Integration of Solar Energy in Waste Management: Modeling Performance Analysis and Degradation Evaluation of a Grid-Connected Photovoltaic Power Plant for an Ecological Sorting Center

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Abstract

Numerous companies and organizations are looking into sustainable solutions for their energy demands as a result of the increasing demand to promote renewable energies and reduce their dependence on fossil fuels within the context of the global energy transition. Waste sorting centers present a perfect chance to incorporate renewable energy sources like solar power because of their high energy usage.

This study analyzes the implementation of a grid-tied photovoltaic power plant to provide electricity to a waste sorting facility. It looks at the implementation's technical and environmental factors, such as system sizing and carbon emission reductions. PVsyst software is used to simulate the system.

Results demonstrate that the system has an exceptional performance ratio of 85%, producing 56.3 MWh of energy yearly. Degradation is predicted to occur at a rate of about 20% for the next 30 year and over the lifespan of the installation, a total of 858.7 tons of CO2 emissions are avoided.

Keywords: *Solar energy, PV, Inverter, Grid-connected, waste management*

1. Introduction

Energy is essential to many different industries and sectors, such as buildings, transportation, manufacturing, agriculture, and households. However, there has been a notable increase in greenhouse gas emissions as a result of the growing reliance on fossil fuels to generate power, which has increased environmental degradation and led to global warming. As a result, it is vital that we move away from fossil fuels and toward greener, more sustainable energy sources like hydro, solar, wind, and biomass [1].

With the introduction of an extensive program for the advancement of energy efficiency and renewable energy (RE), Algeria is starting off a green energy dynamic. Based on a plan focusing on the development of limitless resources like solar energy and their application to diversify renewable energy sources and equip Algeria for the future, this is the government of Algeria's vision. Algeria is entering a new era of sustainable energy through a combination of intelligence and actions. [2]

The revised renewable energy program calls for the installation of roughly 22,000 MW of renewable power for the domestic market by 2030 as shown in Figure 1, with the strategic goal of exporting if market conditions permit [3].

The most common type of solar power system available today is grid-connected photovoltaic systems. [4] Systems that feed power directly into a public electrical grid, or any other large independent grid, are known as grid-connected systems [5].
In a recent study by Jagadale, et al. (2022), the researchers examined the design and simulation of a grid-connected photovoltaic installation in Pune, India, utilizing the PVsyst software. Their work highlights the significance of comprehensive analysis of design parameters to optimize the performance of solar systems in specific contexts. [6]
In another recent study by Uwho, K. O. et al. (2022), the authors investigated the design and simulation of a 500 kW grid-connected photovoltaic system for the Faculty of Engineering at Rivers State University Nigiria, employing the PVsyst software. This research provides valuable insights into the implementation of solar power systems in academic institutions. [7]
Shrivastava, et al. (2023) conducted a comprehensive study focusing on the assessment of solar energy capacity and performance evaluation of a standalone photovoltaic (PV) system. Their research, delves into the intricate analysis of standalone PV systems using the PVSYST software. By examining the capacity and performance metrics, including efficiency, reliability, and energy yield, the authors provide valuable insights into the practical application and optimization of standalone PV systems. This work contributes significantly to the understanding of the technical aspects and operational considerations crucial for deploying efficient and reliable solar energy solutions. [8]
Nanda, S., & Berruti, F. (2021) conducted an extensive review focusing on municipal solid waste (MSW) management and landfilling technologies, their research offers a comprehensive overview of various strategies and technologies employed in MSW management, with particular emphasis on landfilling techniques. By synthesizing existing literature and highlighting advancements and challenges in the field, the authors provide valuable insights into the current state of MSW management practices. This review serves as a valuable resource for researchers, and practitioners seeking to address the environmental and sustainability issues associated with MSW management. [9]
One of the most important steps towards more environmentally friendly waste management is the creation and improvement of a photovoltaic grid-connected energy production system to power the waste sorting center. [10] As a hub for gathering waste and organizing it for further recycling, this center is crucial.
Materials such as glass, plastics, steel, aluminum, newspapers, magazines, paper, cardboard, and plastic containers are among the processed waste. [11]
The procedures of sorting and processing need the use of complex industrial equipment, such as crushers, compactors, and conveyors. These devices currently get their power from the local electrical grid. [12]However, there are serious disadvantages to this reliance on the grid in terms of energy costs and environmental sustainability. It raises operating expenses and increases the facility's greenhouse gas emissions, [13] which causes environmental issues. In addition, this reliance increases the waste management system's vulnerability to power outages, creating operational difficulties and even affecting the effectiveness of waste processing and recycling initiatives. [14]
The aim of this study is to improve the operational sustainability of the sorting center by establishing an adapted photovoltaic system to satisfy its special energy needs. The sorting center may reduce its dependency on fossil fuels and contribute to the reduction of greenhouse gas emissions by producing power from a plentiful and renewable source, [15, 16] such as the sun. Additionally, the photovoltaic system's energy independence can guarantee continuous operation even in the case of main electrical grid disruptions, [17] resulting in a waste management system that is more durable and stable. [18] In the end, this shift to sustainable and clean energy will help to reduce the sorting of waste

center's total environmental effect. [19] The entire system component is simulated using the PVSyst software, which is a well-known academic resource for comprehensive research and modeling of photovoltaic systems.

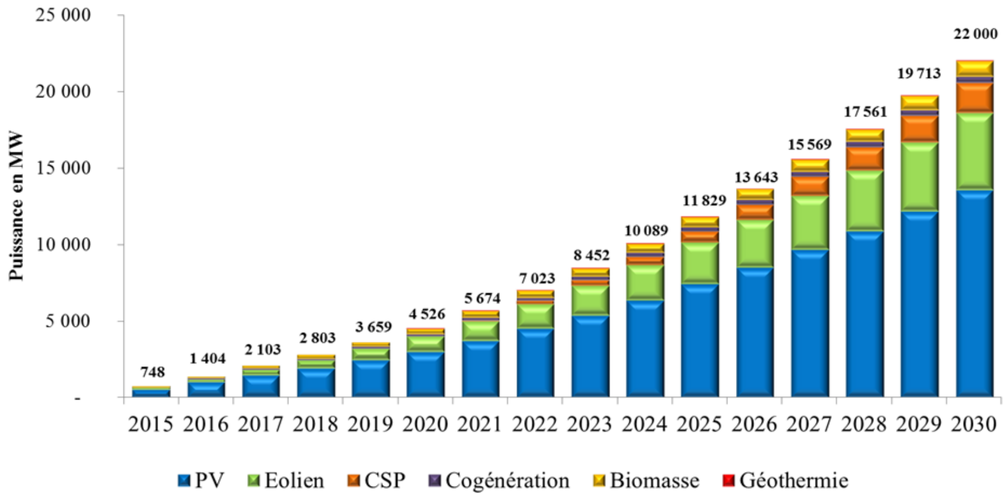

Figure 1. Consistency of the renewable energy program to be achieved for the Algerian market over the period 2015-2030

2. Case of study

Before being recycled, carefully selected waste is sorted, packaged, and stored at waste sorting facilities (Figure 2), also referred to as municipal waste sorting centers. Within the waste kinds treated are:

- Hollow materials: aluminum, steel, plastic, and glass.
- Flat things include periodicals and newspapers, papers, cardboard, glass, steel, and aluminum.

These centers include reception, a space for upstream storage, sorting, packing, downstream storage, removal of packaged items, and reject sorting, among other steps. [20]

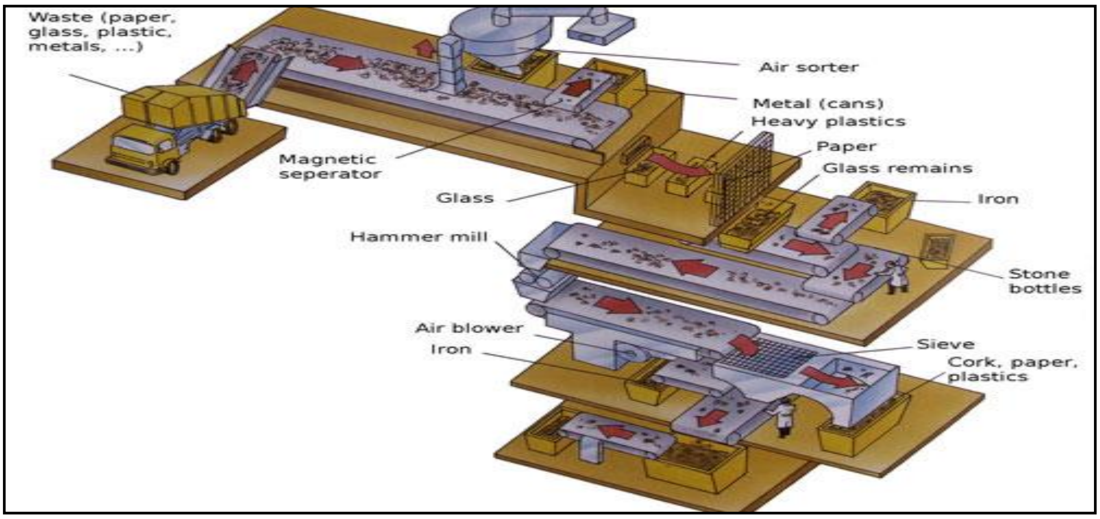

Figure 2. Solid waste treatment site

The sorting and processing operations require the use of sophisticated industrial equipment such as conveyors, compactors, and crushers, which are currently powered by the local electrical grid. However, this reliance on the grid has drawbacks in terms of energy costs and environmental sustainability, [21-22] as it leads to higher carbon emissions and increased vulnerability to power outages.

2.1 Description of Waste Sorting Center Equipment

Figure 3 shows the image of the conveyor, a crucial piece of the waste management center's infrastructure. This device is essential for moving waste through the several steps of the sorting process in an efficient manner. Sustaining the center's maximum production depends critically on its ongoing operational reliability.

Figure 3. Image of Conveyor System in Waste Sorting Facility

Made using SolidWorks software, Figure 4 presents a detailed three-dimensional portrayal providing an encompassing and lifelike representation of the waste sorting facility. This depiction intricately captures the spatial layout of the facility, including the arrangement of multiple sorting stages, storage areas, and various equipment utilized in the sorting process. Through this visualization, observers can gain a comprehensive understanding of the structural and functional organization of the sorting center.
Figure 4 is an invaluable resource for waste management and facility planning stakeholders because it provides a realistic and thorough overview. By offering insights into the facility's layout, working procedures, and possible improvement areas, it facilitates well-informed decision-making and eventually raises the efficacy and efficiency of waste management operations.

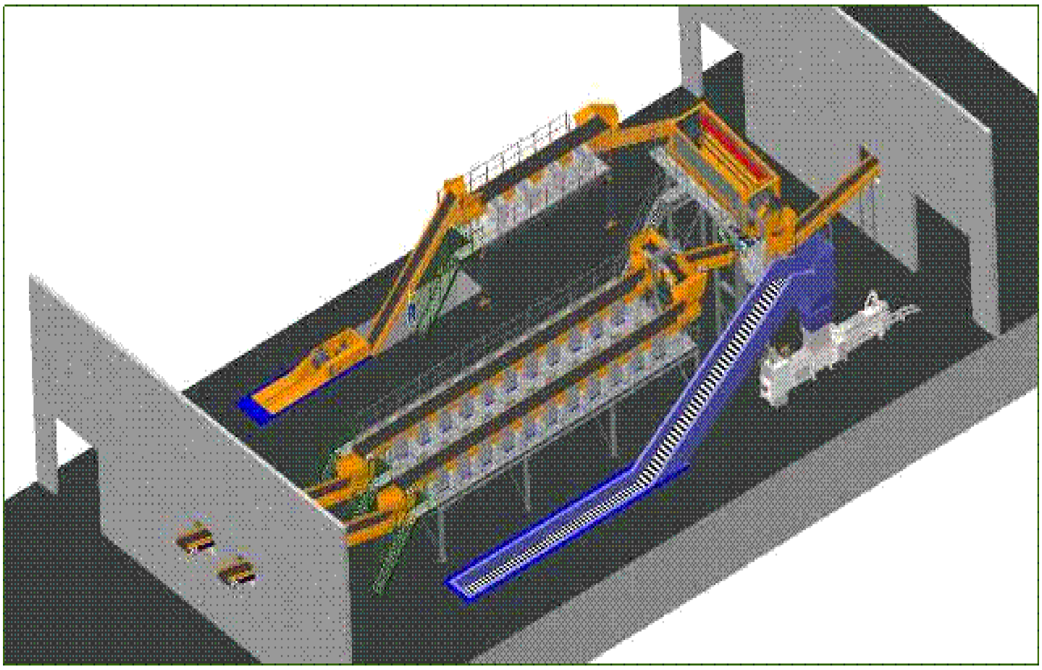

Figure 4. 3D Rendering of Waste Sorting Facility Created with SolidWorks

Table 1 and figure 5 provides a detailed breakdown of the energy consumption and distribution of various equipment used in the system. The table includes the following information:

1. **Equipments**: Lists the types of equipment included in the analysis, such as LED lights, conveyor motors, control automation, pump hydraulic presses, air extractors, loading conveyor motors, and others.
2. **Quantity**: Indicates the number of each type of equipment used in the system.
3. **Power (W)**: Specifies the power consumption of each equipment in watts.
4. **Usage (h/day)**: Shows the average daily usage duration of each equipment in hours.
5. **Total power (W)**: Calculates the total power consumption of each type of equipment by multiplying the quantity with the power consumption.
6. **Daily Consumption Wh/day**: Presents the daily energy consumption of each type of equipment in watt-hours, calculated by multiplying the total power with the average daily usage duration.

This table provides a comprehensive overview of the energy requirements of different equipment in the system, which is essential for designing and optimizing the energy supply, such as the proposed grid connected photovoltaic system [23, 24].

Table 1. Power and Energy Consumption

Equipement	Quantity	Power (W)	Usage (h/day)	Total power (W)	Daily Consumption (Wh/day)
LED lights	15	200	8	3000	24000
Conveyor motors	4	3000	8	12000	96000
PCs and control automation	2	200	8	400	3200
Pump hydraulic presses	1	3200	2	3200	6400
Air extractor	3	500	8	1500	12000
Loading conveyor motors	1	3500	5	3500	17500
Others	1	2000	3	2000	6000
TOTALS				25600	46893,29

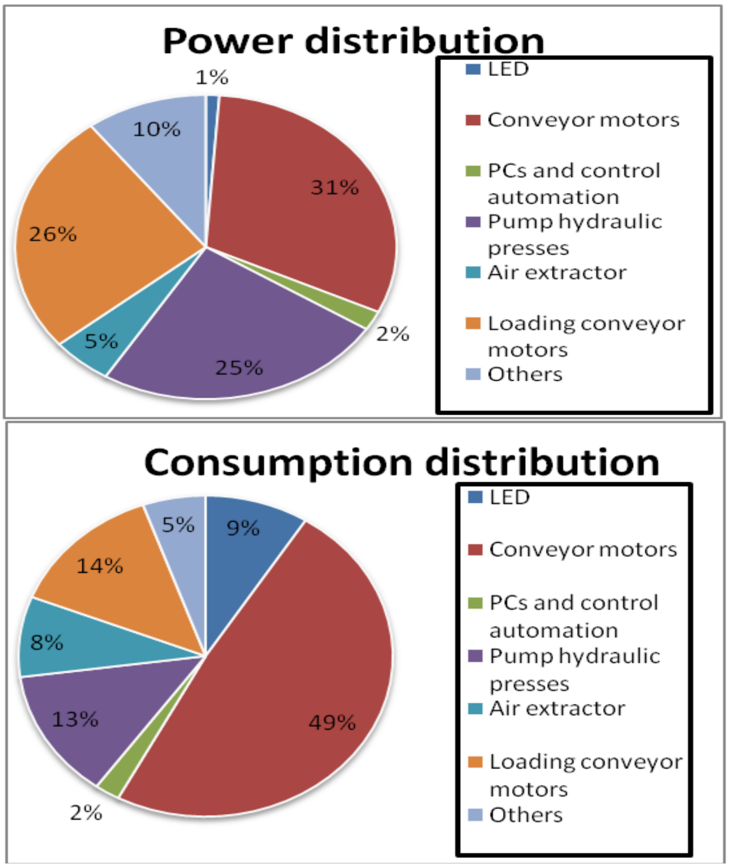

Figure 5. Power and Energy consumption distribution

3. Description of the Solar PV/Grid-connected system

Grid-connected photovoltaic systems are complex installations that incorporate several essential components for the conversion and distribution of solar energy [25]. At their core lies a bidirectional inverter, which plays a crucial role in converting the electricity produced by the photovoltaic panels into alternating current compatible with the electrical grid. Photovoltaic panels capture solar energy and transform it into direct current (DC), which is then routed to a DC bus, where it is regulated and efficiently distributed. Simultaneously, an alternating current (AC) bus facilitates the connection of the photovoltaic system to the electrical grid, ensuring interoperability and synchronization with other energy sources [26].

This type of system offers a significant advantage in terms of efficient utilization of solar energy, as it avoids losses associated with energy storage, which is often the case with battery storage systems. Indeed, the electricity generated by the photovoltaic panels can be directly injected into the electrical grid and instantly utilized by grid-connected electrical equipment. Moreover, grid-connected photovoltaic systems can benefit from energy compensation mechanisms, allowing owners to sell excess electricity generated to the grid and generate additional income.

To illustrate these concepts more concretely, the proposed model is detailed in Figure 6, which was generated using PVSyst software. This visualization provides an overview of the system and its operation, thus allowing a better understanding of its efficiency and potential in the specific context of the simulation project for the grid-connected photovoltaic plant to power the waste sorting center [27].

Grid-connected solar PV power systems consist of the following components:

- PV modules arranged in series and parallel configurations, to produce direct current power from sunlight interception.
- Maximum power point tracking (MPPT) technology, ensuring that photovoltaic solar modules operate at their optimal power output throughout daylight hours.
- DC/AC converters linked to the grid, ensuring that safely converted AC power is supplied to the grid infrastructure.

This system maximizes the use of power generated from solar energy by eliminating energy storage losses [28].

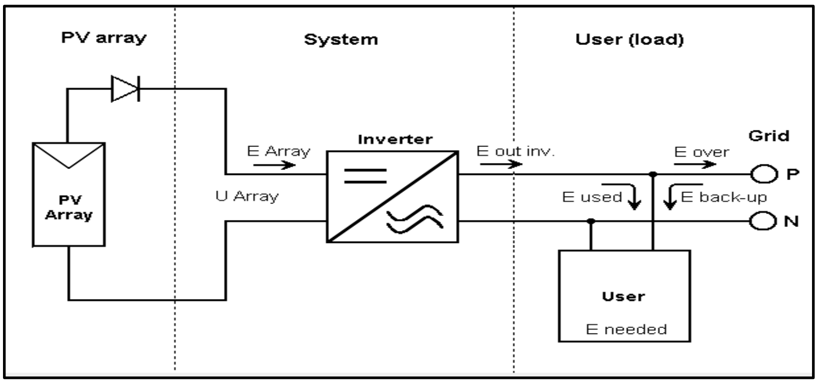

Figure 6. Grid-Connected Photovoltaic System Diagrams without Storage

3.1. Tilt and Orientation

The optimization of the PV system depends on two main parameters: the orientation and the tilt angle.The tilt angle of the panel (Figure 7) will be fixed at t 33° and its orientation will always be directed due south [29].

Figures 7 and 8 present crucial information for the assessment and optimization of the photovoltaic (PV) system's performance. In Figure 4, the "Tilt angle of the PV field" represents the optimal inclination angle of the photovoltaic panels relative to the horizontal surface. This inclination is of paramount importance as it directly influences the amount of solar light captured by the panels, and hence their overall efficiency. [30] A precise solar performance curve, depicted in Figure 5, offers a graphical representation of the PV system's performance based on various parameters such as light intensity, temperature, or other variable environmental conditions. These two figures provide essential data to guide the design and optimization of the photovoltaic system, enabling the determination of the optimal panel tilt angle and prediction of their performance under diverse conditions.

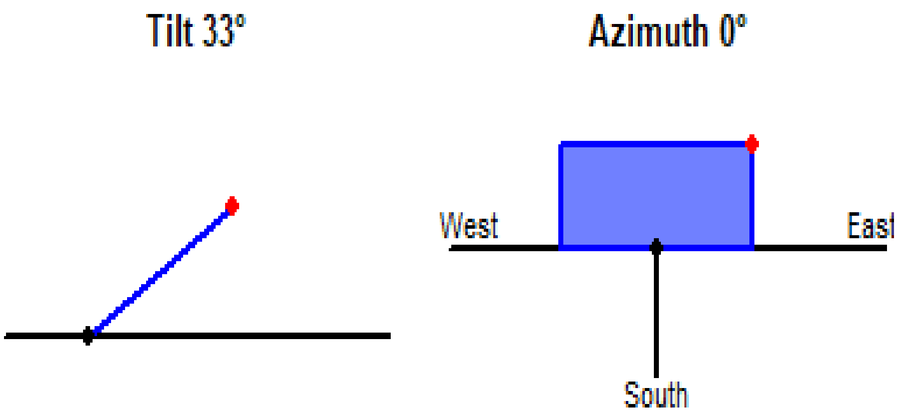

Figure 7. Tilt angle of the PV field.

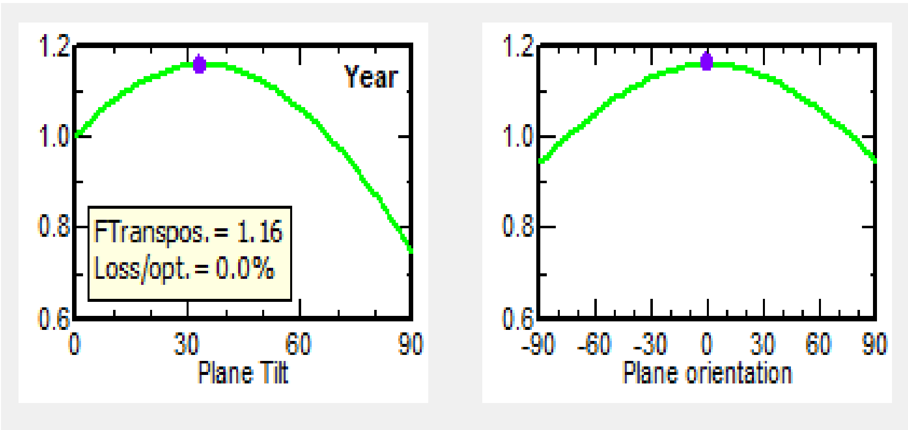

Figure 8. Performance curve

3.2. Photovoltaic field

The photovoltaic field consists of 110 monocrystalline JinkoSolar panels, each with a power rating of 300 watts peak (Wp). These panels are configured in 5 chains connected in parallel. Each chain comprises 22 panels connected in series, resulting in a total power output of 33 kilowatts (kW).

Table 2 provides a comprehensive overview of the specifications of the photovoltaic modules used in this study. Each parameter plays a crucial role in the overall evaluation of the performance and capacity of the photovoltaic system. The nominal power of the module, expressed in watts, represents its maximum energy production capacity under standardized conditions. The module's efficiency, expressed as a percentage, reflects its ability to convert solar light into electricity. Additionally, details on maximum voltage, maximum current, and other electrical characteristics are included to ensure appropriate design of the photovoltaic system, ensuring its efficient and safe operation. These detailed data play an essential role in the accurate assessment of the overall system performance.

Table 2. Photovoltaique Module Specification

Power mpp	301.1W
PTC Power Rating	276.73W [1]
STC Power per unit of area	17.0W/ft^2 (183.3W/m^2)
Efficiency	18.33%
Power Tolerances	0%/+3%
Number of Cells	60
Impp	9.42A
Vmpp	32V
Isc	10.02A
Voc	39.1V
NOCT	45°C
Temp. Coefficient of Isc	0.05%/K
Temp. Coefficient of Power	-0.39%/K
Temp. Coefficient of Voltage	-0,116V/K
Maximum System Voltage	1000V

Figure 9 and 10 respectively depict the current-voltage (I-V) and power-voltage (P-V) characteristics of the photovoltaic solar panels. Figure 9 illustrates the relationship between the applied voltage to the solar panel and the resulting current, providing insight into the panel's electrical behavior under various sunlight and temperature conditions. Figure 10, on the other hand, represents the relationship between the applied voltage and the electrical power produced by the panel, enabling identification of the optimal operating point where electrical power output is maximized. These characteristics are essential for assessing and optimizing the performance of solar panels in photovoltaic systems. It's worth noting that the panel used in this study is the JinkoSolar JKM 300-60.

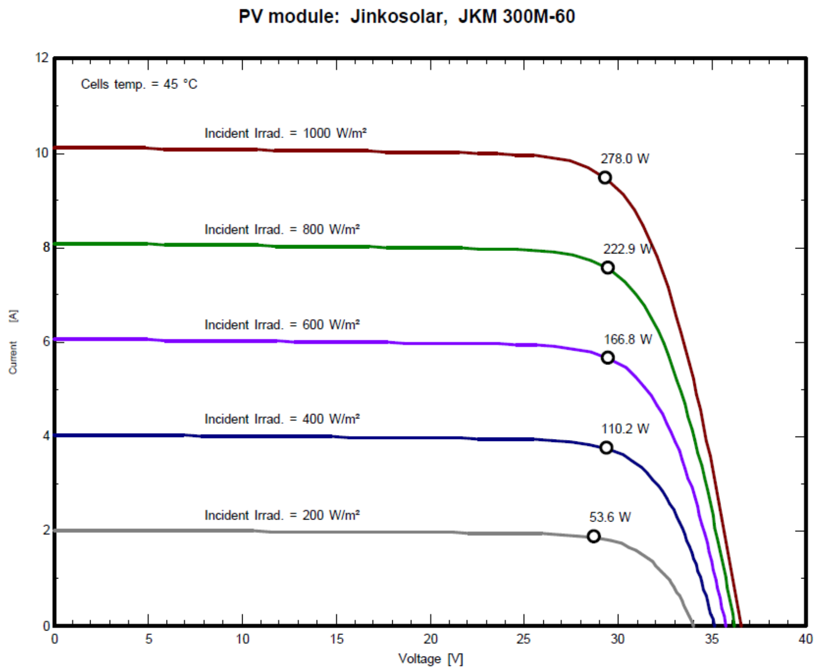

Figure 9. Current-Voltage characteristic

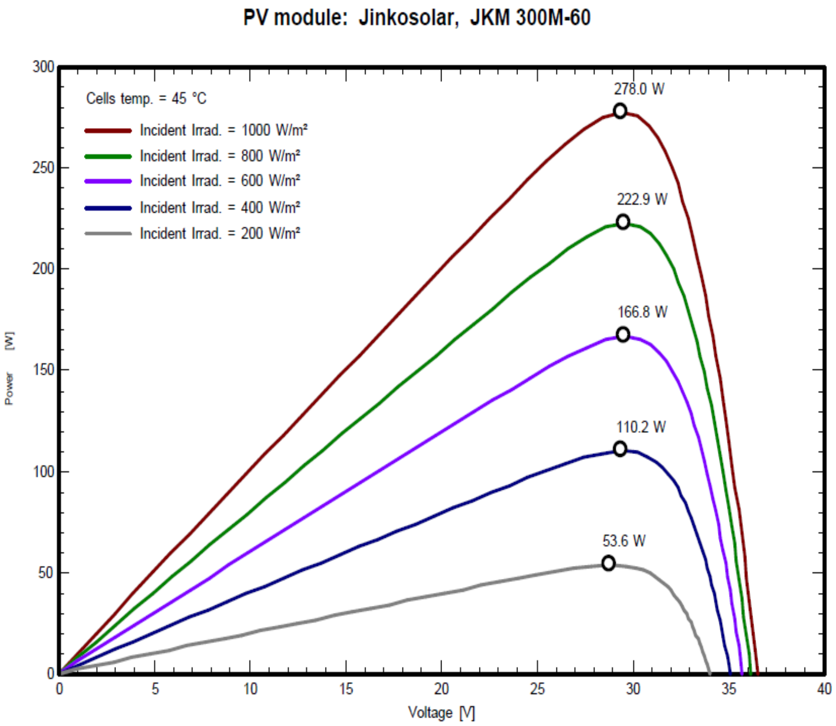

Figure 10. Power-Voltage characteristic

3.3 DC/AC Inverter

Table 3 presents the specifications of the inverter model ABB-PRO-33,0-TL-OUTD used in the photovoltaic system. The table includes details about both the input (DC) and output (AC) parameters of the inverter. Under the input (DC) section, information such as the maximum and minimum input voltage (VDC max and VDC min), the voltage range for maximum power point tracking (VMPP), the number of maximum power point trackers (Multi MPPT), and the number of DC outputs are provided. In the output (AC) section, details such as the maximum AC power output (AC power Max), voltage range of AC output (VAC Output), maximum AC voltage (VAC max), maximum AC current (IAC max), frequency, power factor (Cosφ), total harmonic distortion (THD), number of power phases, and maximum efficiency are listed [31].

Table 3. Inverter Specification

Model	ABB-PRO-33,0-TL-OUTD
Input *(DC)*	
VDC max	950 V
VDC min	610 V
V MPP	580~850 V
Multi MPPT	1
DC output	1
Output *(AC)*	
AC power Max	33 kW
V AC Output	320~480 V
V AC max	400 V
I AC max	50,3 A
Frequency	50, 60 Hz
Cos φ	0,995
THD	< 3 %
Number of power phases	3
Maximum efficiency	98,3 %

In Figure 11, the focus is on the inverter's voltage synchronization process with the PV array. The graph likely illustrates how the inverter adjusts its output voltage to match the voltage generated by the PV array. This synchronization is crucial for optimizing power conversion efficiency and ensuring that the inverter operates within safe voltage limits [32].

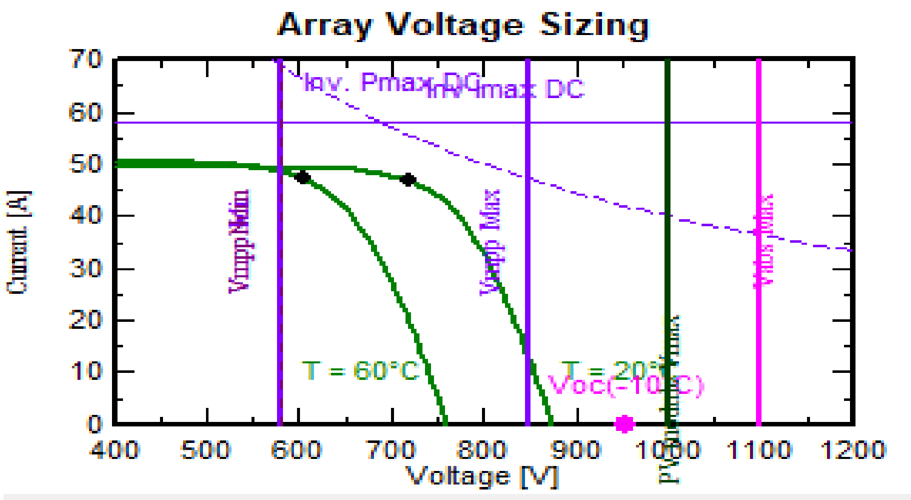

Figure 11. Inverter Voltage Sizing

Figure 12 illustrates the efficiency profile of the inverter concerning input power. The graph displays the relationship between the input power supplied to the inverter and its efficiency. Efficiency is plotted on the y-axis, typically expressed as a percentage, while input power is represented on the x-axis. It is worth noting that the maximum efficiency is 98.3% at 600V voltage. This profile provides valuable insight into how efficiently the inverter converts input power into usable output power across different input power levels. Understanding this relationship is essential for optimizing the performance and energy yield of the photovoltaic system, as it helps identify the most efficient operating points of the inverter under varying load conditions [33].

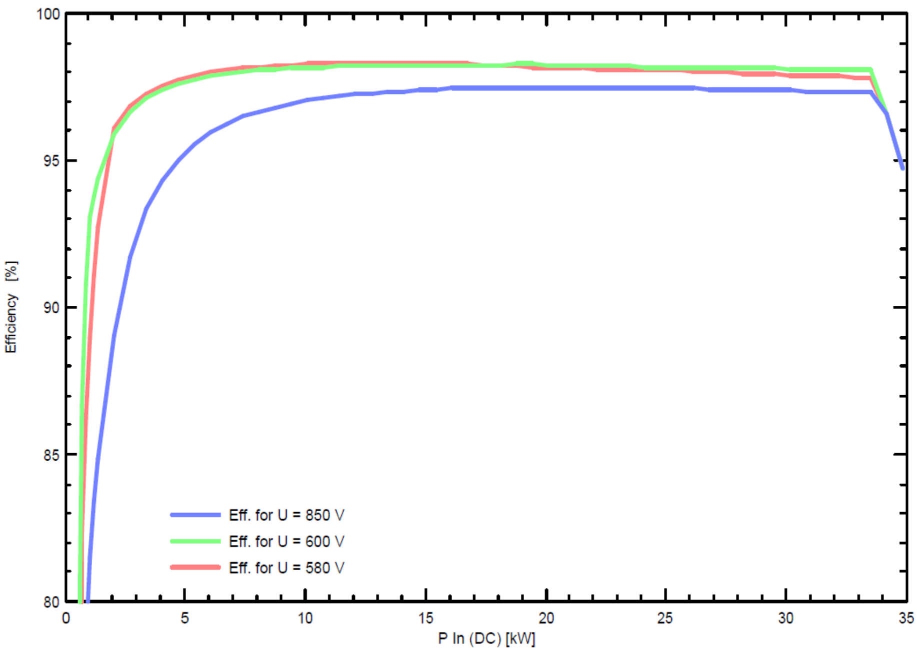

Figure 12. Inverter Efficiency Profile

4. Results and Discussion

Table 3. Balances and Main Results of Grid Connected PV System.

	GlobHor kWh/m²	DiffHor kWh/m²	T Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_Grid MWh	PR
January	81.1	32.79	10.23	129.3	126.4	3.926	3.834	0.898
February	91.4	42.74	10.99	126.8	123.5	3.834	3.747	0.896
March	140.6	63.04	13.55	169.4	164.9	5.007	4.894	0.876
April	166.8	73.09	15.49	176.6	171.3	5.154	5.037	0.865
May	198.0	86.75	19.06	189.2	183.0	5.447	5.325	0.853
June	223.9	80.67	22.90	205.9	199.3	5.797	5.671	0.834
July	238.8	70.58	26.08	225.4	218.7	6.220	6.086	0.818
August	206.6	73.15	26.27	214.1	208.1	5.922	5.797	0.820
September	157.3	58.11	22.99	183.5	178.7	5.168	5.056	0.835
October	123.9	45.82	20.12	168.0	164.0	4.822	4.717	0.851
November	87.1	32.45	14.47	136.6	133.3	4.055	3.966	0.880
December	72.9	27.73	11.80	123.6	120.6	3.734	3.649	0.895
Year	1788.5	686.91	17.87	2048.3	1991.9	59.083	57.778	0.855

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 13 shows the system losses and collection losses of the PV array as well as the useful energy production [5] respectively:

- Lc = 0.71 kWh/kWp/day
- Ls = 0.11 kWh/kWp/day
- Yf = 4.8 Kwh/Kwp/day

According to simulation results, the most favorable month in terms of energy production is July. However, it's important to note that it's also the month with the highest losses due to high temperatures, which can negatively impact the system's efficiency. On the other hand, December produces less energy but is also associated with fewer losses. This trend can be explained by the cooler temperatures in December, which may help maintain the system components at optimal performance levels despite reduced energy production.

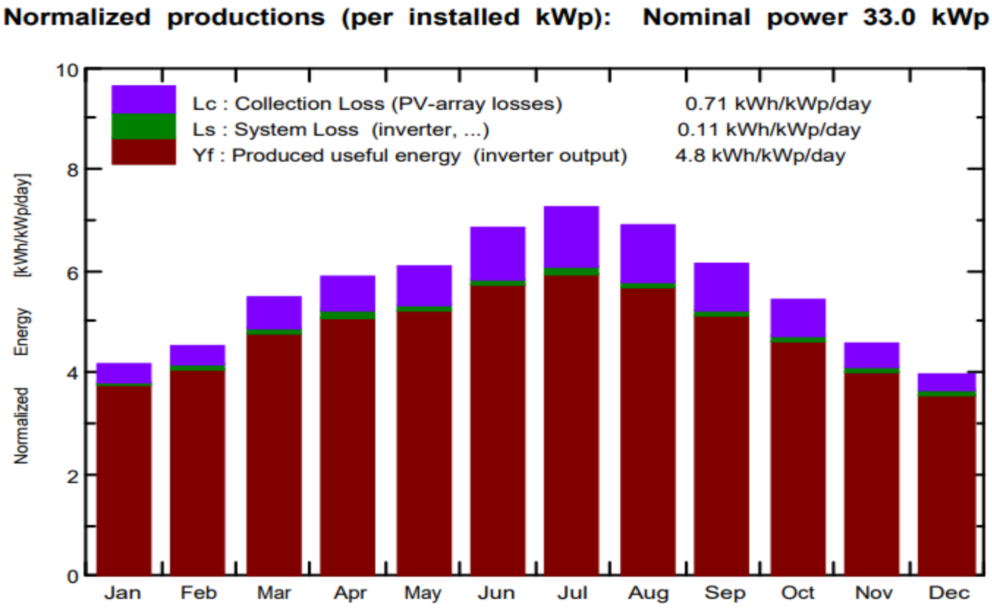

Figure 13. Monthly Nominal Power Graph over the Year

In the analysis of Figure 14, it is notable that the most favorable month in terms of Performance Ratio is December, while the least favorable month is July. This observation underscores significant seasonal trends in the efficiency of the photovoltaic system, where, as discussed previously, winter months generally exhibit superior performance compared to summer months. This difference can be attributed to several factors, including cooler temperatures and more favorable atmospheric conditions during the winter months, thus promoting better conversion of solar energy into electricity. Conversely, higher temperatures in summer, especially during July, can lead to more significant efficiency losses, thereby negatively impacting the Performance Ratio of the photovoltaic system. The average ratio throughout the year is 85.5% indicating that the system's efficiency is very acceptable.

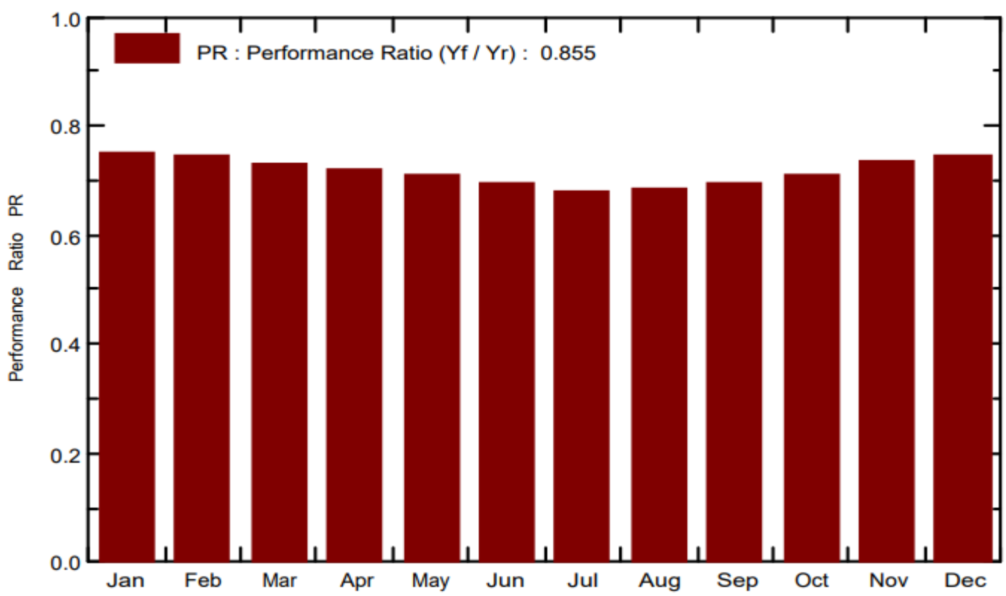

Figure 14. Monthly Performance Ratio PR over the Year

A detailed annual report is shown in Figure 15, which details every loss that occurs in the system, starting with the initial instant solar radiation interacts with the photovoltaic panels and ending with the grid's distribution of electrical energy. It is essential to note that the total horizontal global irradiation is evaluated at 1788 kWh/m2, while the energy captured by the photovoltaic array totals 66.1 MWh, with energy injected into the grid reaching 57.8 MWh. The various losses in the system are meticulously analyzed and expressed as percentages on the corresponding diagram.

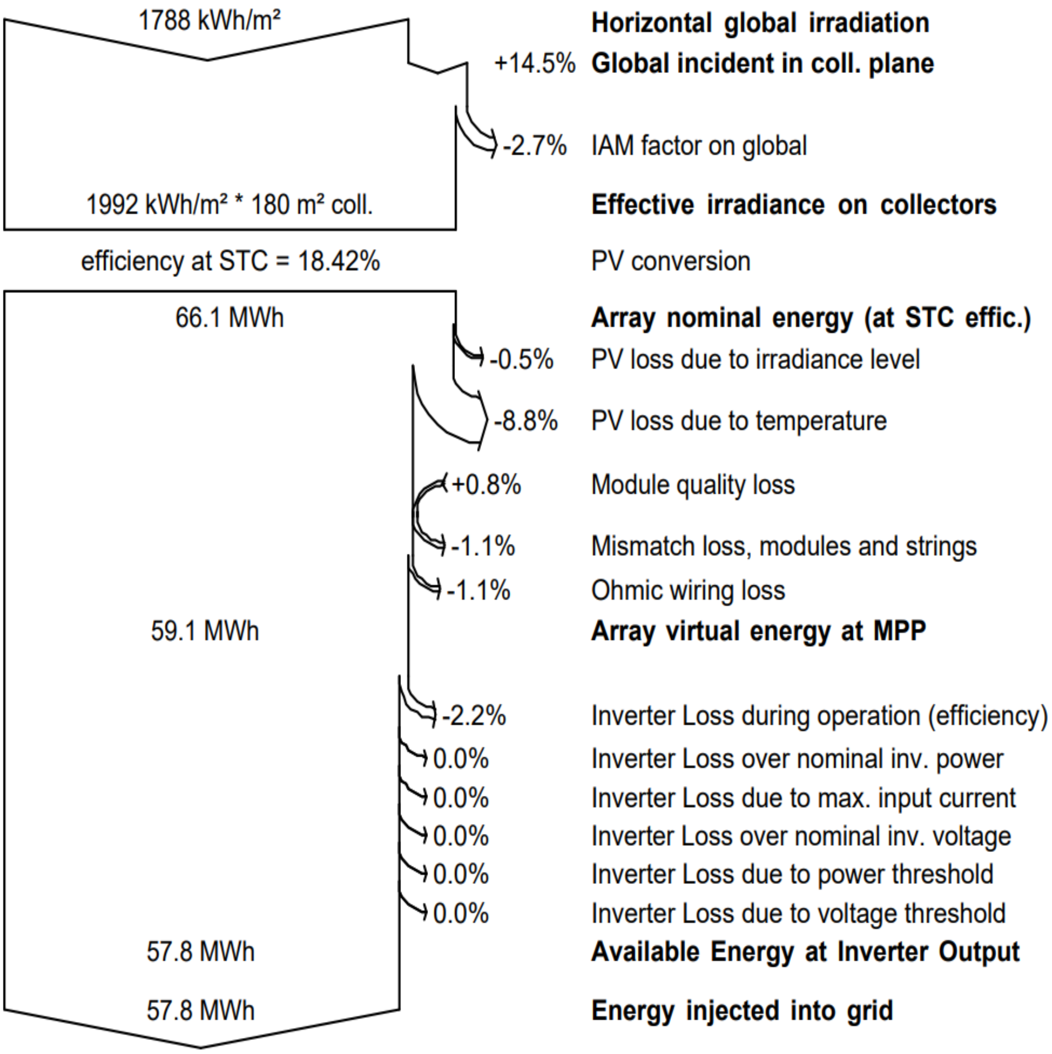

Figure 15. Loss Diagram of the System over the Year

Figure 16 illustrates the relationship between the energy injected into the grid and the global incident plot. The graph likely displays the amount of energy injected into the grid over a specific time period, such as a year, plotted against the global incident solar radiation received during the same period. This plot provides valuable insight into how the energy injected into the grid correlates with the amount of solar radiation incident on the photovoltaic system.

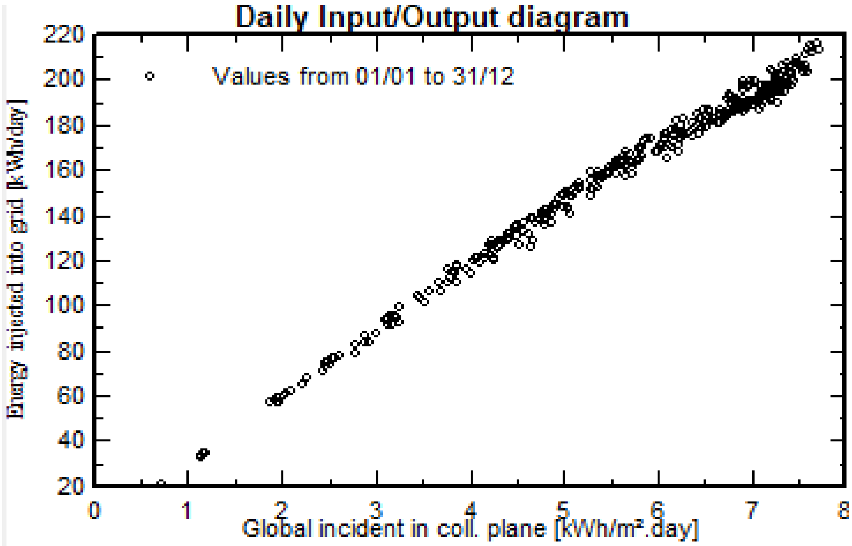

Figure 16. Energy Injected to the Grid

As shown in Figure 17, the Saved Carbon tool offers a thorough evaluation of the expected reductions in CO_2 emissions that will come from the installation of the PV system. This instrument is essential for assessing the solar system's environmental impact and comprehending how it helps reduce greenhouse gas emissions. It is based on Life Cycle Emissions (LCE), which include all CO_2 emissions related to a certain energy amount or component over the course of its whole life cycle, covering stages of production, operation, and maintenance [28].

In this particular instance, the result shows that over the following 30 years, 858.7 tons of CO_2 emissions are saved. This significant decrease in emissions highlights the long-term environmental advantages of funding renewable energy projects such as solar energy systems. Furthermore, this thorough analysis emphasizes how crucial it is to take into account energy system's whole life cycle in addition to its operational phase when evaluating its environmental sustainability.

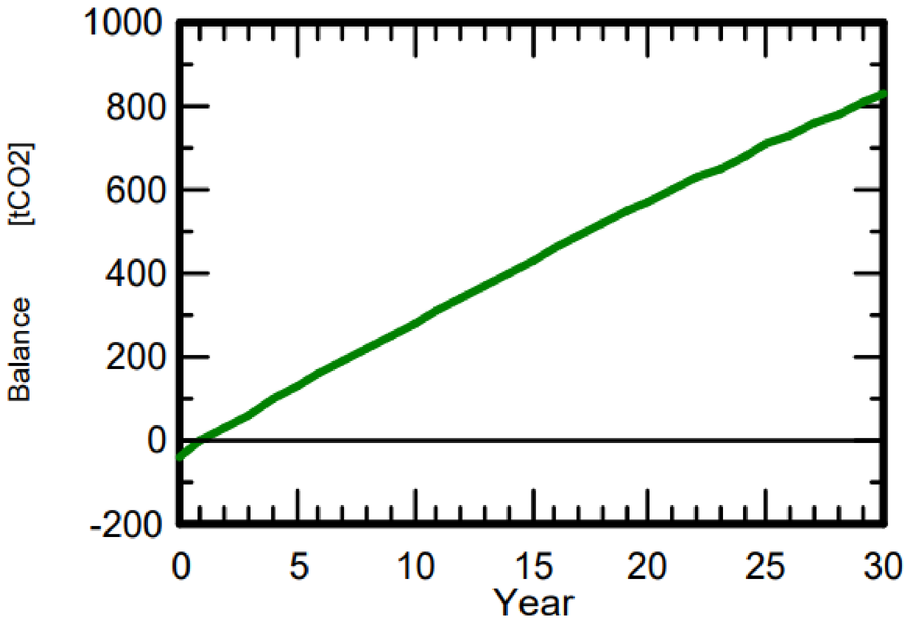

Figure 17. Saved CO2 Emission over the Years

Figure 18, provides a comprehensive analysis of the anticipated degradation of the photovoltaic module over a 30-year period. This figure consists of three distinct plots that offer essential insights into the performance and durability of the module:

1. **Basic Module Degradation**: This plot depicts the gradual degradation of the module's performance over time. It highlights the gradual decrease in the module's efficiency due to factors such as exposure to environmental elements and normal operating conditions.
2. **Degradation with Annual Increasing Mismatch**: This plot illustrates the module's degradation while considering the increasing discrepancies between actual and expected performances, year after year. It showcases how these discrepancies contribute to the degradation of the module's performance over time.
3. **Module Warranty**: This plot represents the performance specifications guaranteed by the manufacturer during the module's warranty period. It provides a reference point for evaluating the actual degradation compared to the initial expectations and serves as a critical indicator of the module's reliability over time.

By examining these plots, we can observe the evolution of the module's degradation over a 30-year period. Notably, according to the orange plot, degradation is expected to reach approximately 20% after 30 years of lifespan. This analysis offers valuable insights for assessing the long-term sustainability and reliability of the photovoltaic system, as well as for effectively planning maintenance and component replacements as needed.

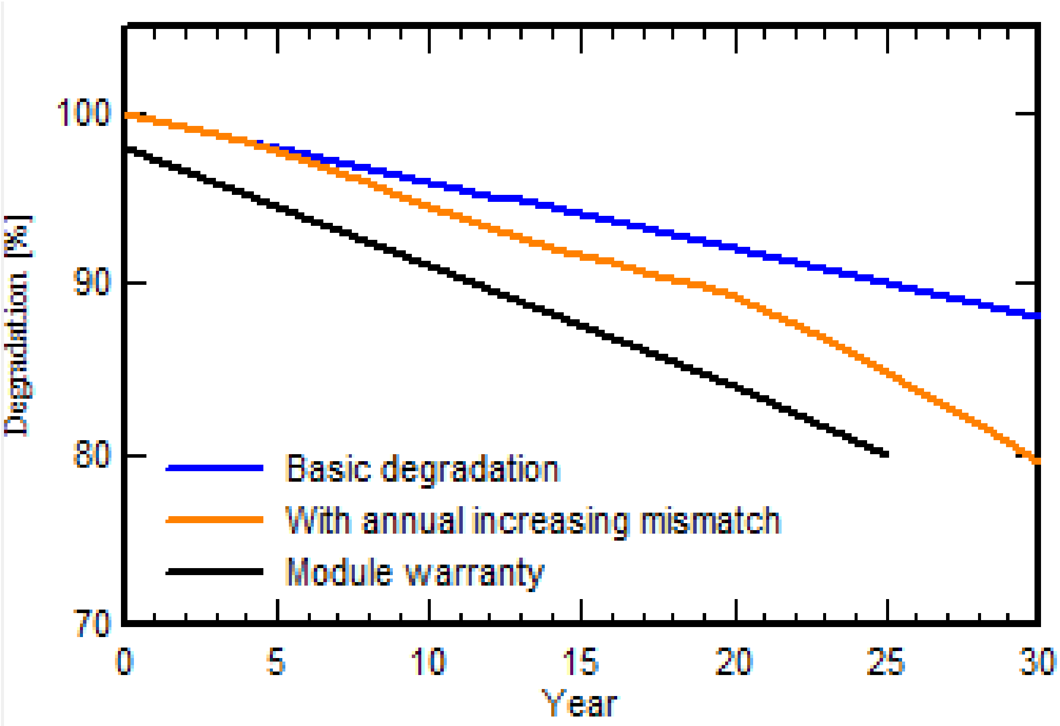

Figure 18. Degradation Diagram

5. Conclusion

This study aims to explore the complex dynamics of grid-connected solar photovoltaic systems, specifically as they relate to powering waste sorting centers in the context of a North African climate. The main goal is to perform a thorough analysis of various performance metrics to assess the effectiveness of such installations. The suggested system configuration consists of 110 300Wp solar panels, each of which is supplemented by 30KW inverters. A thorough combination of simulation and experimentation has led to the conclusion that the ideal tilt angle for optimizing solar energy capture is 33°.
Based on quantitative evaluations, the system can produce 56.3 MWh of energy annually, which is an excellent performance ratio of 85%, and degradation is expected to reach approximately 20% after 30 years of lifespan. These results emphasize how much potential there is to use solar energy resources in North Africa, a region known for its favorable climate and ideal geographic location.
Moreover, there is a real chance to significantly reduce dependency on energy sources produced from fossil fuels by adopting such renewable energy alternatives. During the installation's operating lifespan, this move might possibly reduce up to 858.7 tons of CO2 gas emissions, one of the most significant environmental impacts.
In the future, one possible line of investigation would be to compare the performance of this particular plant with similar installations that operate in different climates. These kinds of projects have the potential to provide important new information about the complex interactions between environmental factors and photovoltaic system efficiency, which will help guide future decisions about the construction of sustainable energy infrastructure.

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