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Techno-Economic Analysis of Grid-Connected PV Power Plants in Different Zones of Egypt

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ABSTRACT

The industrial sector plays a crucial role in driving the economic progress of nations. However, Egypt's ongoing energy crisis stands as a formidable barrier hindering its path to economic growth and development. The utilization of diesel generators as a dependable backup power source in numerous industrial and commercial settings during periods of load shedding significantly escalates the cost per kilowatt-hour (kWh) of energy and contributes to environmental emissions. Grid-connected photovoltaic (PV) plants contribute to elevating the proportion of solar energy within the power grid, thereby mitigating environmental emissions. This study conducts a comprehensive analysis of a 1.4-kW grid-connected PV system installed in Dokii, Cairo, Egypt. Through meticulous examination of metrics such as energy injection into the grid, payback period, and reduction in greenhouse gas (GHG) emissions, the study provides a holistic evaluation from technical, economic, and environmental standpoints. Findings reveal an annual average daily electrical energy production of 6.87 kWh/day, culminating in an approximate annual total of 2507.69 kWh/year. Financial analysis underscores the system's substantial long-term benefits, with a calculated payback period of approximately 6.4 years. Moreover, validation of simulation results through the utilization of PVsyst software, compared against data from an operational 1.4-kW PV solar system in Dokii, demonstrates a notable concurrence between actual and simulated performance. To attract government and investor interest in PV solar projects, we conducted a comprehensive study involving technical, economic, and environmental analyses for a large-scale 1-megawatt grid-connected PV plant in Ras El Hekma and Sohag using simulation software.

Keywords: *Photovoltaic (PV) technology, Grid-connected PV systems, Financial analysis, PVsyst, Payback period*

1. Introduction

The limitations and effects of non-renewable energy resources force people everywhere to focus on renewable energy sources [1]. Developing nations must think of innovative solutions due to increased electrical demand, global warming, greenhouse gas emissions, and shifting oil cost [2]. Common renewable energy sources like solar PV technology have the potential to produce cheaper, more reliable, greener, and more extensible electricity for many years to come [3, 4].

Over the past few decades ,the amount of electricity generated by PV systems has increased [5]. In 2004, the global photovoltaic industry supplied approximately 1,200 MWp of photovoltaic generators worldwide [6]. According to a report on solar photovoltaic electricity enabling the world, PV generated around 345 GW in 2020 and is expected to generate 1081 GW by 2030 [7].

The capacity to generate power is unstable because to factors such as sunset, severe weather, and other natural restrictions. There are two ways that solar photovoltaic systems can be used: standalone and grid-connected [8, 9]. A grid-connected system of photovoltaic conversion can have the following essential components: utility grid, inverters, solar modules, and loads (DC and AC) [10]. It is known as a grid-connected system without a battery backup and is utilized in PV standby power supply units. Battery backup solutions face the challenge of grid supply reliability, although they come at a higher cost and complexity [11].

Egypt is endowed with an abundant solar radiation resource, receiving an average of 3,050 hours of sunlight per year, with direct normal irradiations ranging from 1970 to 3200 kWh/m^2 annually and an annualized total solar irradiance from 2000 to 3200 kWh/m^2[12]. This extraordinary solar potential positions Egypt as a suitable location for various solar energy systems, including photovoltaic and concentrated solar power (CSP) plants .According to the Global Solar Atlas, Egypt's solar energy potential is estimated at 74 billion MWh per year, significantly surpassing the country's current electricity production [13]. In response to this solar abundance, Egypt has initiated numerous economically viable solar energy projects [14]. These endeavors aim to harness solar energy through various technologies depicting solar power projects in Egypt. One noteworthy program facilitating this transition is net metering, empowering property owners to install photovoltaic solar panels and contribute excess energy back to the governmental electricity grid. This program is vital, requiring a connection to the grid and a bi-directional electric meter to measure energy production.

Grid-connected PV systems exhibit a diverse range of applications based on their installed power capacity [15]. The first category encompasses residential systems or small PV plants, tailored for private and domestic use, featuring a power range of up to 5 kW. Moving up the scale, commercial systems or medium PV plants find their place in office buildings and industrial facilities, offering a more substantial power capacity of up to 250 kW. The third category represents PV power plants dedicated to centralized power generation, serving larger-scale energy needs with capacities that can extend to 50 MW or beyond. Various research studies have delved into the performance analysis of these grid-connected PV systems, shedding light on their efficiency across different power scales. In [16], at the State University in Ceará, Brazil, a 2.2 kWp photovoltaic system was installed for performance analysis. Monitored from June 2013 to May 2014, the system exhibited an annual energy yield of 1685.5 kWh/kWp. Daily averages included 5.6 kWh/kWp for reference, 4.9 kWh/kWp for the array, and 4.6 kWh/kWp for the final yield. Annual losses averaged 1.05 kWh/kWp, while efficiencies stood at 13.3% (array), 12.6% (system), and 94.6% (inverter). The performance ratio and capacity factor were 82.9% and 19.2%, respectively, showcasing the system's commendable performance in Brazil's northeast region. In [17], in Tangier, Morocco, a grid-connected photovoltaic (PV) system was installed on a government building's roof. The system, comprising 20 modules of 250 Wp and a 5 kW inverter, aimed to promote solar PV usage in government, commercial, and residential buildings in Morocco. Recorded from January 1, 2015, to December 2015, the PV installation demonstrated an energy output of 6411.3 kWh, with a final yield (Y_f) ranging from 1.96 to 6.42 kWh/kWp. The performance ratio (PR) varied between 58% and 98%, and the annual capacity factor was 14.84%.

This study initially conducts technical, environmental, and financial analyses of a 1.4 kW small grid-connected PV power system established at the Solar Energy Department of the National Research Center (NRC) in Dokii, Cairo, Egypt. The orientation and installation of the plants are meticulously documented, accounting for their specific geographic locations. Performance evaluation relies on measured data collected over approximately one year to assess the plant's production. The financial analysis incorporates the actual costs of the plant's components, as well as expenses for installation, maintenance, and operation, to determine the payback period. Additionally, the analysis considers Egypt's predicted economic growth and the prevailing cost of power. In order to validate the PVsyst software program and leverage this simulation for studying large-scale systems, an examination of 1.4 kW PV system will be undertaken. This examination involves conducting a simulation to compare the actual results of the 1.4 kW PV system with those acquired from the simulation. Subsequently, a comprehensive study involving technical, economic, and environmental analyses for a large-scale 1-megawatt grid-connected PV plant in Ras El Hekma and Sohag using simulation software is conducted. The overarching objective of this research is to explore the efficiency and economic feasibility of transitioning to a 1 MW grid-connected PV system across different climate zones in Egypt.

2. Methodology

A 1.4-kW grid-connected PV system (Small-scale system) established at the national research center in Dokii, Cairo, Egypt for the purpose of economic, environmental, and technical analyses. The national research center is situated at a latitude of 30.08° N and a longitude of 31.25° E, with an elevation of approximately 34 meters above sea level. Furthermore, to attract investors and governmental support for such projects, a study was conducted on a larger scale system. Two distinguished regions within Egypt, Ras El Hekma and Sohag, were selected for their varying climatic conditions and different locations across Egypt as shown in Figure 1. An economic, environmental, and technical analysis conducted on 1-MW solar power plants (large-scale systems) located in Ras El Hekma and Sohag to elucidate the impact of climatic variations on solar energy production. Table 1 presents the coordinate details of several chosen cities. To compare the experimental results, the PVsyst software program used to simulate both small-scale and large-scale studied systems.

Figure 1- Map of Egypt showing selected PV solar system sites

Table 1- The coordinates of the selected cities' locations

S. N.	City	Lat.	Long.	Altitude
1	Ras El Hekma	31.12° N	27.78° E	121 m
2	Sohag	26.45°	31.68° E	68 m

٢.1 Simulation tool

PVsyst enables efficient and precise study and analysis of solar energy systems, making it an indispensable tool for professionals in engineering, research, and education [18]. The software relies on a comprehensive database of meteorological data and PV system components, providing accurate results for performance analysis and economic evaluations, thus contributing to the advancement of solar energy technologies.

٢.2 Technical analysis

The International Electrotechnical Commission (IEC) has formulated the IEC 61724 standards, which have been adopted by numerous countries globally [19]. The standard IEC 61724 encompasses a comprehensive procedure for assessing the performance of various PV technologies, including off-grid systems, grid-connected systems, and hybrid systems. IEC 61724 establishes a universal standard for comparing the performance of PV plants across various locations. An overview of performance parameters outlined in IEC 61724 is presented in Table 2.

Table 2- Performance Parameters Outlined in IEC 61724

Parameter	Equation	Ref.
Reference yield(Y_r) (kWh/ kW/day)	$Y_r = H_t / G_o$	[20]
Array yield(Y_a) (kWh/ kW/day)	$Y_a = E_{dc} / P_o$	[21]
Final yield (Y_f) (kWh/ kW/day)	$Y_f = E_{ac} / P_o$	[20]
Performance ratio (PR) (%)	$PR = Y_f / Y_r$	[20]
System efficiency (η_{sys})(%)	$\eta_{sys} = \eta_{pv} * \eta_{Inv}$	[22]
Inverter efficiency (η_{Inv})(%)	$\eta_{Inv} = P_{ac} / P_{dc}$	[22]
PV module efficiency (η_{PV}) (%)	$\eta_{PV} = E_{dc} / H_t * A_m$	[23]
Specific production (kWh / KWp)	Specific production = annual produced energy / P_O	[24]
System losses (Ls)	$L_s = Y_a - Y_f$	[21]

Using these performance indices, the comprehensive technical performance of the grid-tied PV system can be assessed. Additionally, they can serve as valuable metrics for comparing the performance of any system with similar installations, regardless of their location and installed capacity.

In addition to the monthly and annual performance indices, the performance indices are also estimated on a seasonal basis. These seasonal values represent the average and total values of the performance indices for the respective months within a specific weather season. Cairo, situated in a temperate region, experiences four distinct seasons: spring (March to May), summer (June to August), autumn (September to November), and winter (December to February). As a result of these seasonal variations and the country's geographical extent, there are fluctuations in solar energy received throughout the year across the country. Mathematically, the seasonal total ($\mathbf{T_S}$)and average ($\boldsymbol{A_S}$) of a given performance index are calculated as follows [21]:

$$\boldsymbol{T_S = \sum_{K=1}^{K} M_k} \qquad (1)$$

$$A_S = \frac{1}{k}\left(\sum_{K=1}^{K} M_k\right) \qquad (2)$$

Here, the subscript k represents the number of months in a season (in Cairo, k = 3), while M denotes the performance index under consideration.

2.3 Climatic Data for Cities under Study

The climate data utilized in this study is obtained from Meteonorm 8.1. Figure 2 illustrates the annual solar radiation, while Figure 3 displays the average atmospheric ambient temperature for the selected cities. The range of solar radiation levels varies from 2.71 kWh/m^2/day in December to 7.72 kWh/m^2/day in June for Ras El Hekma, from 2.76 kWh/m^2/day in December to 7.26 kWh/m^2/day in June for Sohag, and from 2.76 kWh/m^2/day in December to 7.26 kWh/m^2/day in June for Dokii .

For assessing the efficiency and output power of PV panels, ambient temperature data are crucial. The lowest ambient temperatures are 13.11°C, 13.06°C, and 14.05°C in January for Ras El Hakma, Sohag, and Dokii, respectively. The highest ambient temperature values recorded are 27.54°C (August) for Ras El Hakma, 32.53°C (July) for Sohag, and 29.96°C (August) for Dokii. The average wind speed data, depicted in Figure 4, reveals that Ras El Hekma experiences the highest average wind speed due to its coastal location. Specifically, the average wind speeds for Ras El Hekma, Sohag, and Dokii are 4.1 m/s, 3.5 m/s, and 3.7 m/s, respectively.

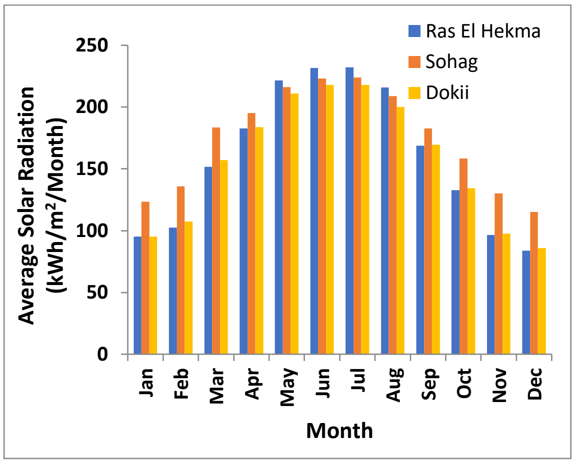


Figure 2- Average monthly solar radiation

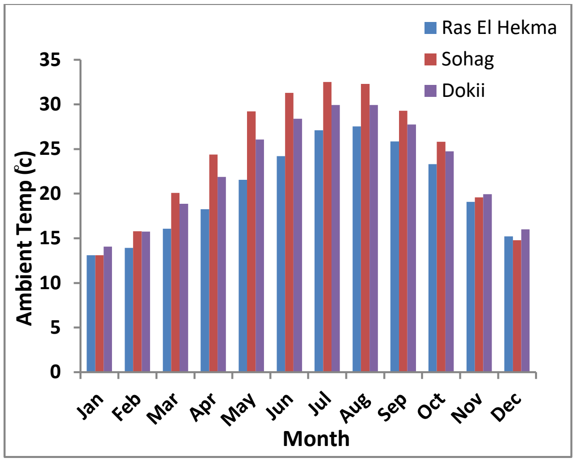


Figure 3- Average monthly ambient temperature

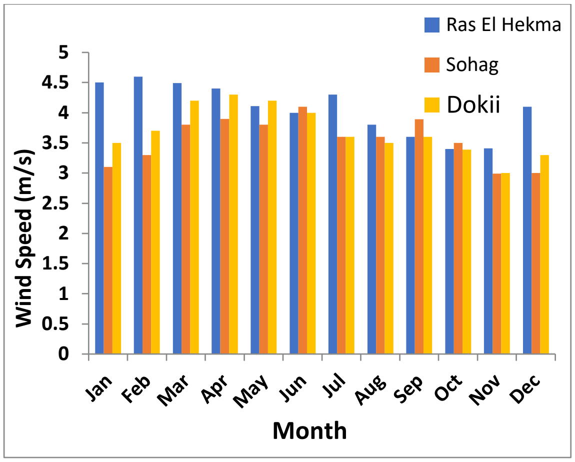


Figure 4- Average monthly wind speed

2.4 Actual Grid-connected System Details

The installation of these plants is uncomplicated, requiring minimal activity and maintenance, and there are no interruptions during the process. These installations are environmentally friendly and emit no CO_2 emissions during operation. The primary components of the grid-connected plant include solar panels, inverters, mounting structures, grid connection equipment, and cables.

2.4.1 System layout

A 1.4-kW grid-connected PV system typically requires approximately 0.007 acres of land, whether installed on the ground or on rooftops, which contrasts with the global standard of 1 MWp per 5 acres[25]. The proposed configuration for this plant includes six PV modules, each with a capacity of 250 W, coupled with a central inverter boasting a capacity of 2 kW, which directly connects to the grid. The recommended tilt angle for the PV panels closely aligns with the latitude of the site, optimizing solar radiation absorption. The unshaded modules were positioned at a fixed angle of 30 degrees facing southward. Furthermore, the modules are installed with an open back, facilitating air circulation behind them. The actual PV system setup is depicted in Figure 5.

Figure 5- The installation of the1.4 kW PV system

2.4.2 Solar panels

The proposed solar panels for the 1.4-kW grid-connected PV system are Sunset brand panels with a rating of 250W. Specifically, 6 modules of 250W each are connected in series to form a string to achieve the desired current and voltage levels required by the inverter, ensuring voltage and current matching at the inverter input. Thus, a total of 6 panels are necessary for this plant, and technical specifications are provided in Table 3.

Table 3- Technical and mechanical Specifications of the PV panels under standard test conditions (STC)*

Item	Specifications for 250 W PV panel
Power rating (W)	250
Rated voltage(V)	29.9
Rated current(A)	7.70
Open-circuit voltage(V)	36.9
Short-circuit current (A)	8.20
Temperature coefficient $V_{OC}(\%/°K)$	-0.320
Temperature coefficient $I_{SC}(\%/°K)$	+0.053
System voltage(V)	240
Dimension(mm)	1667×997×47
Weight (kg)	20.1

* STC are (1000 W/m^(2),25℃, and 1.5 AM)

2.4.3 Inverter

The single-phase on-grid inverter used for the 1.4-kW grid-connected PV system, as illustrated in Figure 6, sourced from the Steca brand, boasts a power rating of 2000 W. This inverter efficiently converts DC electrical signals from the photovoltaic modules to AC for synchronization with the grid. It incorporates galvanic isolation to effectively separate the PV modules from utility power. Additionally, the inverter features a microcontroller-based maximum power point tracker, ensuring consistent maximum power delivery to the grid by continuously adjusting the module voltage. Moreover, it minimizes energy consumption during nighttime by keeping components dormant. The inverter also provides comprehensive protection against overloads, excess temperatures, reverse input polarity, and module disconnection, ensuring optimal performance and safety. The technical specifications of the Steca inverter are detailed in Table 4.

Figure 6- Central inverter for 1.4 kW PV system

Table 4- Inverter specifications

Item	Specifications for 2 kW inverter
DC input voltage (V)	80-400
Rated DC input voltage (V)	300
Rated input current (A)	7
Maximum input power (kW)	2.4
Rated AC output power (kW)	2
Grid frequency (Hz)	47.5-52
Power factor (%)	95>
Inverter efficiency (%)	95
Ambient tem. (℃)	-25 to 60
Dimension (mm)	351× 542× 140
Display	Display, LED

3. Grid-connected System Details for Large-Scale System

Scaling up 1.4-kW grid-connected PV system to 1

MW, a typical 1 MW solar PV plant would necessitate about 5 acres of land. In this proposed configuration, the plant comprises 1725 PV panels manufactured by Jinko Solar, each with a capacity of 580 W, in addition to a central inverter with a capacity of 1000 kW and a power transformer. The PV panels are designed to last around 25 years according to the specifications provided in the data sheet of the PV modules. As for the inverter, its expected lifespan falls within the range of 13 to 15 years. Consequently, it will need to be replaced once over the system's lifetime. Similar to the 1.4 kW project, these panels are arranged in strings to meet the required current and voltage specifications of the inverter. Specifically, 15 modules rated at 580 W each are connected in series to form a string, and a total of 115 such strings are connected in parallel to the inverter input stage to ensure voltage and current matching. Consequently, a total of 1725 panels are required for this plant. The modules were set at the angles specified in Table 5 and positioned facing southward.

Table 5- Orientation of solar panels

City	Ras El Hekma	Sohag
Tilt angle	29°	26°

4. Results and discussion

In this section, technical analysis, economic analysis of a 1.4-kW grid-connected PV system in Dokii are presented. Furthermore, a detailed environmental analysis of this location is provided. To validate the proposed study, a comparison between simulation results and experimental results for the 1.4 kW PV solar system is included. Furthermore, the comparative technical, economical, and environmental analyses of a grid-connected PV solar power plant with a capacity of 1 MW in Ras El Hekma and Sohag using PVsyst simulation are presented.

٤,١ Results for the 1.4-kW Solar PV System

٤,١,١ Technical Analysis

The results for the PV grid-connected system in Dokii indicated that the peak solar radiation was recorded in June, reaching an average of 7.26 kWh/m^2/day. Conversely, the lowest solar radiation intensity was observed in December, averaging 2.76 kW/m^2/day.

Figure 7 shows the total monthly energy output of the PV system, indicating fluctuations from 160.14 kWh in January to 242.15 kWh in August throughout the monitoring duration. The grid received a total annual energy output of 2507.69 kWh (2.5 MWh) from the installed system, averaging 208.97 kWh per month. The yearly specific energy output is calculated as 1817.17 kWh/kWp, providing a valuable metric for comparing the performance of PV systems under similar climatic conditions. Throughout the winter period, spanning from November to February, energy outputs typically decrease owing to factors such as diminished sunlight hours and decreased solar irradiation.

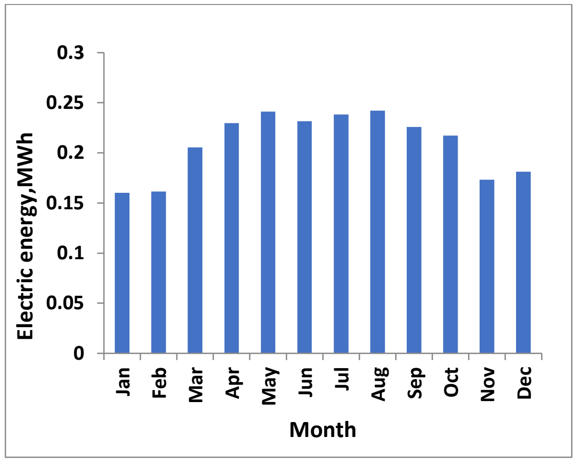


Figure 7- Total monthly energy produced by the 1.4-kW solar PV system

Figure 8 illustrates the seasonal generation of energy by the PV system. The total energy produced varies from 52.89 kWh in winter to 789.40 kWh in summer. As mentioned before, reduced sun hours contribute to lower output during winter. Additionally, it is noticeable that the system's energy output is only around 11.98 kWh higher in summer compared to spring, possibly influenced by relatively lower ambient temperature favoring better performance during spring than the comparatively higher temperatures in summer season. The average energy outputs for each season are approximately 225.429 kWh in spring, 237.41 kWh in summer, 205.44 kWh in autumn, and 167.62 kWh in winter. Meanwhile, the specific energy outputs per season are around 490.06 kWh/kWp for spring, 516.1 kWh/kWp for summer, 446.61 kWh/kWp for autumn and 364.38 kWh /kWp for winter seasons.

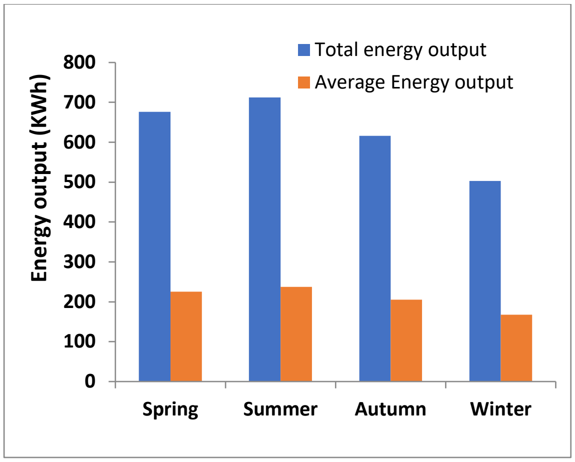


Figure 8- Seasonal variation in energy output of 1.4-kW grid-connected PV system

4.1.2 Economic Analysis

Economic considerations are crucial for evaluating the benefits of investing in PV power systems. Conducting proper economic analyses, such as assessing life-cycle costs (LCC), the cost of energy (COE), and determining the payback period, ensures the profitability of investments in PV systems.

Table 6 provides detailed information on the prices of system components (such as inverters, solar panels, cables, etc.), as well as installation and commissioning costs. The system cost is assumed to be consistent for all proposed plants in selected regions.

Table 6- Details of the system's cost

Item	Unit cost
Cost of PV modules	0.3125 $/watt
Cost of inverters	0.146 $/watt
Cost of installation	8.5% of PV module cost
Cost of operation and maintenance	2% of PV module cost

Annual savings = Annul energy injected into grid × FiT (3)

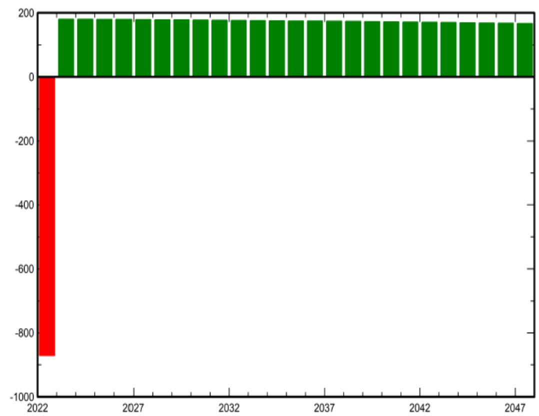
The feed-in tariff (FiT) of 0.0788 USD per kWh has been chosen to calculate the annual savings from the solar system. The PV panels are designed to last around 25 years according to the specifications provided in the data sheet of the PV modules. As for the inverter, its expected lifespan falls within the range of 13 to 15 years. Consequently, it will need to be replaced once over the system's lifetime. In our calculations, the inflation and discount rates have been assumed of 4% and 8%, respectively [26]. The cash flow of the proposed project in the selected location is illustrated in Figure 9. The Levelized Cost of Energy (LCOE), which represents the cost per unit (kWh) of energy produced from the solar plant over a specified time, can be calculated using the following equation [27].

COE = Life cycle cost/Life cycle energy produced (4)

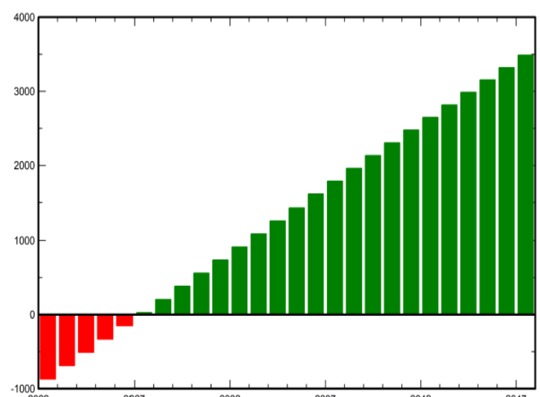
The payback period refers to the duration required for a project to recover its initial investments through the revenue it generates. The primary concept behind the payback method is to assess the feasibility of an investment. The calculation can be derived from the following equation [28].

Payback Period = Initial investments/Annual savings (5)

Eqs. (4) and (5) are used to calculate the COE and payback period, with the COE set at 0.04 USD/kWh and a payback period of 6.4 years.



(a).Yearly net profit(USD)



(b). Cumulative Cash Flow (USD)

Figure 9- The simulation results for Dokii

4.1.3 Environmental analysis

Greenhouse gas (GHG) emissions result from atmospheric gases that absorb infrared radiation. Efficiently removing GHG emissions from the air is crucial for maintaining a clean and healthy environment . These emissions are the primary cause of global warming, which adversely affects millions of people worldwide. While solar PV plants are often considered as zero-emission energy systems, it's important to note that they do have associated emissions. Table 7 provides details of the life cycle emissions of major components of the system for estimating CO_2 emissions from the solar system.

The Equation (6) is utilized to calculate the emissions produced by the solar system[29].

Produced emission = Annual generation× CO_2/kWh (6)

Replaced emission = Annual generation×Emissions Factor (7)

Emission Balance = Replaced emission −Produced emission (8)

Eqs. (7) and (8) are employed to compute replaced emissions and emission balance, respectively.

Table 7- System components life cycle emissions details for 1.4 kW system

Item	Modules	Supports	Inverters
LCE	1713Kg CO_2/KWp	3.05Kg CO_2/Kg	303Kg CO_2/ units
Quantity	1.5 kWp	60 Kg	1 units
Subtotal [Kg]	2569	183	303

Table 8- Emission balance for Dokii

City	Produced Emissions tCO_2	Replaced Emissions tCO_2	Emission Balance tCO_2
Dokii	3.06	32.8	25.4

4.1.4 Validation of simulation results

The simulation results of a 1.4-kW solar system are compared with the experimental performance results of a 1.4 kW solar system installed in Dokii.

4.1.4.1 Actual data monitoring

Solar radiation at the PV module surface is measured using a Kipp-Zonen pyranometer, which converts it into an electrical signal for amplification and estimation. Furthermore, the surface temperature of the modules is monitored using a K-type thermocouple and associated circuitry for amplification. The inverter software records daily electricity generation as well as cumulative production, and it also identifies faults in case of malfunctions.

4.1.4.2 Performance comparison

From Tables 9 and figure 10, it is noted that actual plant performance is closely matched with the simulation results. The comparison of actual energy production and predicted energy production throughout the year is shown in Figure 10.

Table 9- System performance parameters

Performance parameters	Simulation Results	Actual Results
Final Yield	4.66 kWh/kW/da	4.96 kWh/kW/day
Annual performance Ratio(PR)	77.8%	76%

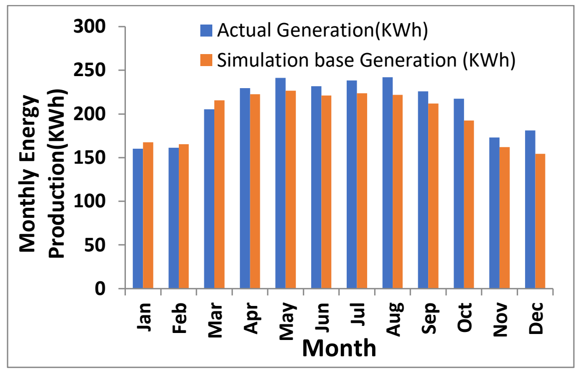


Figure 10- Comparison between simulated and actual energy generation

4.2.Results for the 1-megawatt (MW) Solar PV System

4.2.1 Technical Analysis

The results of simulating the grid-connected system within the studied zones revealed that Sohag experienced the highest solar radiation levels, averaging 7.2 kWh/m^2/day in July. Conversely, Ras El Hekma had the lowest solar radiation intensity, averaging 2.68 kWh/m^2/day in December. Based on the solar insulation data for selected zones, it is evident that Sohag exhibits relatively high solar energy output compared to other areas.

Figure 11 illustrates the monthly average energy output from a 1 MW PV plant in the examined regions. Ras El Hekma had the lowest energy production of 111.8 MWh in November and the highest of 180.15 MWh in May. In Sohag, the lowest energy production was 147.1 MWh in December, while the highest was 181.4 MWh in March.

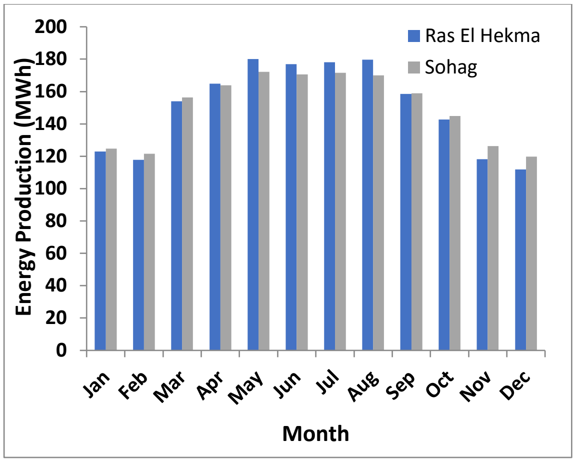


Figure 11- Monthly average energy production from 1 MW PV systems

Figure 12 shows annual energy production in selected zones for 1 MWh solar plant, the lowest energy production is in Ras El Hekma (1982.9 MWh) and highest in Sohag (1805.8 MWh). The solar plant achieves optimal performance in Sohag due to its location in the region with the highest solar resource, resulting in a normalized production of 5.43 kWh/kWp/day. The weather conditions of Sohag with average ambient temperature 24.04 ◦C, average wind speed 3.5 m/s and the average solar radiation 5.74 kWh/m^2/day are best suitable for PV plant generation. The lowest energy production of the plant occurs in Ras El Hekma, primarily attributed to its normalized production of 4.93 kWh/kWp/day and less favorable weather conditions. The main simulation results are compared for all locations in Table 10. Comparing the performance of various systems primarily relies on two crucial parameters: normalized production and performance ratio. Simulation results for two selected locations in Figure 13 have shown the highest normalized production in Sohag city with 86.2% performance ratio.

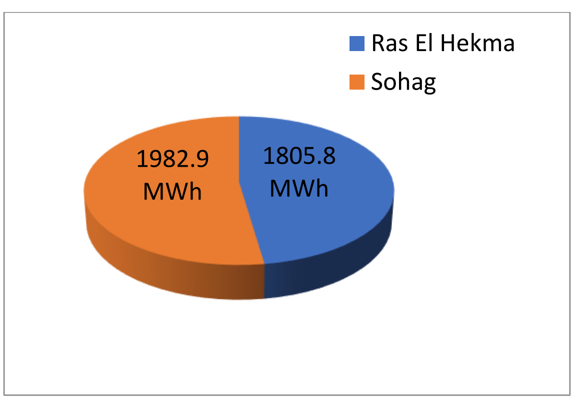


Figure 12- Annual energy generation

4.2.2 Economic Analysis

Based on the component cost data provided in Table 6 and the feed-in tariff, inflation, and discount rates discussed in section 4.1.2, the cash flow of the proposed project in selected locations is illustrated in Figure 14. The analysis reveals that the highest return on investment is achieved in the Sohag location, attributed to its highest annual energy production. Conversely, the Ras El Hekma site exhibits the lowest return on investment due to its lowest annual energy production.

Equations (4) and (5) are then employed to calculate COE and payback period. Table 11 further illustrates the lowest COE and payback period in Sohag, reflecting its highest annual energy generation, while the highest COE and payback period are observed in Ras El Hekma, indicative of its lowest annual energy generation.

Table 10- Main performance results in two climate zones

Performance Parameters	Ras El Hekma	Sohag
System production (MWh/year)	1805	1982
Specific production (kWh/kWp/year)	1805	1982
Average PR (%)	86.10	86.2
Normalized Production (kWh/kWp/day)	4.93	5.43
Array Losses (kWh/kWp/day)	0.74	0.88
System Losses (kWh/kWp/day)	0.06	0.07

Table 11- Cost of Energy and Payback Period

S. N.	Annual Generation (MWh)	COE (USD/kWh)	Payback period (Years)
1	Ras El Hekma	0.04	6.1
2	Sohag	0.03	5.4

4.2.3 Environmental analysis

Table 12 provides an estimation of CO_2 emissions from the solar plant, detailing the life cycle emissions of the major components of the system. Eq. (6) is used to calculate the emissions generated by the solar plant, which are presumed to be consistent across all selected locations.

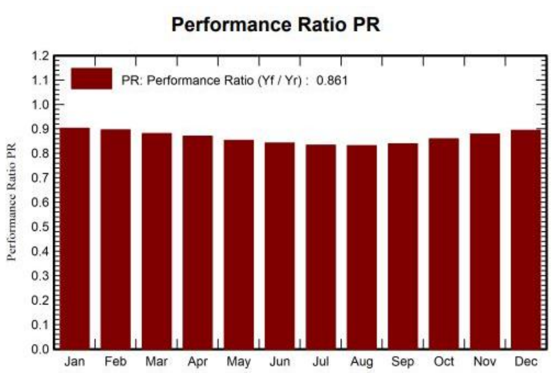
Equations (7) and (8) are employed to determine replaced emissions and emission balance. Table 13 indicates that the maximum reduction in emissions is observed for the Sohag location, while the minimum reduction is observed for Ras El Hekma.

Table 12- Life cycle emission details of system components for 1 MW plants

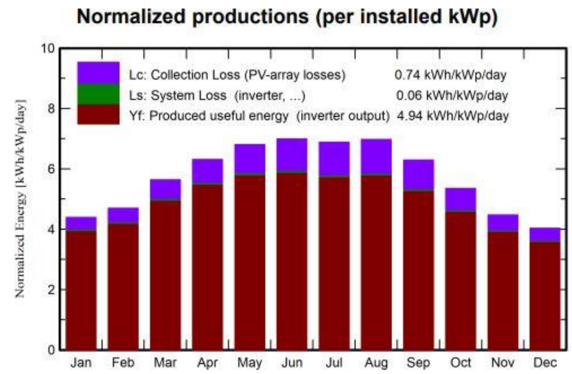
Item	Modules	Supports	Inverters
LCE	1713 Kg CO_2/ kWp	3.05 Kg CO_2/ Kg	303 Kg CO_2/units
Quantity	1000 kWp	17250 Kg	1 units
Subtotal [Kg CO_2]	1713576	52696	303

Table 13- Emission balance across selected cities

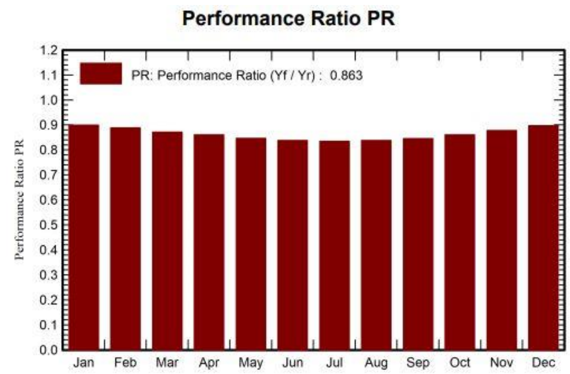
S. N.	city	Produced Emission t CO_2	Replaced Emission t CO_2	Emission Balance t CO_2
1	Ras El Hekma	1766.58	24812	19762
2	Sohag	1766.58	26985.7	21648



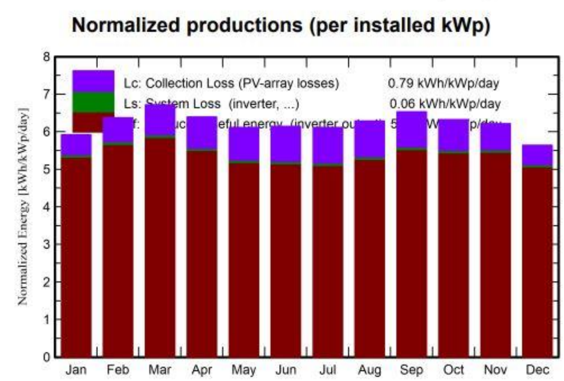
(a). PR for Ras El Hekma



(b). NP for Ras El Hekma

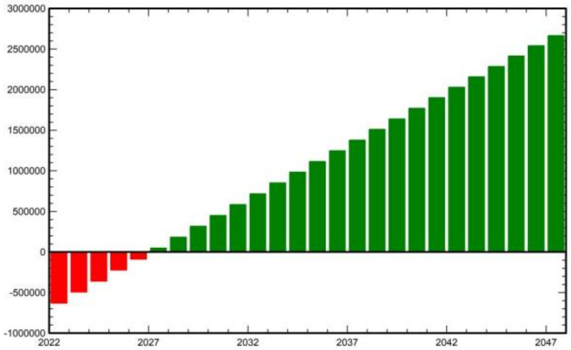


(c). PR for Sohag

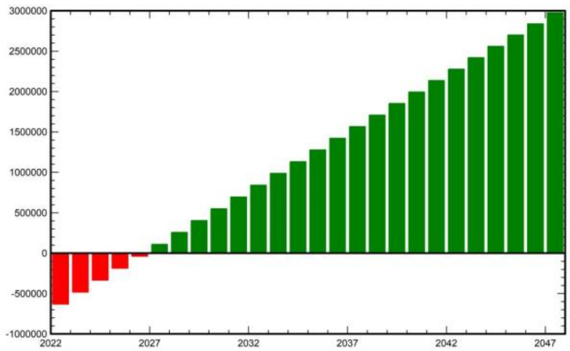


(d). NP for Sohag

Figure 13- Comparison of PR and NP for Solar Projects in Ras El Hekma and Sohag



(a). Ras El Hakma



(b). Sohag

Figure 14- Cumulative Cash Flow Simulation Results (USD)

5. Conclusions

The study provides a comprehensive analysis of a 1.4 kW grid-connected PV system in Dokii, encompassing technical, environmental, and financial aspects. It details site parameters, including ambient temperatures, sunshine hours, wind speed, levels of solar irradiation, and optimal tilt angle. The system comprises 6 PV modules rated at 250 W each, a 2000 W grid-connected inverter, and associated installation components like wiring and switches. The PV modules are mounted on a structure tilted 30 degrees from the horizontal surface. The system generates an average daily electricity of 6.87 kWh/day and an annual output of 2507.09 kWh/year. Financial analysis, considering initial and operational costs and electricity prices, yields a payback period of 6.4 years over a 25-year lifespan. Validation of the system's performance through PVsyst software simulation, aligned with data from a 1.4 kW solar system in Dokii, indicates close agreement between simulated and observed outcomes. Given that PVsyst software results closely match actual mathematical calculations, its use is proposed for preliminary project assessments when physical equipment, such as measurement devices, is unavailable. Additionally, for conducting feasibility studies before project implementation, PVsyst can provide detailed technical and economic analyses. This makes it a valuable tool for planning and evaluating solar energy projects effectively, ensuring reliable insights even in the absence of on-site equipment. A comparative evaluation of grid-connected PV systems in Ras El Hekma and Sohag were conducted, analyzing technical, economic, and environmental aspects through the utilization of PVsyst software. Sohag emerges as the most economically feasible location, characterized by high annual generation, low energy costs, and a short payback period, followed by Ras El Hekma. The study suggests the viability of installing mega-scale grid-connected PV plants at selected locations, contributing to CO_2 emission reduction and environmental sustainability while potentially qualifying for carbon credits. This research aims to guide policymakers and investors in maximizing returns on investment in mega-scale PV projects in Egypt.

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