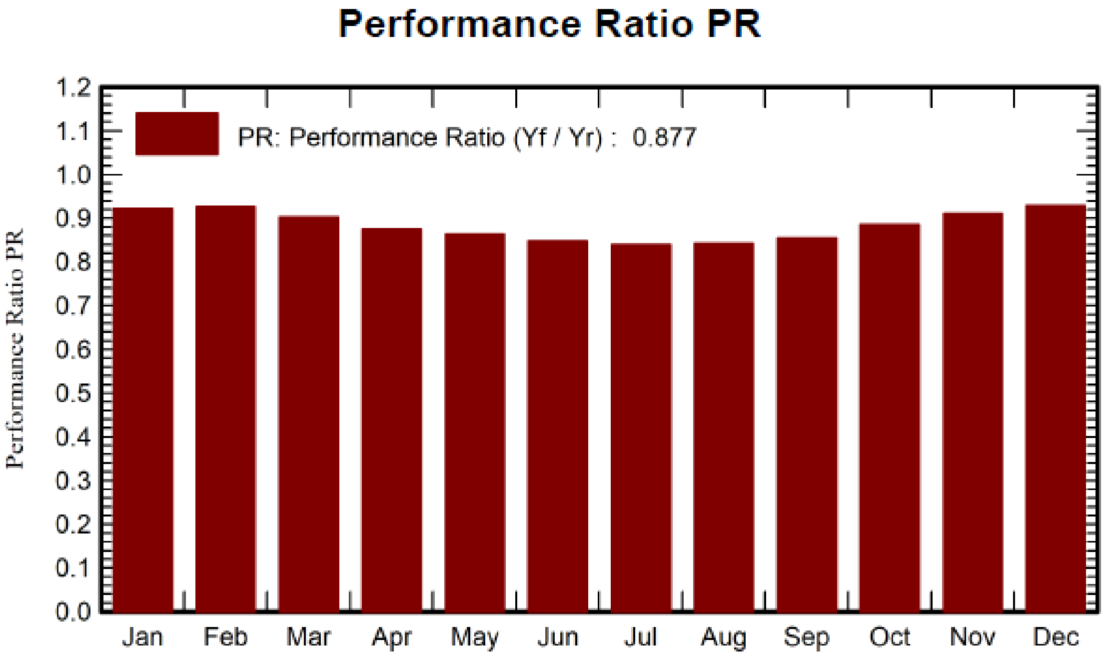


Figure 4.5. Performance ratio on the solar park

Additionally, you can obtain information about the energy balances of solar plant on the table below.

Table 4.3. Energy balances of PV plant

	GlobHor kWh/m2	DiffHor kWh/m2	T-amb	EArray GWh	E-Grid GWh	PR
January	65,1	24,80	2,59	47,24	46,54	0,923
February	79,5	30,52	2,88	50,88	50,19	0,927
March	115,3	47,43	6,03	59,94	59,07	0,904
April	145,8	58,50	12,17	63,20	62,28	0,875
May	186,3	68,51	17,17	70,58	69,55	0,862
June	196,5	69,00	22,17	69,32	68,30	0,847
July	198,7	68,51	24,96	71,43	70,38	0,839
August	171,4	61,69	24,45	68,42	67,46	0,842
September	129,3	49,50	19,95	59,15	58,29	0,854
October	93,6	38,44	14,44	52,74	51,94	0,886
November	63,3	27,00	8,78	43,11	42,44	0,910
December	55,8	22,63	3,99	43,18	42,52	0,928
Year	1500,7	566,53	13,36	699,21	688,95	0,877

In fact, one can calculate the global horizontal irradiation, diffuse horizontal irradiation, ambient temperature, effective energy at the array's output, energy supplied to the network, and performance ratio.

All photovoltaic systems have some inherent energy losses from various factors; all components-from inverter, wiring, and shading to other elements-contribute to these losses. These losses are of a permanent nature and hence very important in system performance analysis. As a fact, one of the most utilized simulation tools for PV systems, PVsyst, breaks all these losses down into their very sources and magnitudes within the system. It is such granular analysis that helps the system designers, operators, and maintenance teams locate the inefficiencies with precision to thus enable targeted interventions aimed at supporting optimization in energy output. The loss analysis provided by PVsyst gives a basis on which all parties involved can work out an effective strategy to curb the effects of this energy shortage in order to increase the efficiency of a photovoltaic installation and its long-term reliability. The very detailed insight into the loss mechanisms is very important with respect to troubleshooting of operational issues, improvement of future designs, and reaching higher levels of energy efficiency in solar power systems. You can get information about losses in the figure below.

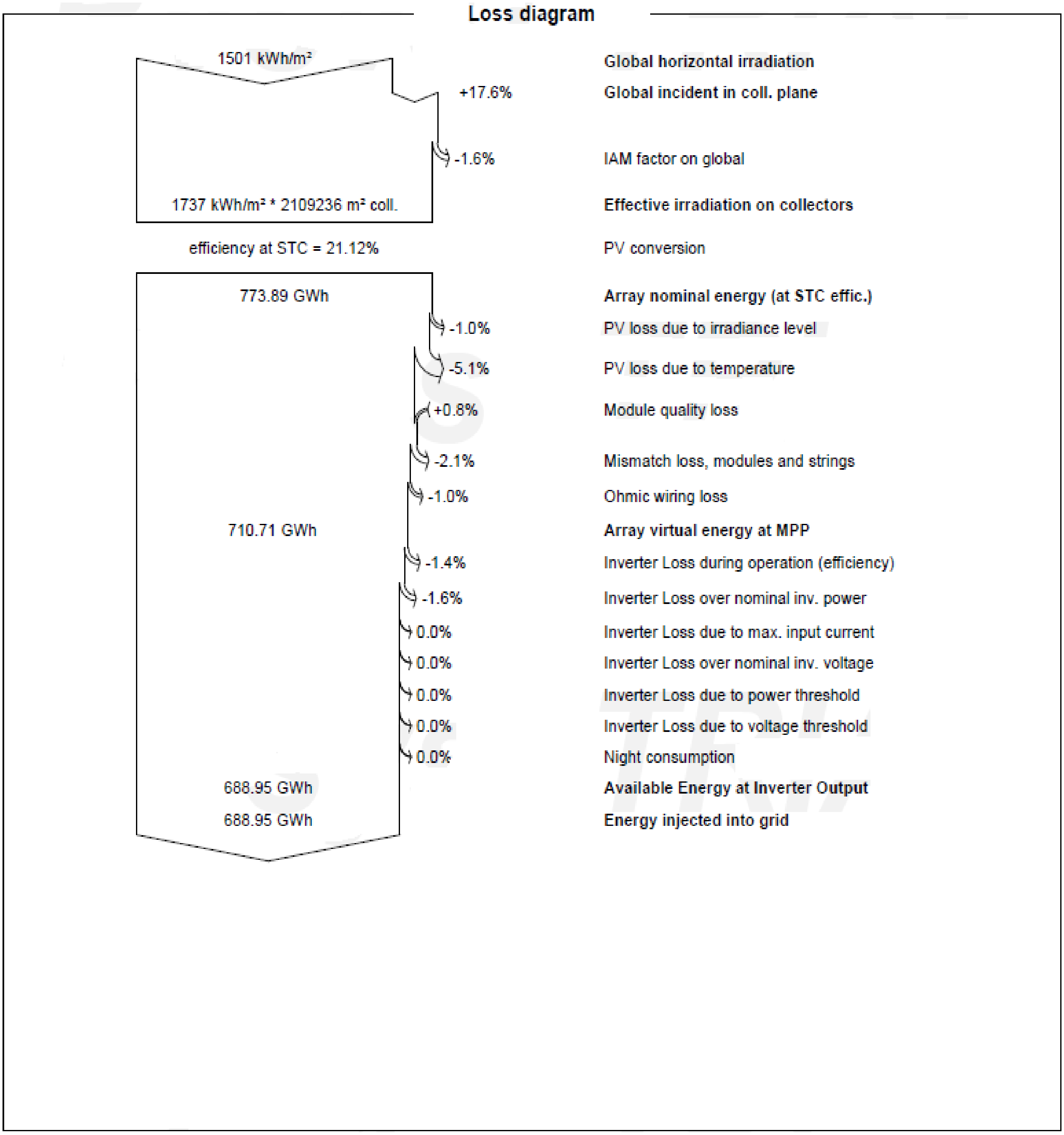


Figure 4.6. Loss diagram of PV plant

4.3. Environmental Impact

The solar park is projected to replace approximately 100.79 $MtCO_2$ annually, assuming a grid emission factor of 491 gCO_2/kWh. Over its 30-year lifespan, this corresponds to over 3 $GtCO_2$ avoided emissions. You can find CO2 emission balance diagram and tables below.

Table 4.4. CO_2 emission balance

Generated emissions	789325.02 tCO_2
Replaced emissions	10079027 tCO_2
System production	684251.69 MWh/year
Grid Lifecycle emissions	491 gCO_2/ kWh
Lifetime	30 years
Annual degradation	1.0 %

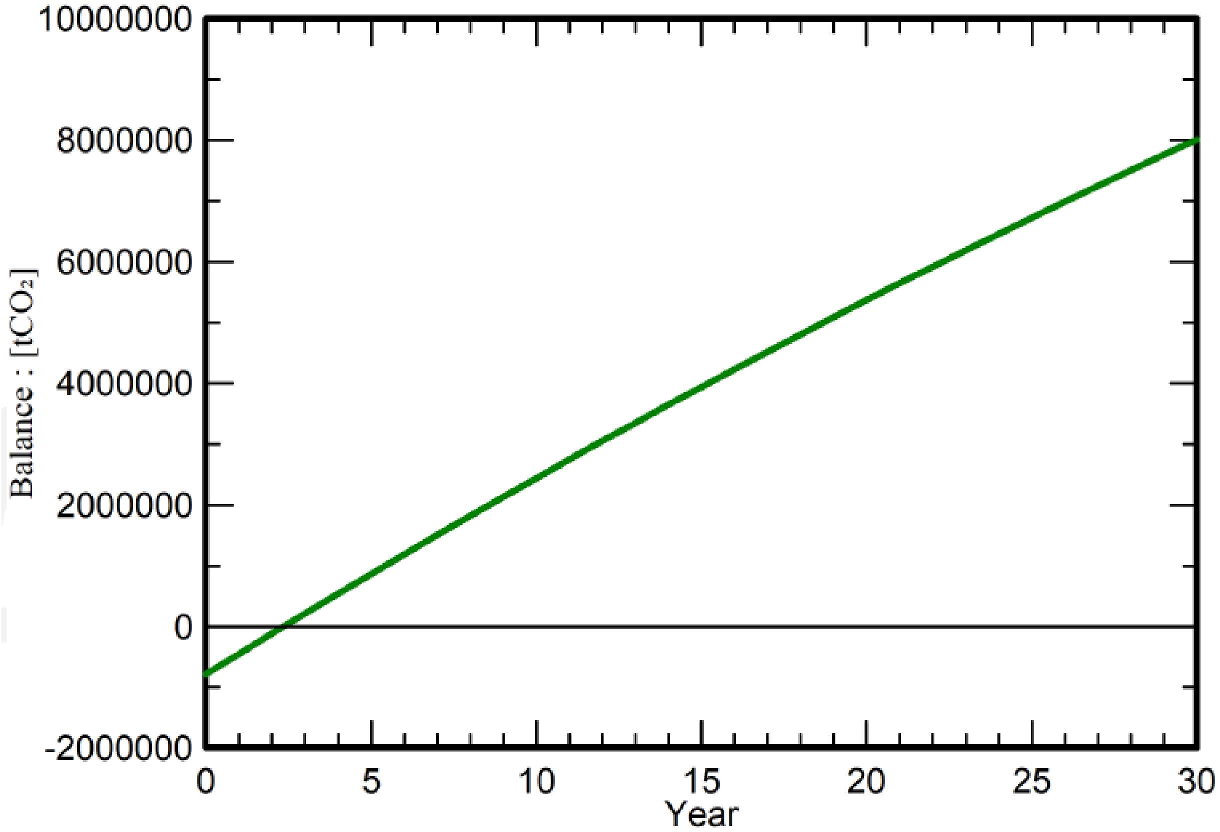


Figure 4.7. CO_2 emission diagram

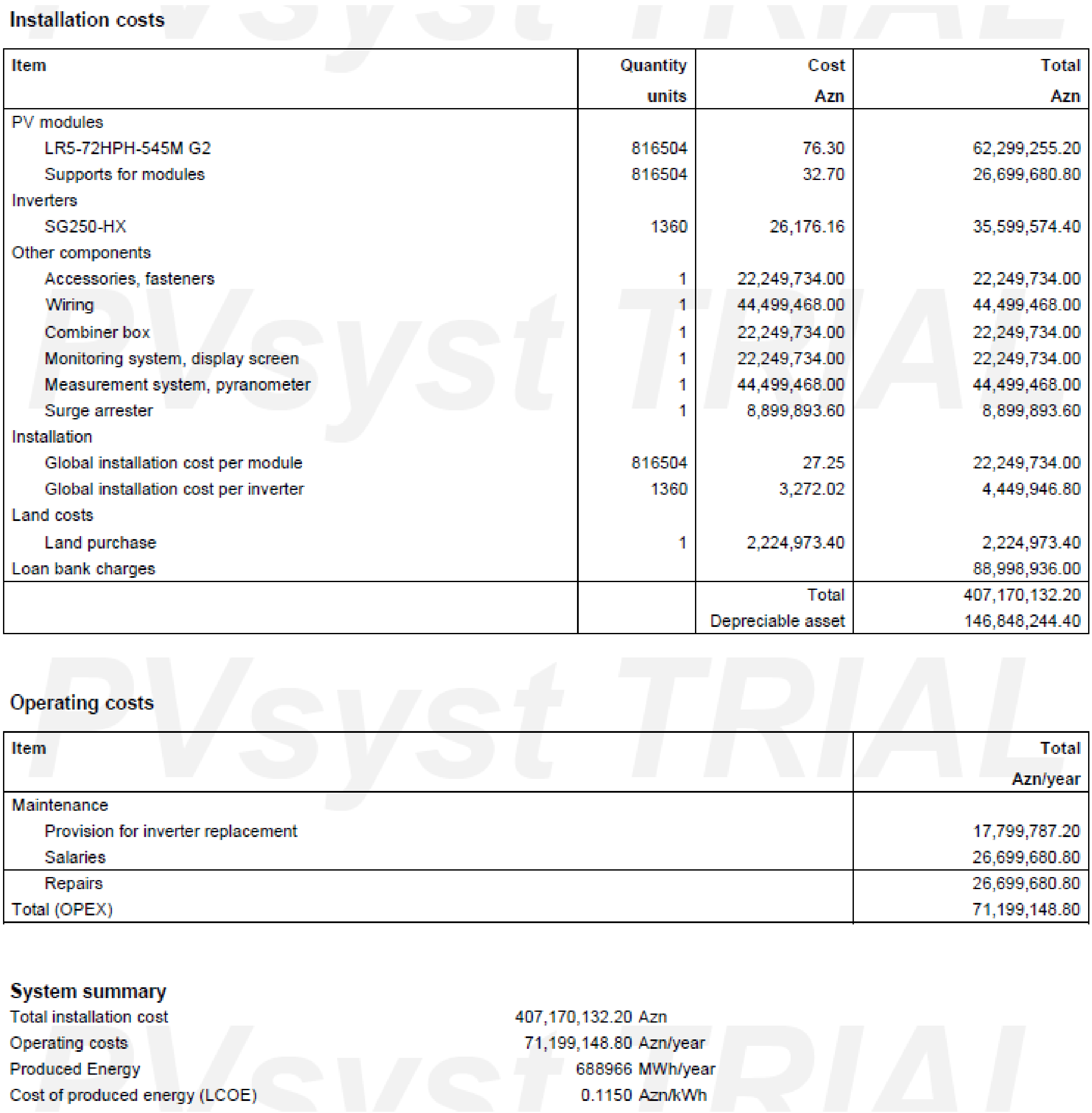
Table 4.5. System Lifecycle emissions details

Item	LCE	Quantity	Subtotal
Modules	1713 $kgCO_2$/kWp	444995 kWp	762151288 $kgCO_2$
Supports	3.27 $kgCO_2$/kg	8165040 kg	26740261 $kgCO_2$
Inverters	324 $kgCO_2$/units	1360 units	441256 $kgCO_2$

4.4 Economic analysis of PV Plant

PVsyst can use economic indicators to assess the viability of a solar system project. These economic indicators also help predict the profitability of investments in the long term. These economic indicators also determine how economically viable a solar energy project is. The tables below illustrate the economic costs of a solar park and how many years it will take to transition to a profitable production process. According to statista.com, the CAPEX of the PV plant is 0.61$/W≈1AZN. Thus, having an SG250(kW)-HX (CAPEX) system, AZN for our PV plant will be 407 170 132.20. Moreover, OPEX according to the world standard will be 71 199 148.80 AZN

Table 4.6. Cost of Solar Park



Installation costs

Item	Quantity units	Cost Azn	Total Azn
PV modules			
LR5-72HPH-545M G2	816504	76.30	62,299,255.20
Supports for modules	816504	32.70	26,699,680.80
Inverters			
SG250-HX	1360	26,176.16	35,599,574.40
Other components			
Accessories, fasteners	1	22,249,734.00	22,249,734.00
Wiring	1	44,499,468.00	44,499,468.00
Combiner box	1	22,249,734.00	22,249,734.00
Monitoring system, display screen	1	22,249,734.00	22,249,734.00
Measurement system, pyranometer	1	44,499,468.00	44,499,468.00
Surge arrester	1	8,899,893.60	8,899,893.60
Installation			
Global installation cost per module	816504	27.25	22,249,734.00
Global installation cost per inverter	1360	3,272.02	4,449,946.80
Land costs			
Land purchase	1	2,224,973.40	2,224,973.40
Loan bank charges			88,998,936.00
		Total	407,170,132.20
		Depreciable asset	146,848,244.40

Operating costs

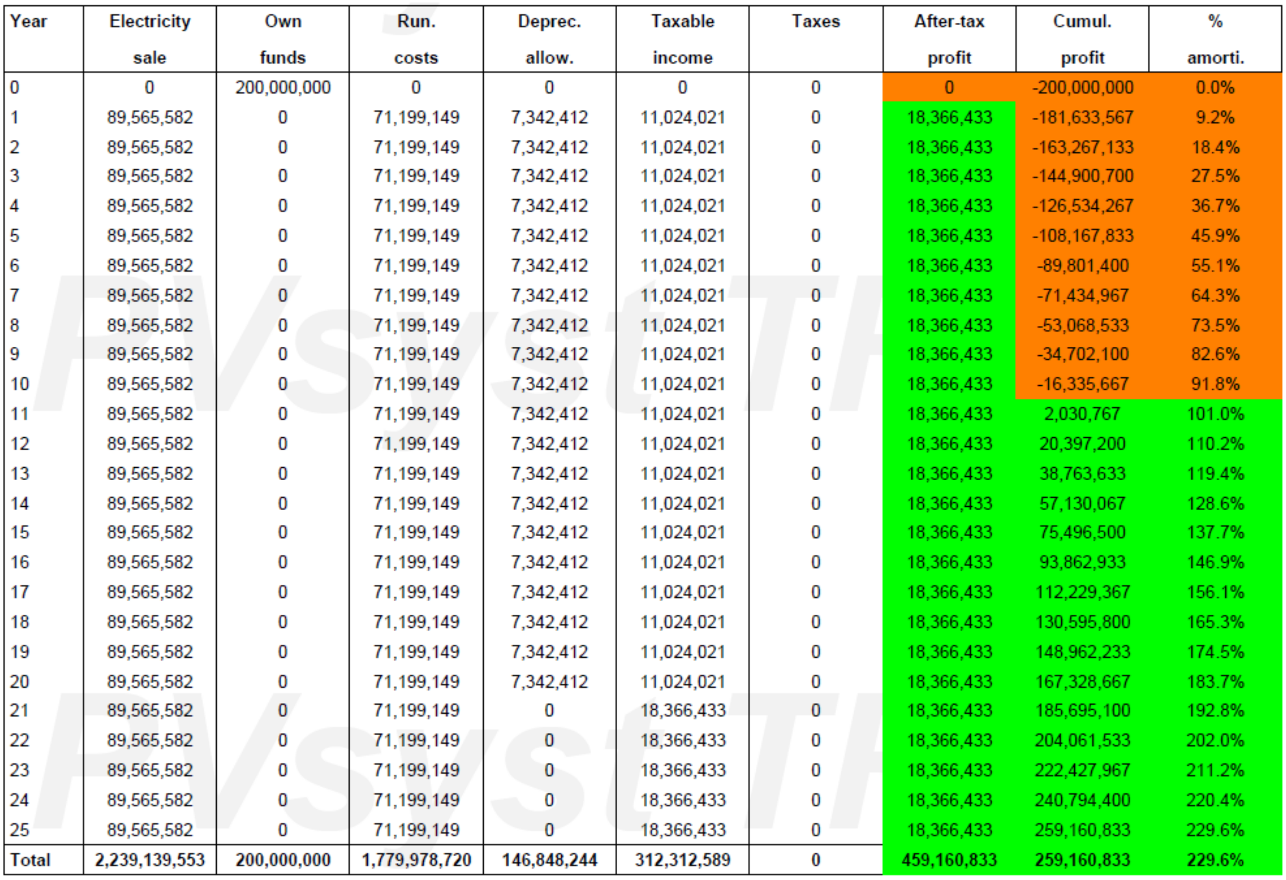
Item	Total Azn/year
Maintenance	
Provision for inverter replacement	17,799,787.20
Salaries	26,699,680.80
Repairs	26,699,680.80
Total (OPEX)	71,199,148.80

System summary

Total installation cost	407,170,132.20 Azn
Operating costs	71,199,148.80 Azn/year
Produced Energy	688966 MWh/year
Cost of produced energy (LCOE)	0.1150 Azn/kWh

The years that did not generate any revenue are represented in red. The revenue from the system will cover all costs and the Solar Park will start generating a profit after 10.9 years. A total return on investment (ROI) of 129.6% was achieved.

Table 4.7. Financial analysis of Solar Park



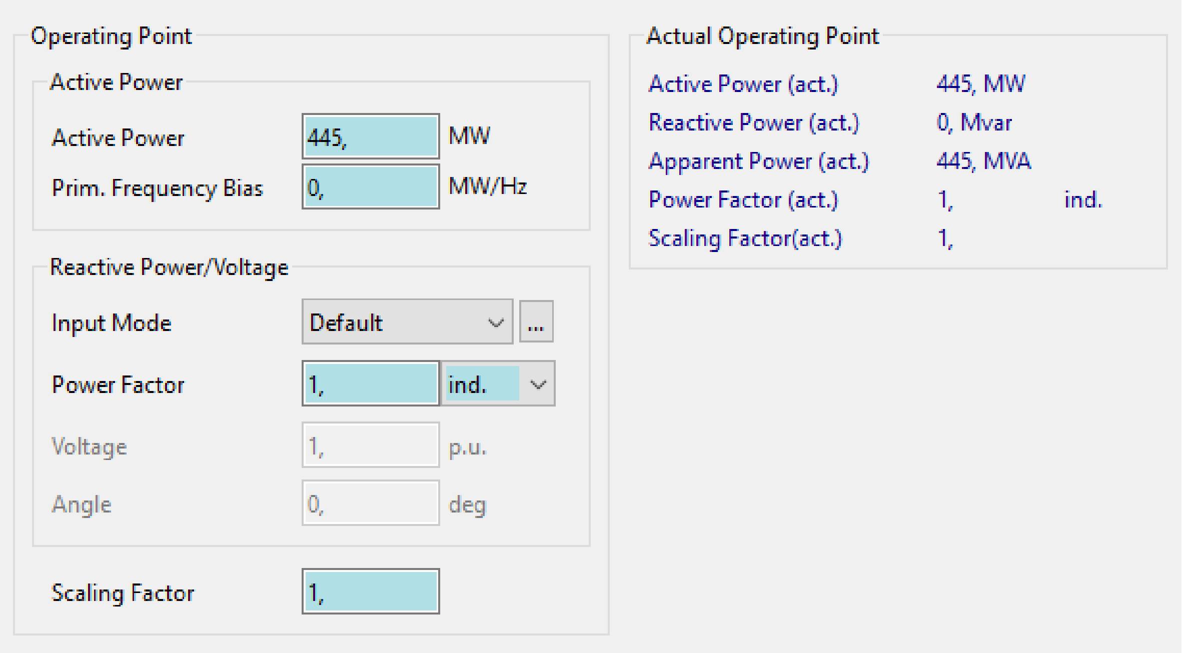
Year	Electricity sale	Own funds	Run. costs	Deprec. allow.	Taxable income	Taxes	After-tax profit	Cumul. profit	% amorti.
0	0	200,000,000	0	0	0	0	0	-200,000,000	0.0%
1	89,565,582	0	71,199,149	7,342,412	11,024,021	0	18,366,433	-181,633,567	9.2%
2	89,565,582	0	71,199,149	7,342,412	11,024,021	0	18,366,433	-163,267,133	18.4%
3	89,565,582	0	71,199,149	7,342,412	11,024,021	0	18,366,433	-144,900,700	27.5%
4	89,565,582	0	71,199,149	7,342,412	11,024,021	0	18,366,433	-126,534,267	36.7%
5	89,565,582	0	71,199,149	7,342,412	11,024,021	0	18,366,433	-108,167,833	45.9%
6	89,565,582	0	71,199,149	7,342,412	11,024,021	0	18,366,433	-89,801,400	55.1%
7	89,565,582	0	71,199,149	7,342,412	11,024,021	0	18,366,433	-71,434,967	64.3%
8	89,565,582	0	71,199,149	7,342,412	11,024,021	0	18,366,433	-53,068,533	73.5%
9	89,565,582	0	71,199,149	7,342,412	11,024,021	0	18,366,433	-34,702,100	82.6%
10	89,565,582	0	71,199,149	7,342,412	11,024,021	0	18,366,433	-16,335,667	91.8%
11	89,565,582	0	71,199,149	7,342,412	11,024,021	0	18,366,433	2,030,767	101.0%
12	89,565,582	0	71,199,149	7,342,412	11,024,021	0	18,366,433	20,397,200	110.2%
13	89,565,582	0	71,199,149	7,342,412	11,024,021	0	18,366,433	38,763,633	119.4%
14	89,565,582	0	71,199,149	7,342,412	11,024,021	0	18,366,433	57,130,067	128.6%
15	89,565,582	0	71,199,149	7,342,412	11,024,021	0	18,366,433	75,496,500	137.7%
16	89,565,582	0	71,199,149	7,342,412	11,024,021	0	18,366,433	93,862,933	146.9%
17	89,565,582	0	71,199,149	7,342,412	11,024,021	0	18,366,433	112,229,367	156.1%
18	89,565,582	0	71,199,149	7,342,412	11,024,021	0	18,366,433	130,595,800	165.3%
19	89,565,582	0	71,199,149	7,342,412	11,024,021	0	18,366,433	148,962,233	174.5%
20	89,565,582	0	71,199,149	7,342,412	11,024,021	0	18,366,433	167,328,667	183.7%
21	89,565,582	0	71,199,149	0	18,366,433	0	18,366,433	185,695,100	192.8%
22	89,565,582	0	71,199,149	0	18,366,433	0	18,366,433	204,061,533	202.0%
23	89,565,582	0	71,199,149	0	18,366,433	0	18,366,433	222,427,967	211.2%
24	89,565,582	0	71,199,149	0	18,366,433	0	18,366,433	240,794,400	220.4%
25	89,565,582	0	71,199,149	0	18,366,433	0	18,366,433	259,160,833	229.6%
Total	**2,239,139,553**	**200,000,000**	**1,779,978,720**	**146,848,244**	**312,312,589**	**0**	**459,160,833**	**259,160,833**	**229.6%**

Table 4.8. ROI (return on investment)

Payback period	10.9 years
Net present value (NPV)	259,160,833.28 AZN
Internal rate of return	7.77%
Return on investment	129.6%

4.5. Grid Integration

The integration process presents the loading conditions of two high-voltage (330 kV) power transmission lines of the solar park in two different scenarios while integrating into the energy system. Case 1: Two transmission lines are under normal conditions, each line loaded to 28.6% of its capacity. Case 2: Under the case of one line out of operation for maintenance or due to an unforeseen incident, the remaining line is loaded to 57% of its capacity, ensuring continuous integration of the solar park into the grid. Furthermore, a yearly load profile was created with the same simulation program used in the integrating process and provided very critical results regarding the performance of the system. PowerFactory simulations confirmed that the integration of 445 MW solar capacity maintained grid stability, even during peak solar generation periods. I share with you what was obtained from the beginning to the end of the simulation through pictures.



Operating Point

Active Power

Active Power: 445, MW
Prim. Frequency Bias: 0, MW/Hz

Reactive Power/Voltage

Input Mode: Default
Power Factor: 1, ind.
Voltage: 1, p.u.
Angle: 0, deg

Scaling Factor: 1,

Actual Operating Point

Active Power (act.)	445, MW	
Reactive Power (act.)	0, Mvar	
Apparent Power (act.)	445, MVA	
Power Factor (act.)	1,	ind.
Scaling Factor(act.)	1,	

Figure 4.8. Operation point on DIgSILENT

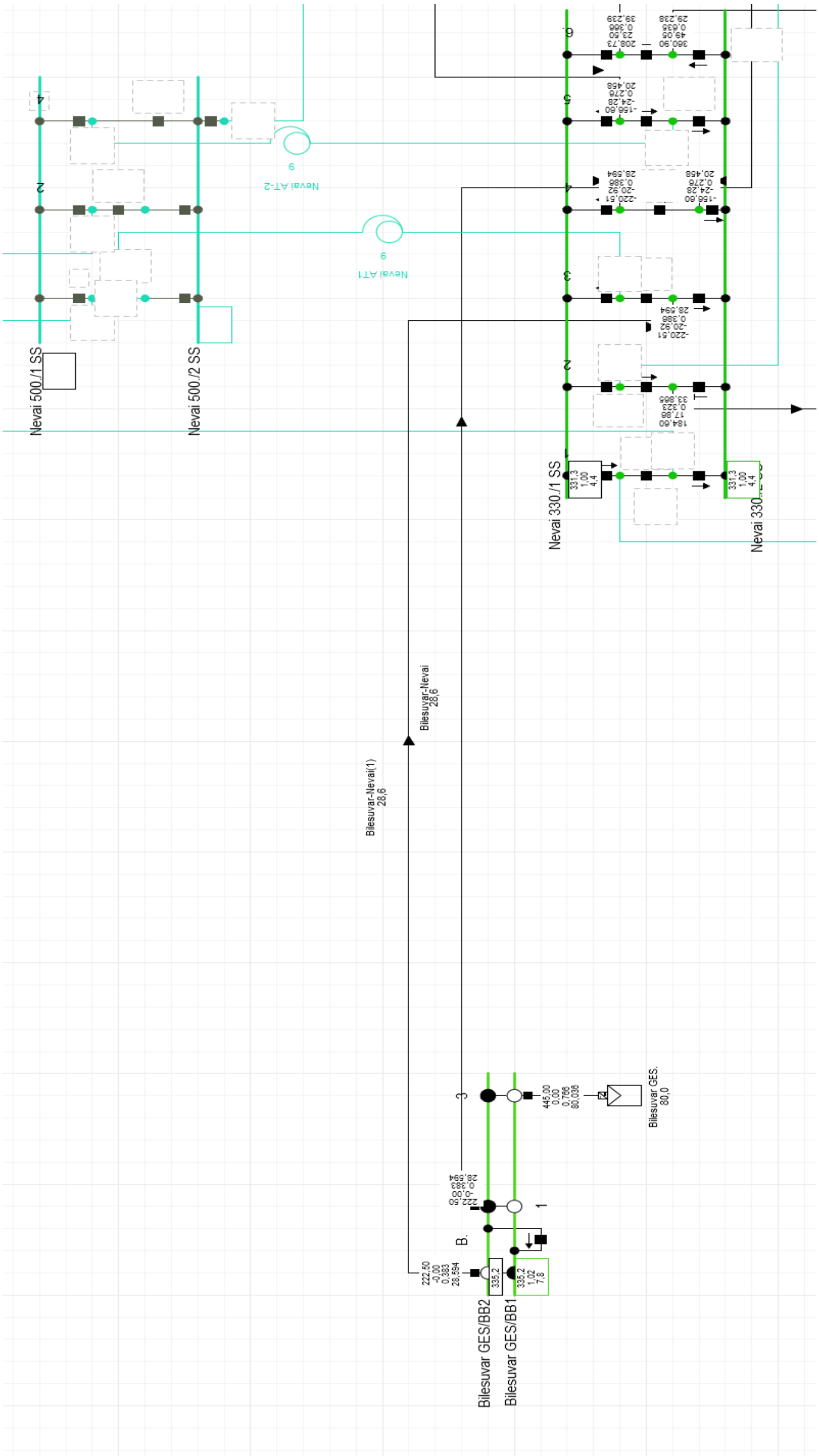


Figure 4.9. Connection scheme of integration process with two HV transmission lines

You can see energy flowing process via two high voltage transmission lines. It is given below

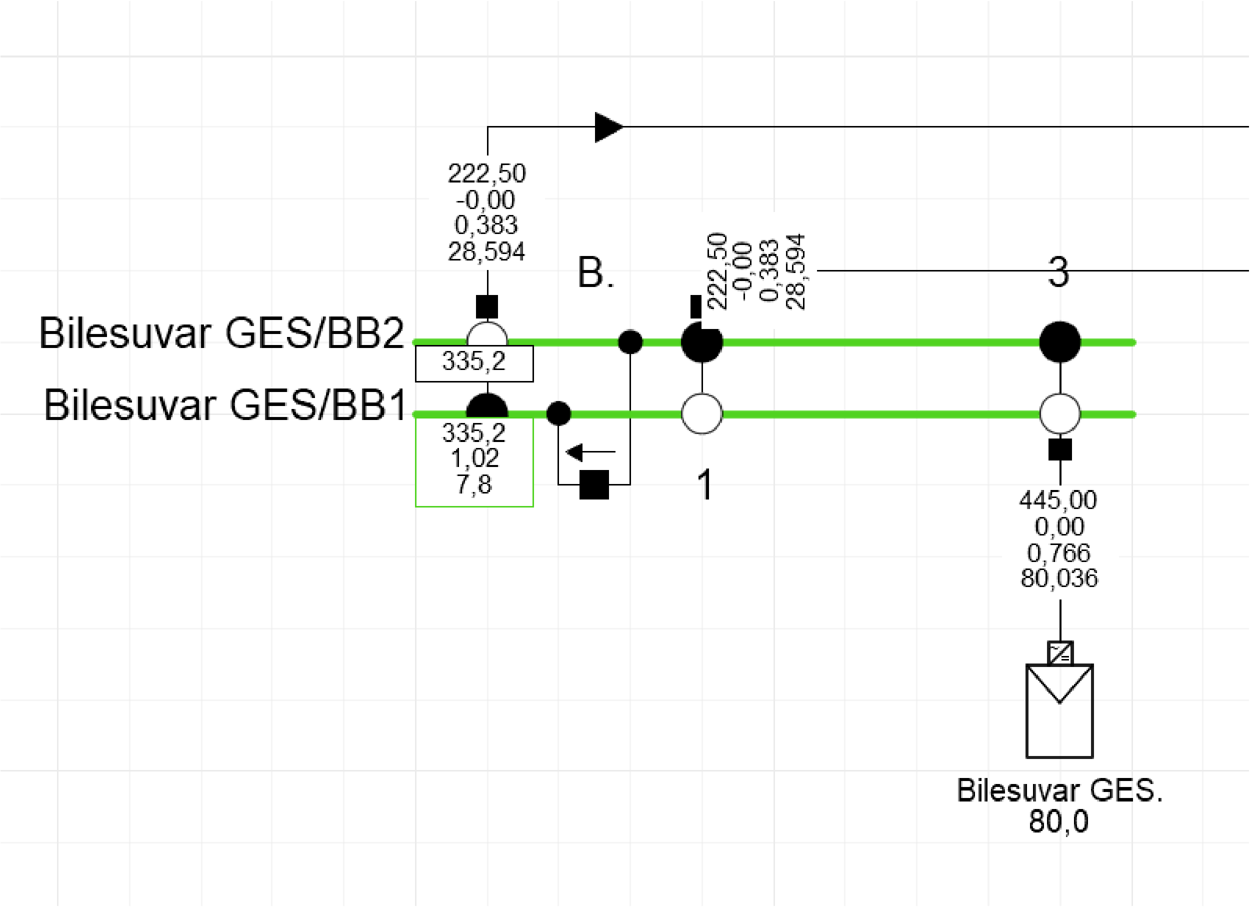


Figure 4.10. Connection scheme via two HV transmission lines

P=222,50 MW; Q=0 MVar, I=0,383 kA, Loading=28,594% these values are electrical output parameters of Bilasuvar Solar Park which is shown on the above single line electrical diagram.

Considering second case, you can see energy flowing process via one high voltage transmission line. It is given below.

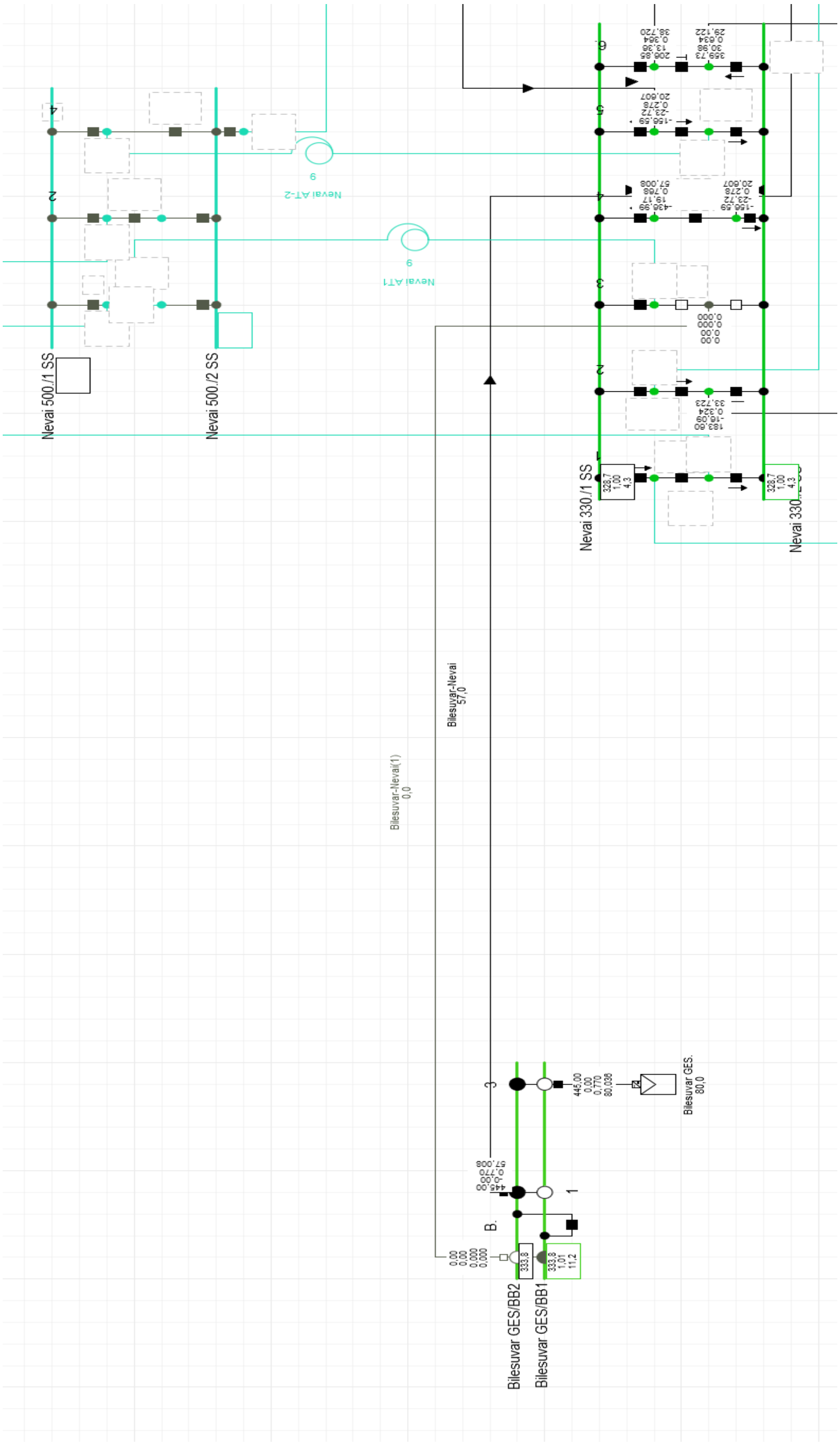


Figure 4.11. Connection scheme of integration process with one HV transmission line

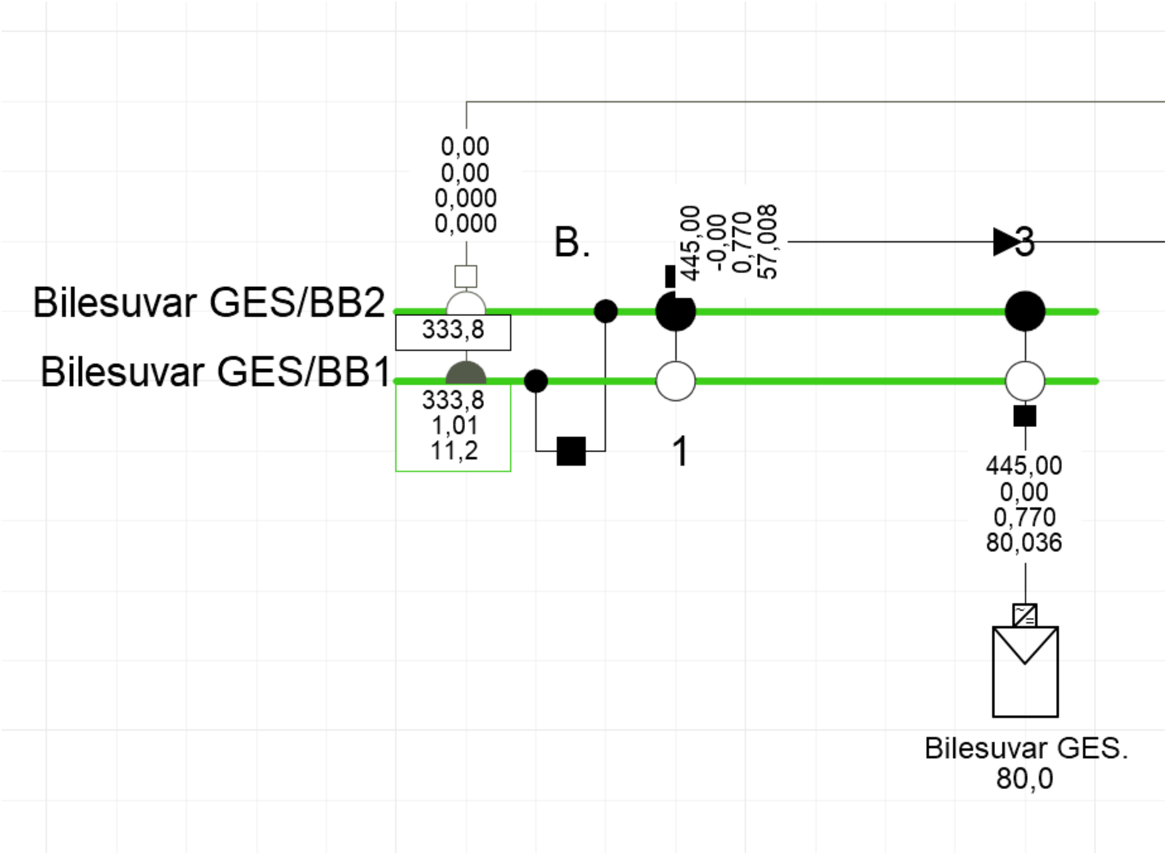


Figure 4.12. Connection scheme via one HV transmission line

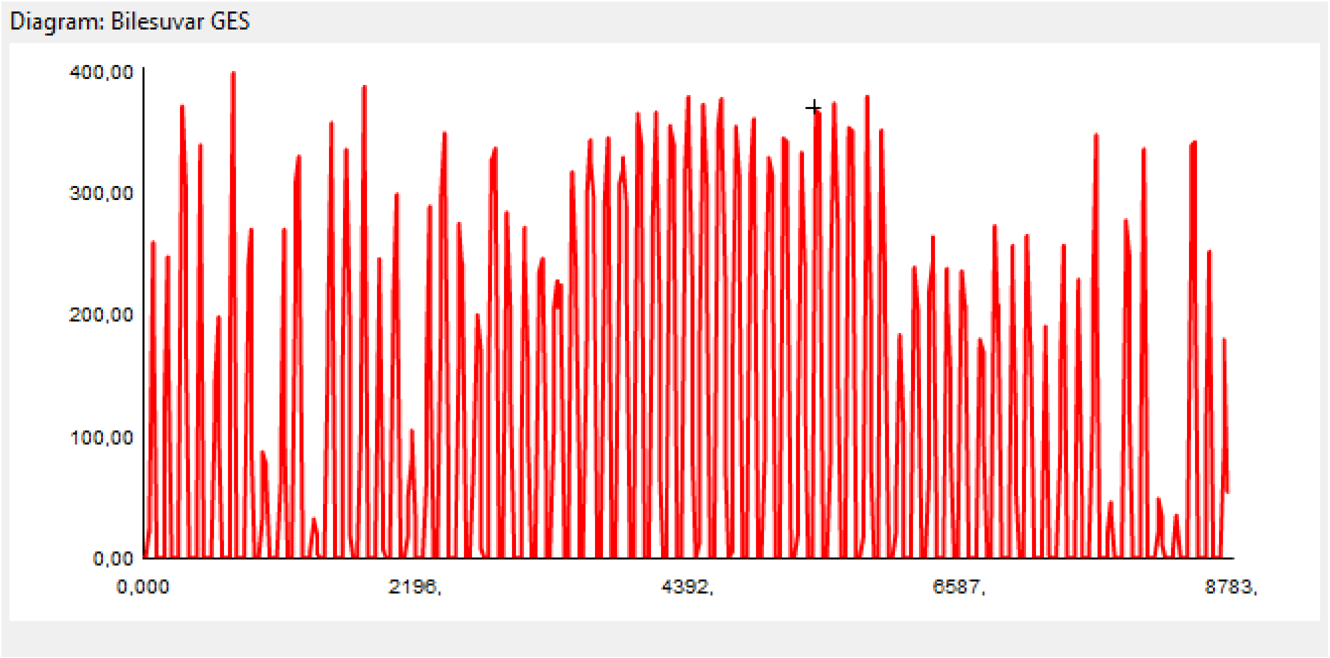


Figure 4.13. Annual load analysis of Bilasuvar Solar Park

DISCUSSIONS AND CONCLUSIONS

The integration of the Bilasuvar Solar Park into Azerbaijan's energy infrastructure demonstrates the applicability and benefits of large-scale renewable energy projects. Detailed simulation in PVsyst and PowerFactory gave a comprehensive analysis regarding the efficiency of the systems, stability of the grid, and environmental and economic impacts.

The Bilasuvar Solar Park achieved an annual energy generation capacity of 684 GWh and had a PR of 87.7%. The higher value of PR proves that the installed PV modules have been exploited well under real operating conditions. Figure 4.5 presents the month-wise variation of PR, almost constant over the year, except for slight deviations during the hotter months of the year due to thermal losses. Figure 4.6 presents the modules which most affect the energy losses: Module Minor efficiency reductions because of differences in the characteristics of the PV modules. Shading Losses: Optimization in the design of the site reduced these losses to a minimum, but during some months of the year, due to the environment, this is unavoidable. Wiring Losses: This was within acceptable limits due to the proper sizing and laying of conductors.

The utilised advanced inverters, such as the SG250HX, featured high conversion efficiencies that consequently confined the power conversion losses.

Apparently, these results put weight on the use of advanced technologies and system design to enhance overall energy generation.

This project will make a substantial difference in mitigating climate change by saving more than 3 gigatons of CO_2 emissions within its 30-year design life. Figure 4.7 illustrates the annual CO_2 emissions avoided and the environmental implication due to switching from fossil fuel-based energy to solar energy.

In particular, Table 4.4 and Table 4.5 present the amount of emission savings, showing the importance of renewable energy projects in meeting the climate goals of Azerbaijan. These results further highlight the environmental benefit of switching to renewable sources of energy in general but, in particular, in regions characterized by high solar potential-like conditions such as the ones in Bilasuvar.

PowerFactory simulations were performed in order to analyze the grid dynamic behavior under integration of solar energy. Figure 4.9 and Figure 4.10 present, respectively, the operation of two circuits of 330 kV transmission lines under normal conditions and during maintenance. The system remained stable even in the case of single-line operation: the second line was loaded up to 57% of its capacity. This testifies to the strength of the transmission infrastructure and to its potential to host substantial renewable penetration.

Figure 4.13 presents the yearly load analysis: energy delivery is uniformly distributed throughout the year. Such strong grid stability outcomes give further confirmation to the possibility of replicating this type of renewable energy project on an extended area within Azerbaijan.

The financial outcome gives a good payback period of 10.9 years, along with an ROI of 129.6%. The good economic viability is the result of efficiently using resources, as can be observed from Figure 4.6, with high energy yield due to using advanced technologies. These sorts of results render projects bankable and of interest to public and private investors in continuous investment for further renewable development.

Although the loss diagram identifies the main reasons for inefficiency, further optimizations are called for in the areas of module and wiring design.

The analysis also suggested the development of hybrid systems-linking into one unit different renewable sources of energy, like wind and solar-to come up with a more stable, efficient energy system.

The Bilasuvar Solar Park project epitomizes the critical role of renewable resources in combating climate change while enhancing energy security. Applying Azerbaijan's abundant solar resources and advanced technologies, the project has set the bar high for all future renewable projects.

The research outlines that only with very detailed planning, state-of-the-art simulation tools, and stakeholder coordination is it possible to understand the full potential of renewable energies. Though challenges remain ahead, especially on grid integration and optimization issues, the findings can be framed robustly to overcome such barriers.

By scaling up similar projects and including innovative solutions in the sector, Azerbaijan will be able to make more significant contributions toward renewable energy targets and global sustainability goals.

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