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Performance Evaluation, Economic Assessment and Environmental Impact of a 134.55 kWp Grid Connected Solar Photovoltaic (PV) Power Plant in Palestine

تقييم الأداء والتقييم الاقتصادي والأثر البيئي لمحطة توليد الطاقة الكهروضوئية المتصلة بالشبكة قدرتها القصوى 134.55 كيلوواط في فلسطين

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Abstract: This research investigates the techno-economic elements of a 143.55 kWp solar photovoltaic (PV) system erected on the main building's rooftop at Palestine Technical University-Kadoorie (PTUK) in Tulkarm, Palestine. The system includes 414 PV panels that were monitored throughout 2019. The PVsyst software was used to design solar PV systems and determine the expected monthly energy production, final yield, and performance ratio based on climate information data that was derived from Metronome 8.0. In addition, the system's performance, and the PV power generated and supplied into the grid were compared to simulation results. The project's outcomes included an exceptional yearly energy output of 206.6 MWh, a normalized final system yield of 4.03 kWh/kWp/day, a performance ratio (P_R) of 79.6% and a capacity factor (C_F) of 16.8%. The economic analysis results are quite positive, indicating a great possibility for the widespread use of PV systems in Palestine. The system's payback period was determined to be 3.4 years, and the estimated levelized cost of energy is USD 0.03/kWh. Furthermore, the project is expected to minimize carbon emissions by 141.71 tons per year. These data highlight the benefits of using university roofs for PV system installations in Palestine, emphasizing the need to adopt this renewable energy source more extensively.

Keywords: Solar Energy, photovoltaic, PVsyst, performance ratio, grid-connected PV system.

المستخلص: يبحث هذا البحث في العناصر التقنية الاقتصادية لنظام الطاقة الشمسية الكهروضوئية (PV) الذي تبلغ قدرته 143.55 كيلوواط، والذي أقيم على سطح المبنى الرئيسي في جامعة فلسطين التقنية - خضوري (PTUK) في طولكرم، فلسطين. يشتمل النظام على 414 لوحة كهروضوئية تم رصدها طوال عام 2019. تم استخدام برنامج PVsys لتصميم أنظمة الطاقة الشمسية الكهروضوئية وتحديد إنتاج الطاقة الشهري المتوقع، والعائد النهائي، ونسبة الأداء بناءً على بيانات المعلومات المناخية المستمدة من Metronome 8.0. بالإضافة إلى ذلك، تمت مقارنة أداء النظام والطاقة الكهروضوئية المولدة والمزودة بالشبكة بنتائج المحاكاة. تضمنت نتائج المشروع إنتاجًا سنويًا استثنائيًا للطاقة قدره 206.6 ميجاوات ساعة، وعائد نظام نهائي قياسي يبلغ 4.03 كيلو واط في الساعة / كيلوواط في اليوم، ونسبة أداء (PR) 79.6٪. نتائج التحليل الاقتصادي إيجابية للغاية، مما يشير إلى وجود احتمال كبير للاستخدام الواسع لأنظمة الطاقة الكهروضوئية مثل هذه. تم تحديد فترة استرداد النظام بـ 3.4 سنوات، وتبلغ التكلفة التقديرية المقدرة للطاقة 0.03

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دولار أمريكي / كيلوواط ساعة. علاوة على ذلك، من المتوقع أن يقلل المشروع من انبعاثات الكربون بمقدار 141.71 طنًا سنويًا. تسلط هذه البيانات الضوء على فوائد استخدام أسطح الجامعات لمنشآت أنظمة الطاقة الكهروضوئية في فلسطين، مما يؤكد الحاجة إلى اعتماد مصدر الطاقة المتجددة هذا على نطاق أوسع.

الكلمات المفتاحية: الطاقة الشمسية، الخلايا الكهروضوئية، برنامج ال PVsyst، نسبة الأداء، نظام الكهروضوئية المتصل بالشبكة.

INTRODUCTION:

The Palestinian energy sector's main problem is the lack of electrical energy provision. The Palestinian Authority currently relies heavily on imports, with 66.6% coming from Israel and 8.5% coming from Egypt, while the remaining 24.9% is generated by a local power plant. To reduce dependence on external sources, the Palestinian Energy and Natural Resources Authority are working to increase the use of renewable energy resources to generate power (Nassar & Alsadi, 2019).

The population of Palestinians is rapidly increasing, resulting in a corresponding increase in energy demand. To ensure energy security in the future, the use of suitable renewable energy resources in this region is considered vital. Palestine's geographic location has a high potential for solar energy, with an annual average of 5.4 kWh/m^2/day of solar radiation on a horizontal surface and 3000 sunshine hours per year. Investing in solar energy is a motivated solution to address the shortage of electricity supply, reduce dependency on external sources, and provide power to remote and isolated areas of Palestine where electricity is not available 24 hours a day. The Palestinian government, through the Palestinian Energy Authority, has implemented initiatives to promote and use green energy technologies to achieve 500 MW of electricity needed from renewable energy sources by 2030. As part of this strategy, 400 MW of electricity will be supplied by solar PV systems (Milhem, 2021).

A grid-connected PV system converts the sunlight into active power in order to inject them directly into the utility grid without using any storage systems such as batteries. Using rooftop buildings is considered a good choice to install solar PV systems because it does not need any extra space on the land and are installed faster than other types of renewable energy sources. In addition, renewable energy resource based on a solar system does not release carbon dioxide and other greenhouse gases into the atmosphere which causes global warming and climate change. Figure (1) displays a schematic of a grid-connected PV system.

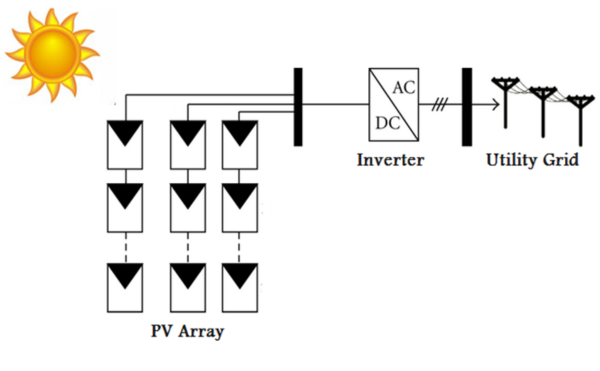


Figure (1). Schematic of a grid-connected PV system

The output of potential energy PV systems can be evaluated by utilizing a performance assessment study of PV systems in a certain area. To determine the performance of the PV system, it needs to analyze and monitor over 12 months various parameters such as performance ratio, array yield, system efficiency, capacity factor, system losses, final yield and reference yield. To achieve a comparison between the actual and the expected output energy of the PV system, there are many software tools based on an advanced computer which are used to predict the way of behaving PV systems under different factors such as geographic location, installation components, etc.

There are some papers reported analyzing the performance of photovoltaic modules established in various countries. (Omar & Mahmoud, 2018) analyzed the feasibility of a 5 kW photovoltaic system over a two-year period in Palestine and found that it had an annual yield of 1756 kWh/kWp. The economical results show the pay-back period for 5 kW photovoltaic systems needs 4.9 years. For that, the study outcomes encouraged to use of this system on rooftops of buildings. A rooftop grid-connected PV system was presented by (Adaramola, 2015; Milosavljević et al., 2015; Sharma & Goel, 2017) for locations in Norway, Eastern India, and Serbia. Energy production and economic analysis were also studied and evaluated. A simulation of a 5.94 kWp photovoltaic (PV) panels that is connected to the electrical grid in Morocco, was carried out on the three different types of PV technologies using the PVsyst software (Baghdadi et al., 2018). The results show that mono-crystalline technology has the best performance, whereas amorphous has the worst evaluation. Similarly, in the study that was provided by (Ahmadi et al., 2017), both amorphous and polycrystalline PV technologies have been deployed in both the North and South West regions of Tunisia. Annual energy production has been evaluated in two locations. The results encourage investing in the installing PV system in the South West region. Moreover, (Almarshoud, 2017; Chaurasia et al., 2023; Divya Navamani et al., 2023; Pillai & Naser, 2018) studied the technical, economic, and environmental feasibility of implementing a grid-tied solar PV system and compare the results with similar systems in various geographical regions.

This study focusses on rooftop PV systems installed in educational institution such as university campuses. Thus, it will be reviewed a variety of studies the potential of solar PV utilization, power generation and economic revenue at the scale of university campus and school. In a study conducted by (Al-Otaibi et al., 2015), the performance of two rooftop photovoltaic systems with copper indium gallium selenide (CIGS) thin film technology, one with a capacity of 85.05 kWp and the other with 21.6 kWp, installed in Kuwaiti schools was evaluated over a 12-month period. The performance ratio of both systems remained consistently between 0.74 and 0.85, with an annual energy yield of approximately 1642.5 kWh/kWp. (Hassan & Elbaset, 2015) also conducted an evaluation of a grid-connected photovoltaic system installed on the rooftop of Minia University in Egypt, assessing its energy output and conducting a techno-economic analysis. The evaluation of grid-connected photovoltaic (PV) systems at the Hashemite University in Jordan was demonstrated by (Hammad et al., 2017) .The yearly energy output of two PV systems with and without tracking components, each with a capacity of 7.98 kWp, amounted to 2572 kWh/kWp and 1959 kWh/kWp, respectively. This translates to a total cost savings of USD138,825 and USD105,737 over a span of 20 years. In their study conducted in 2018, (Ayadi et al., 2018) examined the performance of a grid-connected photovoltaic system at the University of Jordan. The findings indicated that the system's final energy yield ranged from 1600 to 1715 kWh/kWp, and the payback period was approximately 3 years. (Alshare et al., 2020) analyze the performance of a 5 MWp photovoltaic system installed at Jordan University of Science and Technology, correlating energy and power generated, efficiency, and losses with climatic characteristics such as insolation, temperature, and wind speed. The economic analysis showed an annual internal rate of return of 30.11% and a payback period of 4.32 years, and a comparison was made between actual and simulated performance using System Advisor Model. In the study conducted by (Mokhtara et al., 2021) at an Algerian university campus, grid-connected rooftop photovoltaic (PV) systems were implemented in educational buildings. The findings revealed that 60% of the roof area was found to be suitable for optimal PV installations. Moreover, it was determined that the maximum yearly power output achievable was 2333.11 MWh/year. (Ali & Alomar, 2023) observed that by including local generators, the payback period of the solar power systems connected to the grid constructed at Zakho University in Iraq may be reduced to four years. This result emphasizes advantageous the suggested PV systems for Iraqi university campuses. (Waewsak et al., 2023) analyses different scenarios of 1MW PV grid connected system at rooftop of Thaksin University in Thailand. The researchers found the best annual energy production is 1537.7 MWh when the tilt angle is10^{o} and PV modules facing to south direction.

The literature review above suggests that PV systems installed on rooftop building in universities offer advantages in terms of power generation and economic issues only. However, existing research primarily focuses on fixed configuration PV systems, neglecting environmental impact study. Moreover, there is a lack of comprehensive assessments considering energy potential, economic study and environmental advantages specifically for PV systems installed on rooftop in government building in Palestine.

Therefore, the primary aim of this study is to provide a qualitative and quantitative evaluation of rooftop solar PV systems in university campuses within Palestine. This evaluation is crucial in identifying the potential contributions of solar PV, particularly in replacing diesel generators, to foster urban development, generate additional income, and garner political support. The insights gained from such solar projects can pave the way for future expansion into other areas, ensuring appropriate design of solar PV systems under real-life environmental conditions. Moreover, this work aims to compare the real energy production of a rooftop photovoltaic system installed at the main building (PTUK, Tulkarm, Palestine) with the expected energy production estimated using the PVsyst software. In addition, the paper also presents a comparing study of performance parameters such as P_R, final system yield and capacity factor of photovoltaic systems located in other cities.

Methodology

The research begins by comprehensive reviewing of previous papers related to installing PV system in university buildings. The methodology for assessing photovoltaic (PV) systems typically involves the following steps:

Firstly, data collection is conducted to gather relevant information about the PV system, including details about its location, technical specifications, components, installation methods, and operational parameters. This process entails evaluating documentation, visiting sites, and working with system owners or operators. Following that, performance is monitored by installing data loggers or monitoring devices. Data is collected in real time on energy generation, ambient conditions (such as solar irradiation and temperature), and system performance metrics (such as voltage, current, and power output). The system is monitored throughout time to capture various weather conditions and seasonal fluctuations. After that, simulation and modeling are carried out utilizing software tools such as PVsyst or other PV modeling packages. Based on design parameters, local climate data, and system characteristics, these tools simulate the system's expected performance. To evaluate the model and assess any variations, the simulated results are compared to the actual performance data. Data analysis is performed to process the collected data and examine the performance of the system. Metrics such as energy yield, capacity factor, performance ratio, and specific yield are evaluated. Based on the system's design parameters and software simulations, actual performance data is compared to expected performance. The performance indicators are then evaluated to determine the system's efficiency, dependability, and general health. Any concerns, such as underperformance, losses, or equipment faults, are noted, and probable reasons are investigated.

The research also evaluates photovoltaic systems' environmental effect, examining their potential advantages in terms of decreasing carbon emissions, air pollution, and environmental degradation associated with conventional energy sources.

Finally, based on the evaluation results, the findings, conclusions, and suggestions are presented in a complete report. In summary, the evaluation process involves data collection, performance monitoring, simulation and modeling, data analysis, performance evaluation, environmental effect assessment, reporting, and recommendations. These procedures add up to a complete evaluation of the PV system's performance and environmental effects. Figure (2) depicts the technique flowchart was used in this paper.

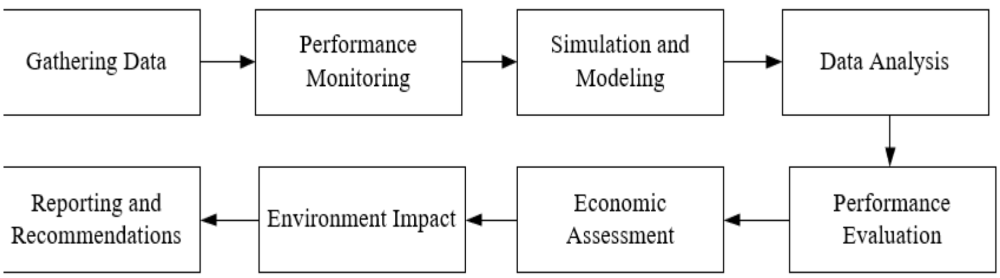


Figure (2). Research methodology flowchart

PV system simulation tool

PVsyst 7.2 is a detailed technical, evaluation and financial software. It permits users to simulate energy production and financial study for various PV systems under different conditions. The technical options include the selection of electrical, and mechanical specifications and the available area of the installed PV array with a matched inverter. In addition, the orientation of PV panels (tilt and azimuth angles) and are also determined.

On the other hand, PVsyst includes many databases such as PV modules and inverters which are based on manufacturer data sheets. A meteorological database is also available to provide hourly data for weather such as solar radiation, wind speed, and temperature at different locations around the world. Moreover, loss parameters can be determined by PVsyst software according to system specifications and the experience of the engineer about the site of the project. Shading, wiring loss, ohmic losses, soiling loss factor, PV module quality and thermal loss are the main loss parameters that are selected in software to calculate the expected energy output. After determining all parameters in PVsyst, it should be run the simulation in order to export a technical report containing a group of data such as annual energy generation in (kWh/year), PR, and L_S (kWh/kWp). Figure (3) shows the simulation process by PVsyst software.

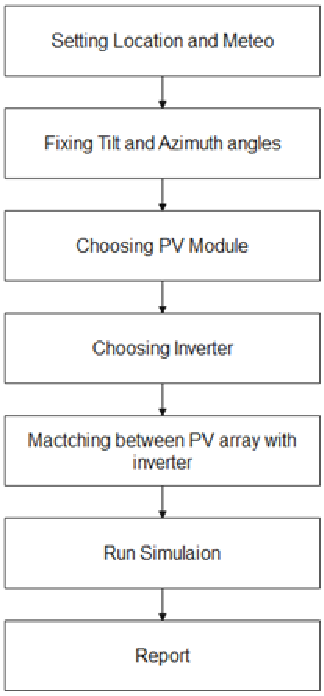


Figure (3). Flowchart of procedure simulation of PVsyst software

To determine the electrical component, the PVsyst can be selected based on the electrical specifications and availability in markets. Figure (4) shows the procedure of selecting the electrical equipment's of PV system.

1-Calculating the energy that needs to be produced by solar arrays

$$E_{PV,required}\left(\frac{Wp}{day}\right) = 1.3 \times \sum\left[P_{Load}(W) \times time\left(\frac{h}{day}\right)\right]$$

↓

2-Calculating the required power of the PV system

$$P_{PV,required}(Wp) = \frac{E_{PV,required}}{\text{Solar radiation capacity } (\text{kWh}/m^2/\text{day})}$$

↓

3-Calculating number of panels to be installed

$$N_{panel,required} = \frac{P_{PV,required}}{P_{panel,rate}}$$

↓

4-Selecting the power inverter according to:

$$P_{inverter}(Wp) \geq 125\% \times P_{Load}$$

↓

5-Determining number of modules per string

$$Max\ Number_{module\ per\ string} = \frac{\text{Maximum input MPPT DC voltage of the Inverter given by the manufacturer (V)}}{\text{Maximum DC Voltage of PV Module (V)}}$$

Figure (4). Flowchart of procedure selection PV system components

In this study the electrical component was selected based on the PV syst software as shown in Figure (5).

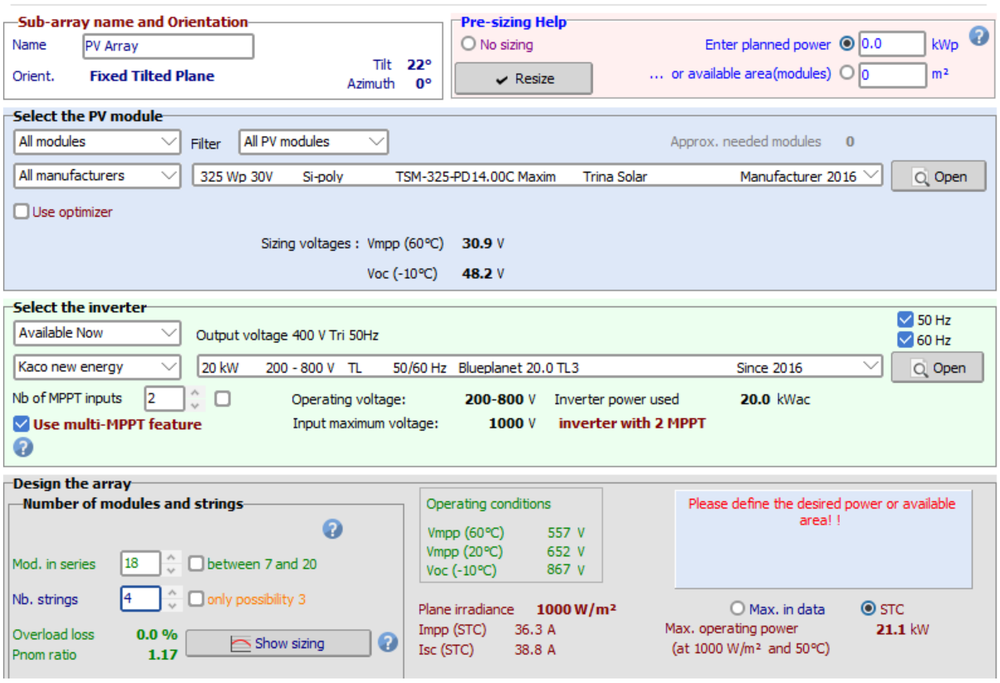


Figure (5). Selection the electrical component using PVsyst software

Performance parameters of grid-connected photovoltaic plant

The energy output of grid-connected photovoltaic plant can be assessed by employing multiple parameters to determine its efficiency. The International Energy Agency has set certain parameters, which are outlined in IEC Standard 611724 (Commission, 1998). These parameters consist of reference yield Y_R, final yield Y_F, performance ratio P_R, capacity factor C_F, and energy loss L. The metrics are employed for comparing the system to comparable PV systems situated in other places. This study will investigate these parameters and their computations. This includes the computation of the reference yield Y_R, which is determined by dividing the total amount of incident irradiation G_{incd} on the panel (measured in kWh/m^2) by the reference irradiance (G_0) under standard temperature at a rate of 1 kW/m^2, as illustrated in Equation (1)(Congedo et al., 2013).

$$Y_R = \frac{G_{incd}}{G_0} \tag{1}$$

The efficiency of a photovoltaic (PV) system is also determined by its final annual yield (YF), which is , calculated by finding the ratio of the total AC energy generated by the plant and sent to the electrical network in a year (measured in kWh as E_{grid}) to the rated power capacity of the PV array at standard test conditions (P_{PV}, rated, in kWp) (Divya Navamani et al., 2023). This parameter is determined using Equation (2)(Congedo et al., 2013).

$$Y_F = \frac{E_{grid}}{P_{PV,rated}} \tag{2}$$

The array yield (Y_A) represents the efficiency of the photovoltaic (PV) array and is determined by dividing the total DC energy produced by the array over a year (E_{DC}, measured in kWh) by the rated power capacity of the PV array under standard test conditions (P_{PV}, rated, measured in kWp). This parameter is determined using Equation (3)(Congedo et al., 2013).

$$Y_A = \frac{E_{DC}}{P_{PV,rated}} \tag{3}$$

The performance ratio (P_R) can be determined by calculating the quotient obtained by dividing the final energy yield (Y_F) of the PV system by the reference yield (Y_R), as presented in Equation (4) (Congedo et al., 2013).

$$P_R = \frac{Y_F}{Y_R} \times 100 \tag{4}$$

The calculation of the Performance Ratio aims to evaluate the quality of a PV system and compare it with other PV systems under real operating conditions.

The Capacity Factor (C_F) relates the actual annual generated AC energy (Egrid, kWh) to the maximum annual power that a photovoltaic system would produce if it worked at full rated power for 24 hours in a given day. as given in Equation (5) (Congedo et al., 2013).

$$C_F = \frac{E_{grid}}{P_{PV,rated} \times 8760} \quad (5)$$

Energy losses in a photovoltaic plant can be divided into two categories: array capture losses and system losses. System losses (L_S, kWh/kWp) can be generated by the inverter and other electrical components required for grid connection. The system losses can be calculated by subtracting the final system yield (Y_F) from the array yield (Y_A) as shown in Equation (6) (Ali & Alomar, 2023).

$$L_S = Y_A - Y_F \quad (6)$$

Array-captured losses (L_A, kWh/kWp) occur in the PV array result of temperature increase of the PV cells, dust accumulation, and partial shading. These losses can be calculated as the Equation (7) (Ali & Alomar, 2023).

$$L_A = Y_R - Y_A \quad (7)$$

Finally, the ratio of AC energy produced from the PV plant and fed into electrical network (E_{grid}, kWh) to the total irradiation falling (G, kWh/m^2) on the surface area of the PV system (A_{PV}, m^2) is called the system efficiency (η_{SYS}). The system efficiency is given in Equation (9) (Adaramola & Vågnes, 2015).

$$\eta_{SYS} = \frac{E_{grid}}{\mathrm{G} \times A_{PV}} \times 100\% \quad (8)$$

Cost-Effectiveness Assessment of On-Grid Photovoltaic Systems

In order to evaluate the cost-effectiveness of introducing on-grid photovoltaic systems in Palestine and to ascertain the financial feasibility of such an undertaking, an economic analysis will be carried out. The objective of this analysis is to determine the costs related to electricity procurement and assess the potential for a reliable and financially beneficial investment.

-**Simple payback period Simple**

The Simple Payback Period (SPBP) is a technique used to assess the viability of a project by determining the time required to recoup the initial capital investment. If the SPBP is shorter than the projected lifespan of the project, it signifies its feasibility. Conversely, if the SPBP surpasses the project's lifespan, it implies that the project may not be economically viable. The calculation of SPBP can be performed using Equation (9).

$$SPBP\ (year) = \frac{Investment}{Saving\ cost\ per\ year} \quad (9)$$

-Net present value

To determine the Net Present Value (NPV) or Present Worth, one can compare the present value of cash inflows with the present value of cash outflows for a specified duration. This calculation requires inputting the cash flows associated with each year of the solar system's operation, including both positive inflows and negative outflows like the initial capital investment. In the specific case study, the NPV is calculated utilizing Equation (10).

$$NPV\ (\$) = -Invvstment(\$) + C\left(\frac{\$}{kWh}\right) \times [E(1) \times (P/F\ , i, 1) + \sum_{n=2}^{20} E(n-1) \times (1-d) \times (P/F\ , i, n)] \quad (10)$$

Where: C is the cost of one unit of energy ($/kWh), E (1) represents the initial PV energy output in kWh at the first year after installation. n represents the time n (in years) after installation. E (n) represents the current PV energy output in kWh at time (n) (in years) after installation. E (n-1) represents the previous PV energy output in kWh at time (n-1) (in years) after installation. d represents the degradation rate per year which equals 0.005 in this study. (P/F) is the factor from the interest tables, i is the interest rate which is 10%.

-The Levelized Cost of Energy (LCOE)

LCOE is a metric used to estimate the average cost of producing electricity from a particular energy source over the lifetime of a power plant. It can be estimated by equation (11)

$$LCOE\ (\$/kWh) = \frac{Invvstment}{E(1) + \sum_{n=2}^{20} E(n-1) \times (1-d)} \quad (11)$$

Environmental Impact

The implementation of the rooftop solar project not only addresses electricity scarcity issues but also plays a vital role in curbing CO_2 emissions in the environment. The following equation shows estimated amount of CO_2 emission:

$$amount\ of\ CO_2 = \sum_{n=1}^{20} (E_{grid_n}) \times e\_factor \quad (12)$$

Where: E_{gridn}: the energy produced by the system in nth year; e_factor (the CO_2 emission factor of the Palestine grid) = 0.75 kg CO_2/kWh (Ibrik, 2020).

DESCRIPTION OF THE INSTALLED ROOFTOP PV SYSTEM:

The 134.55 KWp PV power plant in this study was installed on the rooftop of Palestine Technical University's main building in Tulkarm, Palestine. The system is composed of 414 multi-crystalline silicon PV modules, each with a maximum power output of 325 Wp under standard testing conditions (STC) and an efficiency of 16.6%. These modules were manufactured by Trina Solar, the modules used in the system have a combined surface area of 818 m^2 modules includes 726m^2 cells. In addition, the PV modules are positioned with a tilt angle of 22 degrees and an azimuth angle of 0 degrees. To increase the voltage, the modules are linked in series, and then three to four strings are connected in parallel to raise the current using a suitable box. This box aims to combine the direct current (DC) output from multiple solar panel strings into a single DC output. It typically includes overcurrent protection devices, fuses, and surge protection components, and can also be equipped with monitoring capabilities to measure current and voltage at the string level. Six inverters with a 20 kW power output and 98.4% efficiency are connected to these combiner boxes (model: blue-planet 20.0 TL3 INT, 400V). A data acquisition system with sensors for measuring solar irradiance and ambient temperature is also in place, and the collected data is sent to a server. To link the inverters to the grid, a fuse box and an electrical meter are utilized as illustrated in Figure (6). Figure (6) depicts the single line diagram of PV system in PTUK to utility grid. In addition, figure (7) shows the layout of the distributed photovoltaic system on the rooftop of the main building using AutoCAD software. Table (1) shows the electrical specifications of the PV modules, and Table (2) shows the technical specifications of the inverters. Figure (8) shows the sensors for data acquisition that was used in the project to record all data and display them on a specific website. Figure (9) depicts the installed 134.55 kWp on-grid PV system in the main building at PTUK university.

Table (1). The electrical specifications of the TSM-325 -PEG14 PV module

Electrical Data	Specification
Power Output Tolerance-P_{MAX} (W)	325
Peak Power Watts-P_{MAX} (Wp)*	0/+5
Maximum Power Voltage-V_{MPP} (V)	37.4
Maximum Power Current-I_{MPP} (A)	8.69
Open Circuit Voltage-V_{OC} (V)	46.1
Short Circuit Current-I_{SC} (A)	9.14

STC: Irradiance 1000 W/m^2, Cell Temperature 25 °C, Air Mass AM1.5
* Measuring tolerance: ±3%

Table (2). The technical specifications of the 20.0 TL3 INT inverter which was used in the project

Electrical Data	Specification
Input Variables	
Maximum PV generator power	24 000 W
MPP range at P nominal	515 V ... 800 V
Operating range	200 V - 950 V
Min. DC voltage / starting voltage	200 V / 250 V
No-load voltage	1 000 V
Max. input current	2 x 20 A
Number of MPP trackers	2
Max. power/tracker	15kW
Number of strings	2×2
Output variables	
Rated output (@ 230 V)	20 000 VA@230 V
Line voltage	400 V/230 V(3N/PE)
Rated current	3 × 29 A
Rated frequency	50 Hz / 60 Hz

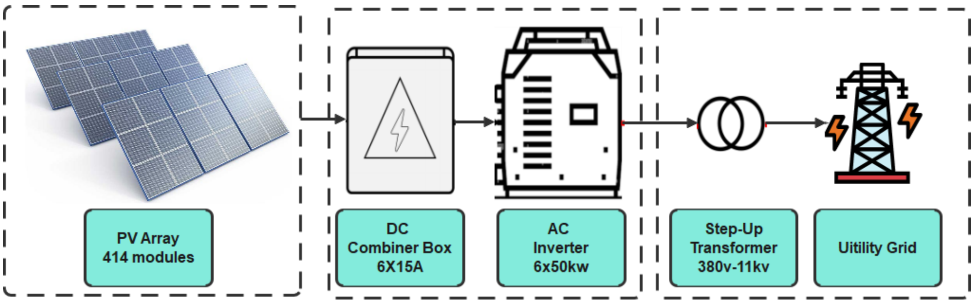


Figure (6). Single line diagram of PV system- PTUK to utility grid

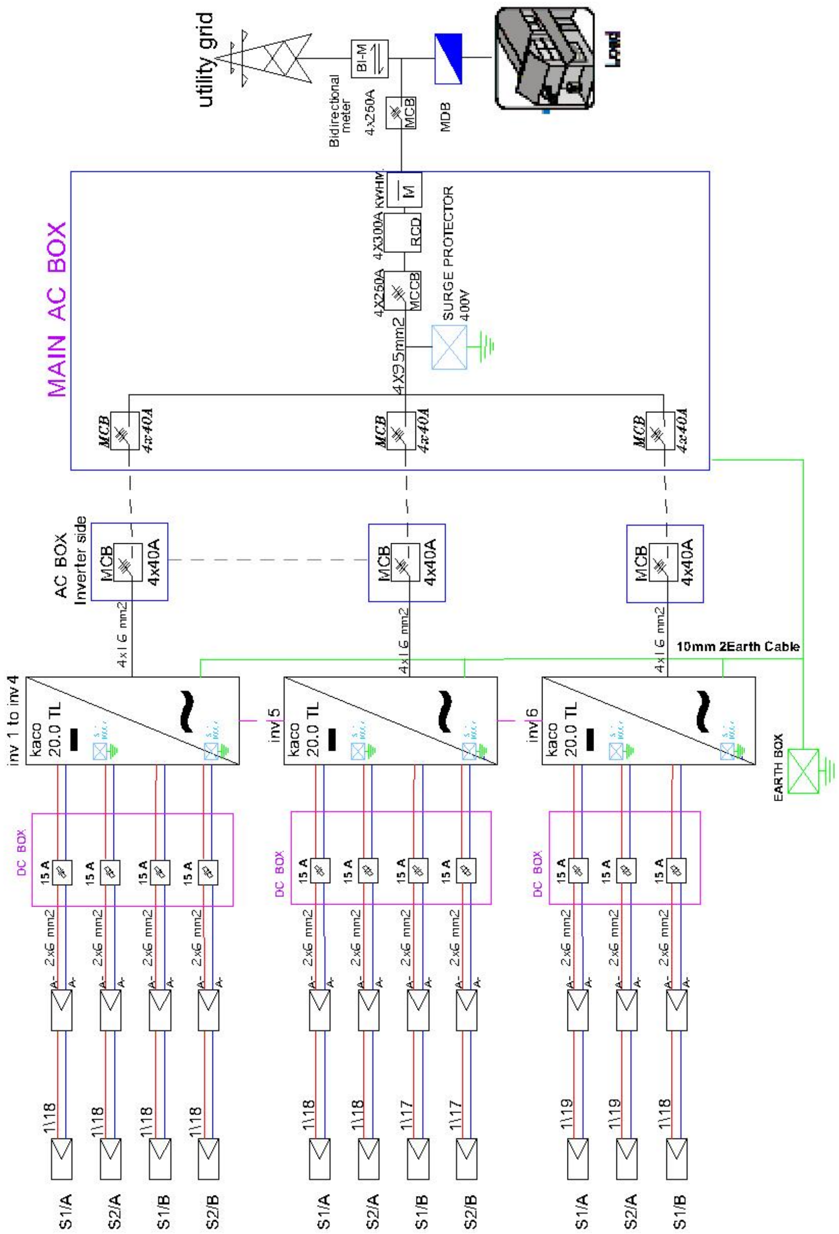


Figure (7). The electrical installations of the PV system project

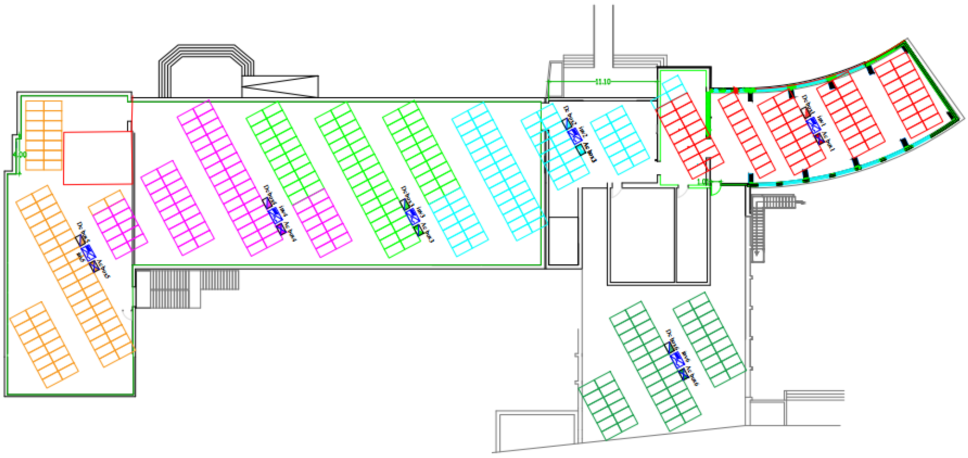


Figure (8). The layout of the distributed photovoltaic system on the rooftop of the main building

Figure (9). The metrological station at the site of the project

Figure (10). The installed 134.55 kW on-grid PV system in the main building at PTUK university

Results and Discussion

The weather data for this study was collected by the meteorological station installed on the rooftop of the main building. The quantities of Global horizontal irradiance, Ambient temperature and wind speed were measured by using a pyranometer, Pt100 sensor and anemometer, respectively. CR1000 datalogger collects these physical quantities for recording, monitoring and viewing data using the PC200W software. The data was taken every 150 ms, and since the recording proceeds in steps for each month, mean monthly values were determined from the raw data. To find the average solar irradiation per hour, divide the total amount of solar insolation measured during that hour by the number of data points recorded during that hour. The average monthly solar irradiation, wind speed, and ambient temperature have also been calculated using the same procedure. This study only includes measurements from the year 2019. In addition, long-term data from Meteonorm (covering the period from 1990 to 2010) was also utilized in this study. The chart in the following shows the comparison of average monthly solar radiation in kWh/m^2 between measurements collected in 2019 and the Meteonorm for average solar irradiation values at the site of the PV system project.

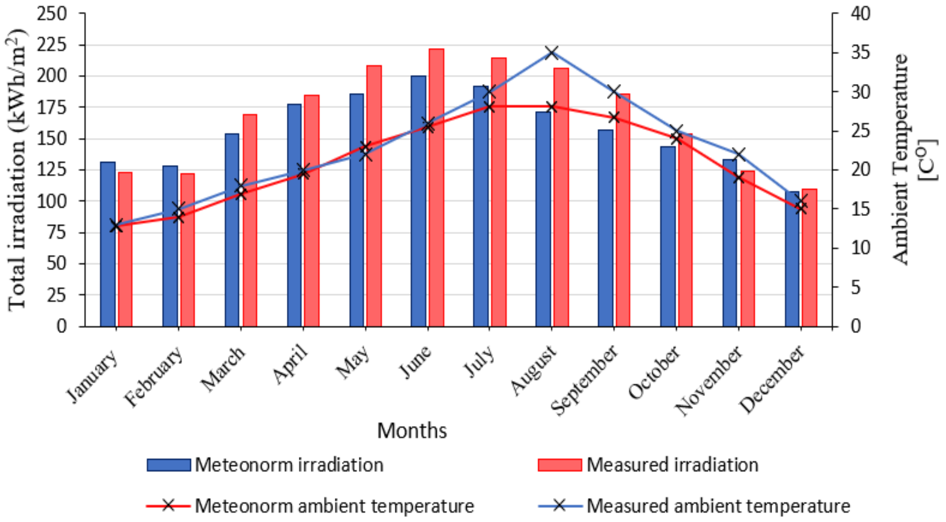


Figure (11). Average monthly solar irradiation and ambient temperature in Tulkarm

It can be seen in Figure (11) that The Meteonorm data, which is based on long-term statistical averages, may not perfectly align with measured values for a specific month. However, it provides a useful reference. As shown in Figure (11), the measured solar irradiation and ambient temperature values were often higher than the Meteonorm data. Moreover, the average irradiation changes from 131 kWh during the winter season and 200.04 kWh during the summer season. The month with the highest average is June, with an average of about 6.9 kWh/m^2/day. While the average ambient temperature changes from 13°C during the winter season and 35°C during the summer season. The month of August has the highest average temperature. Table (3) shows the average monthly of ambient temperature, global radiation and electrical energy output from PV system that was obtained from PVsyst.

Table (3). Monthly data of weather and output energy of PV system that was obtained by PVsyst

Month	Tamb* (°C)	GlobHor* (kWh/m2)	GlobInc* (kWh/m2)	GlobEff* (kWh/m2)	EArray* (kWh)	E_Grid* (kWh)	EffArrR* (%)	EffSysR* (%)
January	12.8	75	97.8	92.1	11397	11119	16.05	15.66
February	14	93	114.6	108.7	13255	12946	15.93	15.56
March	16.9	138	158.3	150.8	17982	17562	15.65	15.28
April	19.5	158	166.3	158.2	18617	18180	15.42	15.06
May	23	208	204	194.4	22441	21924	15.15	14.8
June	25.5	218	206.5	197	22403	21886	14.94	14.6
July	28.1	228	219.5	209.9	23271	22731	14.6	14.26
August	28.1	208	213.9	204.9	22073	21560	14.21	13.88
September	26.7	168	188.5	180.6	20056	19599	14.66	14.32
October	24	128	157.5	150.5	17275	16875	15.11	14.76
November	19.1	88	114.9	108.7	12799	12493	15.34	14.98
December	15	67	87.8	82.1	9976	9730	15.65	15.26
Year	**22.74**	**1777**	**1929.6**	**1837.9**	**211545**	**206605**	**15.1**	**14.75**

* "Tamb" is the ambient Temperature, "GlobHor" is the Horizontal Global irradiation, "GlobInc" is the Global Incident irradiation in the collector plane, "GlobEff" is the Effective Global correction for shadings, "EArray" is the effective Energy at the output of the Array, "E_Grid the Energy injected into the Grid, "EffArrR" the Efficiency of the Array and "EffSysR" the Efficiency of the System.

Table (3) displays the average ambient temperatures, global irradiation on both horizontal and collector planes, and the effective global irradiation which factors in shading and soiling losses. The yearly global irradiation on the horizontal plane is 1777 kWh/m^2, the yearly global incident energy on the collector before optical losses is 1929.6 kWh/m^2, and the effective global irradiation after optical corrections is 1837.9 kWh/m^2. PVsyst simulation outputs three main findings for the PV system: total AC energy produced by the system which is 206605 kWh/year; yearly specific production per installed kWp, which is 1535.52 kWh/kWp/year; and the mean yearly performance ratio, which is 79.57% (as demonstrated in Table (4)). Furthermore, the photovoltaic array generated 211544 kWh of DC energy annually, and 206605 kWh of AC energy was fed into the power grid, accounting for the efficacy of the PV array and electric component losses. On average, the annual efficacy of the photovoltaic array was 13.40%, and the system's average annual efficacy was 13.15%. It's noteworthy that PVSyst can simulate monthly soiling loss as an irradiance loss. Table (4) illustrates the performance ratio and the amount of energy penetration into the electrical network based on PVsyst's Meteonorm weather data.

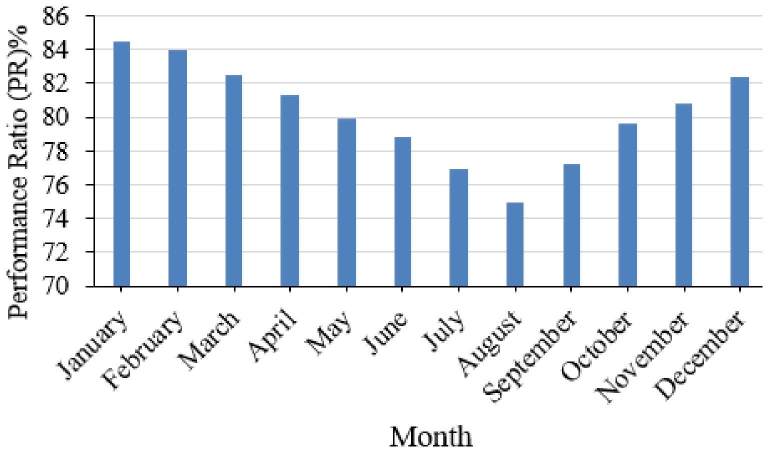
Table (4). The energy penetration level and the performance ratio of the photovoltaic system using PVsyst.

Month	E_Grid* (kWh)	E_Grid _monthly* (kWh/kWp)	E_grid_daily* (kWh/kWp)	PR (%)
January	11119	82.64	2.67	84.5
February	12946	96.22	3.44	83.96
March	17562	130.52	4.21	82.45
April	18180	135.12	4.5	81.25
May	21924	162.94	5.26	79.87
June	21886	162.66	5.42	78.77
July	22731	168.94	5.45	76.97
August	21560	160.24	5.17	74.91
September	19599	145.66	4.86	77.27
October	16875	125.42	4.05	79.63
November	12493	92.85	3.1	80.81
December	9730	72.32	2.33	82.36
Year	**206605**	1535.53	4.21	**79.6**

*"E_Grid" is the total energy injected into the grid, "E_Grid _monthly" is the monthly amount of production of electrical energy and "E_grid_daily" is the daily amount of production of electrical energy.

The DC energy generated by the PV array is converted by inverters for use on a utility grid, but some losses occur due to wiring. As shown in Table (4), the total energy injected into the grid by the 134.55 kWp PV system is 206605 kWh per year, with an average monthly production of 1530.39 kWh/kWp and an annual average daily final yield of 4.19 kWh/kWp. The highest amount of energy injected into the grid is 22731 kWh in July, and the lowest amount is 9730 kWh in December.

The PV system exhibited an annual performance ratio of 79.6 %, as illustrated in figure (12), which presents the monthly fluctuation of P_R values obtained from Table (4). The maximum P_R value of 84.5% was documented in January. It's important to mention that P_R values were mainly elevated during winter months from December to February. This may be attributed to a drop in ambient temperature that helps prevent excessive module surface temperatures.



.Figure (12). Monthly performance ratio

Figure (13) shows a comparison bar chart between a measured and simulated of monthly of AC energy.

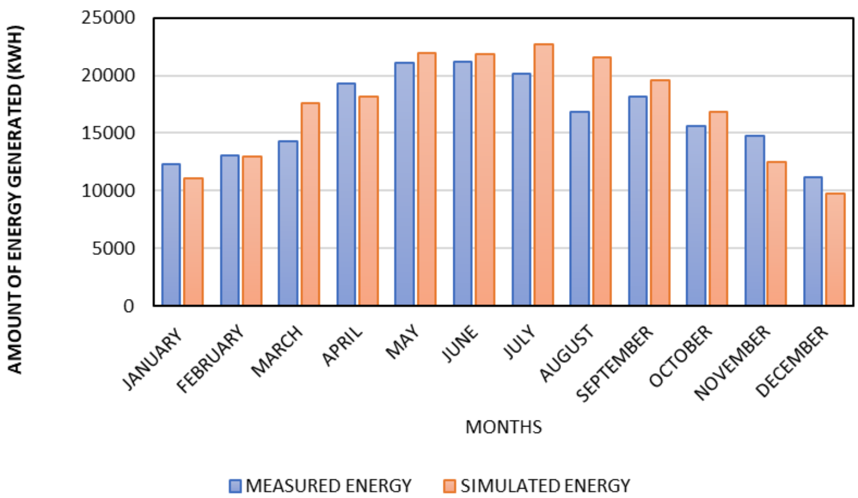


Figure (13). Monthly energy output from inverters of PV system in 2019

In Figure (13), there is a small contrast between the monthly energy output measurements and simulations of the PV system's inverters. This discrepancy could be due to issues with the measurement equipment or inaccuracies in the PV system's simulation results. To ensure accuracy, the data inputs for PVsyst software should be based on actual operational conditions like solar radiation, ambient temperature, and wind speed. However, in this simulation study, average meteorological data from Meteonorm was used. Furthermore, the actual capacity factor C_F was 16.8%, while the simulated value was 17.52%. Additionally, the measured final yield was 1472.24 kWh/kWp/year, whereas the simulated value was 1535.5 kWh/kWp/year based on Meteonorm data. In addition, the actual performance ratio was 78.2%, while the simulated value is 79.6%.

Indeed, when applying a performance assessment for a PV system and comparing it with other PV installations in different locations, the PV system size does not take into consideration. Thus, the normalized energy output is used by making some energy parameters in standard form. According to this definition, any parameters of energy are expressed as [kWh / kWp / day]. The normalized energy output is described by JRC (European Joint Research Center) (CODE, 1998). In this study, the average monthly useful energy output from inverters of the PV system (Y_F) was 4.2 kWh/kWp/day, system loss (L_S) was 0.1 kWh/kWp/day and collection loss (L_C) was 0.2 kWh/kWp/day. From figure (14), the monthly averaged of produced useful energy varied between 2.33 and 5.45 kWh/kWp/day in December and July, respectively. It can be also noticed, the energy outputs from November to February are low due to reduce in number of sun hours in winter season.

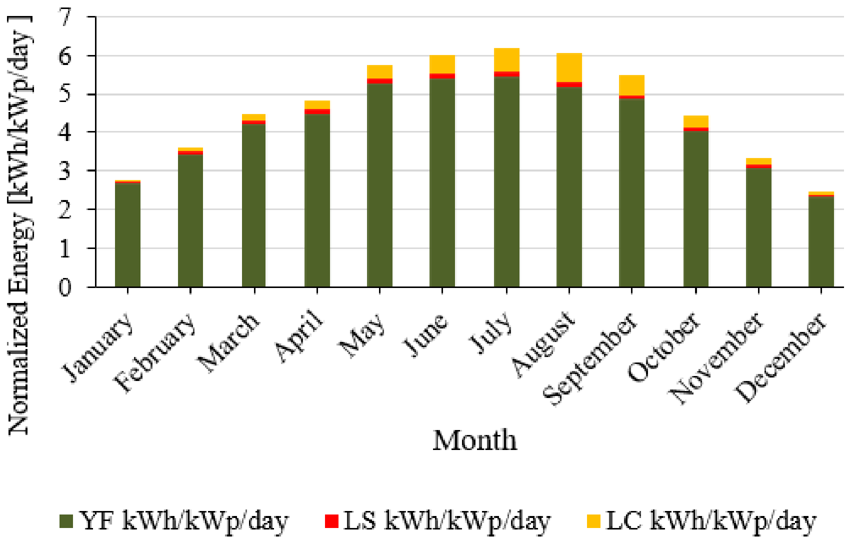


Figure (14). Monthly produced useful energy output from inverters of the PV system (YF), system loss (LS) and collection loss (LC)

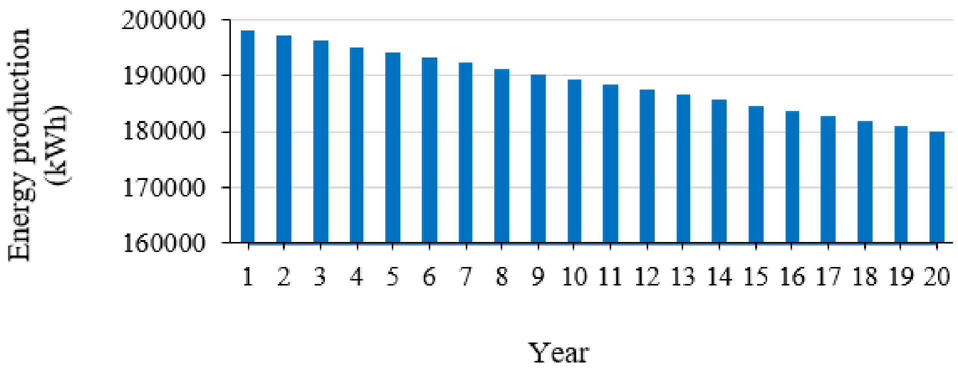
To compare the PV system in this work with other systems, Table (5) shows some performance parameters of PV systems in several geographical locations. It can be noted, the PV system in this study had a higher performance ratio, capacity factor and final yield than other systems due to the long number of sun hours with a moderate ambient temperature in this region.

Table (5). Comparison of Performance parameters in several locations

Reference	Location	Monitoring Period	Installed power (kWp)	Performance Ratio (%)	Capacity Ratio (%)	Final Yield (kWh/kWp/day)
(Pérez et al., 2020)	Spain	2003	20	65	10.8	2.27
(Sharma & Chandel, 2013)	India	2011	190	74	9.27	2.23
Present study	Palestine	2019	134.55	78.2	16.8	4.03
(Kymakis et al., 2009)	Crete	2007	171.36	67.4	15.3	3.66
(Adaramola & Vågnes, 2015)	Norway	2013-2014	2.07	83	10.6	2.55

Economic analysis and environmental impact of the project

The project incurred a total capital cost of USD135182.75, with first year energy generation of 198090 kWh. In the city of Tulkarm, the cost of one unit of energy (kWh) is USD 0.2. As a result, the savings for the year 2019 amounted to USD146,290. By applying equation (9), the Simple Payback Period (SPBP) for PTUK is calculated as 3.41 years. Moreover, the energy Production for the next 19 years is illustrated in figure (15). Thus, by using equation (10), the NPV equals USD 191389.9872. finally, the Levelized Cost of Energy (LCOE) is 0.036 USD/kWh. It can be concluded this project is visible.



.**Figure (15). Energy Production of the plant for 20 Years**

Replacing diesel generators with solar PV systems has a significant environmental impact, specifically on the atmosphere, as it reduces the need for combustion processes. The amount of CO_2 emitted per kilowatt-hour (kWh) varies depending on the method of generation, such as diesel, coal, gas, and others. In this study, it is estimated that there is an average annual reduction of around 141,717.8247 kg of CO_2 emissions.

CONCLUSION:

The evaluation conducted in this article focuses on the technical and economic feasibility of establishing a PV plant at Palestine Technical University-Kadoorie (PTUK) in Tulkarm, Palestine. The assessment considers various factors such as the space of rooftops, environmental considerations, available resources, and feasibility analysis. The outcomes of this study can provide valuable guidance for future planning and encourage governmental organizations and policy-makers to implement incentive policies to promote the expansion of solar energy production. In summary, the key findings of this study are as follows:

The technical and financial research strongly supports the construction of a 135.55 kW PV plant on the rooftop of the main building in PTUK. By utilizing only 818 m2 of rooftop space, the plant can generate 206.6 MWh of electricity annually, taking advantage of the average annual solar radiation in Palestine of 5.4 kWh/m^2-day. The PV systems yield an impressive output of 1535.3 kWh/kWp-year, equivalent to 4.21 kWh/kWp-day. The project's performance ratio (PR), simulated using PVsyst software, reaches 79.6%, while the actual PR is 78.2%, indicating a high level of adherence to the project plan. The capital expenditure for the project amounts to USD 135,182.75, which can be recovered within a payback period of 3.41 years. The levelized cost of electricity (LCOE) is estimated at USD 0.036/kWh, and the net present value (NPV) during 20 years is calculated as USD 191,389.98.

Furthermore, implementing the planned facility would significantly contribute to the country's efforts to mitigate the effects of climate change by substantially reducing CO_2 emissions. It is estimated that the facility would be able to reduce emissions by 141.717 tons annually. These findings highlight the substantial potential of government rooftop buildings equipped with solar PV systems as a realistic solution for achieving Palestine's renewable energy targets.

Finally, this research underscores the importance of continuous investment and innovation in the renewable energy industry, not only for the benefit of Palestine but also to ensure a sustainable energy future for the entire global community.

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