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Design, Installation, and Performance Monitoring of a 105 kWp Rooftop Solar PV System

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ABSTRACT

Rooftop Solar PV systems are gaining growing attention on the path toward carbon neutrality. Hence, a great effort must be exerted to ensure smooth and efficient penetration of such systems into the existing utility grids. In the current work, a 105 kWp rooftop solar system is designed and installed to fulfil part of the electric demand of the faculty of Engineering, Zagazig University, Egypt. The performance parameters of this grid-connected solar PV system are optimized for the least-cost of electricity supply through using industry-standard software NREL SAM. For the current rooftop system, fixed orientation of an optimized tilt angle of 23 degrees is preferred over sun-tracking systems due to the reduced operating and maintenance costs. The annual energy production of the system is 175,700 kWh with a capacity factor of 19.1%. Through using parametric optimization and inter-connected financial analysis algorithms, it was possible to define the least cost for the electricity supplied to the grid to be 0.55 EGP/kWh, which achieves grid parity in Egypt. The project is finically profitable without any subsidy, with a discounted payback period of 7.9 years, and IRR (on equity) of 20.1 % and saves 1882-ton CO_2 over its lifetime. Sensitivity analysis showed that the electricity escalation rate greatly enhances the project finances. In the first year of operation, the system performed fairly well compared with the theoretical design, provided that the system is frequently cleaned (at least once a week) and continuously connected.

1. Introduction

Global warming reduction, with the associated Green House Gas (GHG) reduction, combined with the increased demand call for more renewable energy production. This results in an increased demand for renewable energy as a sustainable and clean source of energy [1]. According to the Egyptian sustainable energy strategy up to 2035, the share of the RE is planned to reach 42% of the electricity mix. This share increases to 61 % by 2040. This includes 31.3 GW of solar PV, 20.6 GW of wind, and 12.9 GW of solar thermal plants [2]. With this anticipated lion's share of Solar PV in Egypt's 2035 vision, long-term strategies are to be implemented to help the deployment of such a big share of generation. Solar PV is a promising technology for supplying renewable electricity worldwide.

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There is a significant growth generation with photovoltaic systems mainly from tax incentives, regulatory reforming, and from the reduction in PV energy costs. However, their dependency on environmental factors, like the temporal variation of solar radiation, and large initial investments (CAPEX) poses significant reliability concerns regarding system design and operation, and slightly retards the deployment and integration of such systems in existing utility grids. Growth in utility-scale level PV is very optimistic, showing huge, anticipated reductions in CAPEX, as one of the major drivers for cost reductions. On the other hand, rooftop PV systems still face some financial feasibility challenges. Small-scale and lack of government incentives are major barriers to their wide deployment. Despite the reductions in hardware costs, soft costs are still a challenge [3]. While CAPEX and subsidies play an important role in the uptake of such rooftop PV systems, urban form of buildings has an additional important impact as studied by Akrofi and Okitasari [4] in addition to neighborhood-level spatial determinants which need to be taken into consideration [5]. Hence, for a rooftop system to be economically viable; site characteristics, CAPEX, system size, and local electricity price all need to be carefully optimized.

The literature is rich in rooftop PV installations due to their wide popularity. The major topics covered are the techno-economic feasibility of rooftop projects with and without financial subsidies, the system connection to the grid, and the solar tracking systems. These topics will be covered here in more detail.

Regarding the Techno-economic feasibility of rooftop projects, a good review for rooftop solar PV adoption shows the current and future trends [6]. Ahshan *et al.,* [7] designed a solar PV system for a sports building. They provided a detailed techno-economic assessment of the system over its 25-year lifetime. The system was profitable with a payback period of 10 years. A study was carried out to simulate the performance of a 6.4 kWp rooftop solar system that is connected to the grid [8]. Annual yield was 1528.125 kWh/kWp with a 75.01% performance ratio. Yadav and Bajpai [9] studied the performance of a rooftop PV system of a 5 kWp capacity along with the ambient temperature effect on the performance of the system. Their system produced 3.99 kWh/kWp/day and has an annual energy output of 7175.4 kWh. The lowest system performance was in the hottest month of May as expected. A techno-economic assessment of a 2.1 kWp grid-connected solar PV system was performed in Norway [10]. They did their analysis with and without governmental incentives. Their project was viable only with governmental incentives. Al-Najideen and Alrwashdeh [11] designed a solar PV system with a capacity of 56.7 kW to satisfy the demand of the Engineering school at a University in Jordan. The system covered the annual energy demand of 97 MWh with a 5.5-year payback period. Arcos-Vargas *et al.,* [12] modeled the environmental and economic performance of different rooftop PV systems. The project is profitable in all the locations analyzed in Madrid. A similar economic analysis was performed by Zeraatpisheh *et al.,* [13] under different charge Tariffs**.** A similar study was performed by Albadi *et al.,* [14] for a 50 kWp solar system with feasibility is done using RETScreen software. Their project was not profitable under the current electricity tariff. Tarigan and Kartikasari [15] simulated the environmental and economic performance of a one kWp grid-connected PV system for an Indonesian household. The system provided 1.3 MWh/year with a 6.5-year payback with governmental incentives. The system cuts 1295 kg CO_2 per year. Without incentives, the system was not feasible under their market conditions. Satellite imagery was used to automatically identify residential solar PV systems' locations and generation capacities for large geographical areas in Korea [16]. Similar work was done using GIS data in China and in Spain [17,18]. To evaluate the sustainability of rooftop PV systems, Paiano *et al.,* [19] used Energy and environmental indicators for a residential 3 kW PV system in Italy. Panicker *et al.,* [20] used the same energy indicators for the assessment of a building-integrated PV system in India. Similar work was done by Abo-Khalil *et al.,* [21] and Motlagh *et al.,* [22].

Regarding the grid-connection methods, PV systems may be grid-tied (Grid-Connected) or Grid-Independent (Off-Grid). Off-grid systems use batteries to store any excess energy as DC power and is used to cover shortages in demand supply. Due to the high cost of batteries, such systems are only economically feasible under certain conditions like the availability of the grid, electricity prices, and governmental incentives. Tervo *et al.,* [23] numerically modeled the techno-economic performance of rooftop PV systems with Li-ion batteries using a MATLAB library in different US-States. With appropriate sizing of PV systems and battery capacity, PV/battery combination surpasses the performance of PV-only systems. These combined systems can reach grid parity when appropriate incentives are applied [24]. His results indicate that grid-independent PV systems are not feasible unless combined with significant reductions in battery costs. Similar work was done by Weniger *et al.,* [25] who modeled rooftop PV battery systems with their different combinations and capacities. For rooftop battery PV systems, efficiency was evaluated for 26 systems in Germany [26]. The energy management of such rooftop photovoltaic batteries was studied by Zou *et al.,* [27], Ouedraogo *et al.,* [28], Oprea and Bâra [29], Irshad *et al.,* [30], and Erdinç [31] using dynamic programming and embedded optimization.

A rooftop PV system (grid-connected) is generally composed of a utility grid network, a Photovoltaic cell array, and an inverter with an optional storage battery. Figure 1 shows the operation of a typical grid-connected system. The inverter converts the DC current (generated by the PV panels) to AC electricity before power is provided to the loads [32]. Meanwhile, surplus DC power generated from the system is exported to the local grid. To calculate the net energy exported to or imported from the grid, the Net Energy Metering (NEM) meter is used. NEM is a mechanism of compensating customers for the solar PV electricity they export to the grid [33]. In addition to the NEM, there are other forms of compensation for the exported energy—*e.g.*, net billing, feed-in tariffs, and buy all-sell all. NEM is the compensation methodology that many countries follow, including Egypt [34]. To integrate PV generation systems in utility grids, around 65 countries all over the world have adopted net-metering policies [35]. Net metering is found to be more profitable than energy storage [36,37].

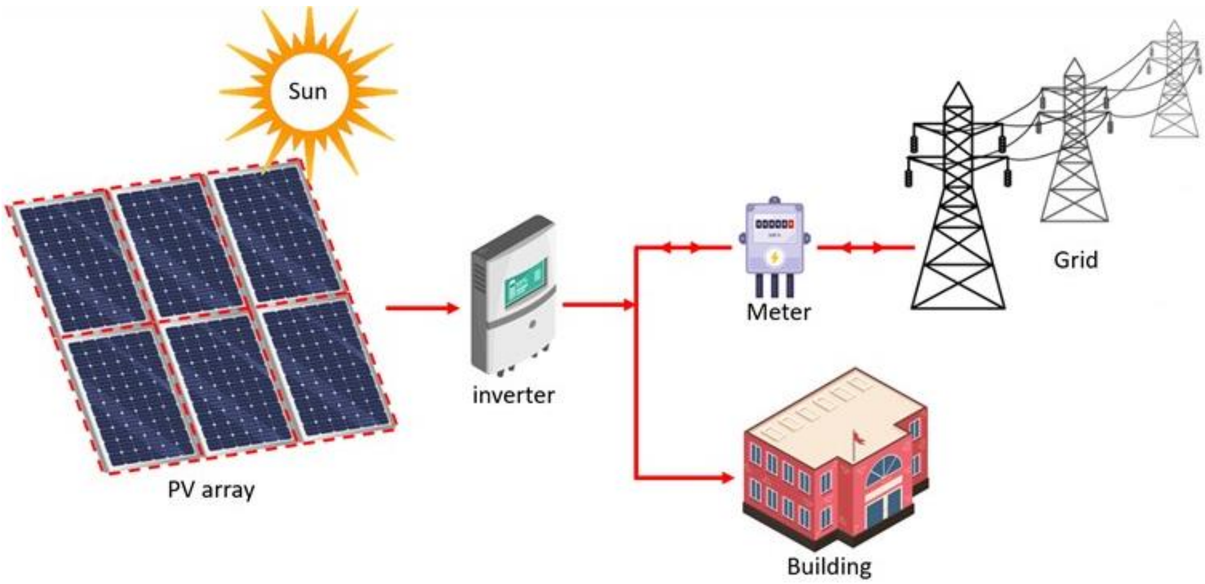


Fig. 1. Schematic of the proposed rooftop grid-connected system

A tracking system is a necessary component of a solar system in large utility scale solar PV systems as it significantly increases the energy yield despite efficiency sometimes reduced. Dual-axis tracking system increased the energy yield by 45 to 63% compared to the fixed-tilt depending on the analysis period and weather conditions as reported by Sawicka-Chudy *et al.,* [38]. Gönül *et al.,* [39] studied the techno-economic performance of fixed-tilt, single- and double-axis trackers against manually adjusted trackers for three provinces in Turkey. Results show that the payback period of fixed-tilt systems is around 12 years. Double-axis tracking systems gave the highest payback of 16.7-24 years, despite increasing the energy yield by 30 -34 % compared to the fixed-tilt systems. Manual tracking increased the yield by 5% and gave a payback period of 9.6-12.6 years. Similar conclusions were obtained by Bahrami *et al.,* [40] who tested different single and dual-axis trackers in Nigeria. Liang *et al.,* [41] developed a simple robot solar tracker that improved the solar conversion efficiency by 10.5% compared to the fixed tilt panels. For small-scale or rooftop installations, tracking systems are normally ignored due to the added CAPEX and OPEX compared to the project's overall costs. This is why most of the rooftop installations only use fixed-tilt mounted panels. Regarding the simulation tools used in designing PV systems, Wijeratne *et al.,* [42] investigated the performance of 23 software packages used in the design of distributed PV systems. Tools like SAM, PVsyst, HOMER, PV Sol, and RETScreen were investigated. None of the tools were sufficient to resolve all PV design aspects.

From the reviewed literature, one can notice the scarcity of comprehensive studies that entail design, commissioning, techno-economic feasibility study, performance monitoring, and sustainability plans of small-scale rooftop PV systems. In addition, most cited work uses costly commercial software packages to design and optimize rooftop PV systems which may not be available for individuals or young researchers. Finally, very few studies followed up on installed PV systems and monitored their performance to pinpoint problems as they appear and describe reasonable corrective actions and maintenance policies. The current study will bridge this gap by addressing all these shortcomings in a comprehensive way. It will provide a detailed explanation for the aforementioned stages validated with the performance monitoring of the system.

The current study aims at designing and monitoring a pilot 105kWp grid-connected solar PV system to cover part of the electricity demand of the faculty of engineering at Zagazig University Campus, Egypt. Site characteristics are well-defined, and the expected solar radiation profile is estimated for the whole year on an hourly basis. A specialized publicly available PV design tool is used to optimize all PV system components for the least cost of electricity. Site characteristics, modules, tracking systems, inverters, array layouts, and losses are all optimized for the least-cost performance. The industry-standard available software NREL SAM (System Advisor Model) is used in designing and optimizing the individual components of the Solar PV plant to minimize the cost per kWh supplied through its built-in financial model based on a recent market price research. A comprehensive techno-economic feasibility study will be performed. In addition, after the system installation, a full year period of monitoring is performed, and the system performance is compared to the design conditions. Performance enhancement plans are suggested to sustain the PV system performance as designed.

2. Site Characteristics

2.1 Site Overview

The engineering school at Zagazig University is one of the biggest schools on campus. It is located at [30.587 N, 31.484 E]. The school has 8 major buildings in addition to attached 3 separate labs and testing facilities. Figure 2 shows a Google Earth image of the site with a focus on the faculty of engineering buildings and labs. Buildings are numbered from 1 to 8 for easy identification. Buildings

1-6 were chosen for the pilot system installation, and the design is optimized based on the net floor areas, shadow analysis, and best orientation of PV modules, as will be discussed later. The installed solar PV system appears in the figure on the roof of these buildings. Figure 3 shows a simpler 3D orientation of the Faculty of Engineering buildings, the home place of the proposed pilot project. Buildings 1-6 are used for further design analysis.

Fig. 2. Google Earth Image of the Engineering School with the PV System installed [43]

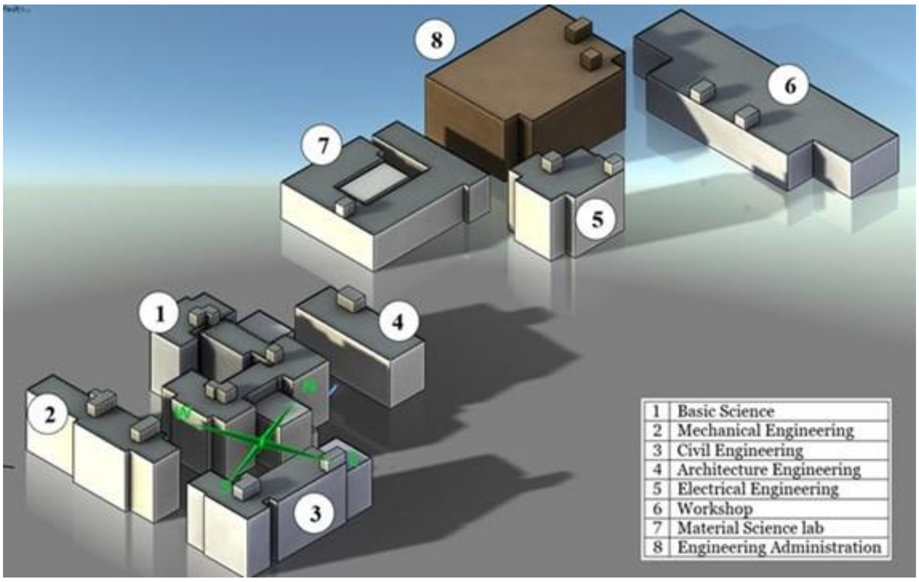
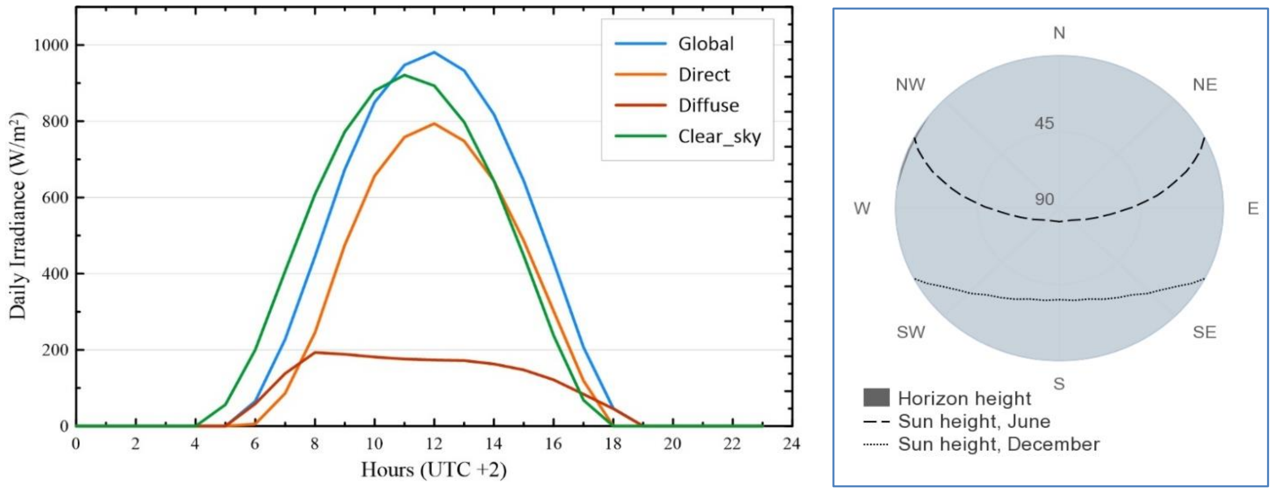


Fig. 3. 3-D modeling and orientation of the Faculty of Engineering buildings

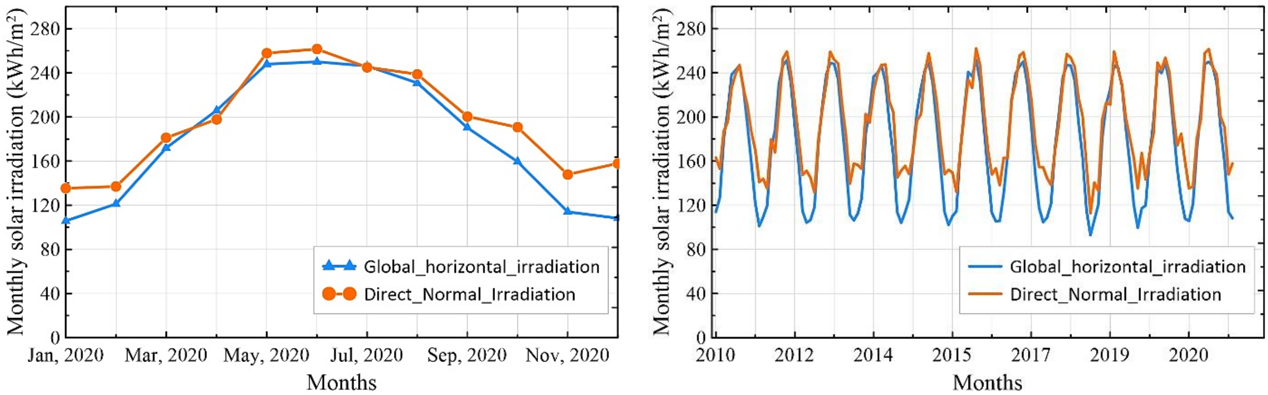
2.2 Site Solar Resource data

To well understand the site characteristics, a closer look is needed at the weather conditions year around. Figure 4 to Figure 6 show the daily, monthly, and inter-annual averaged daily variation of the solar Irradiance. Figure 4(a) shows the daily solar irradiance at the site's coordinates. The daily strongest irradiance happens around noon, which matches the daily consumption pattern of the faculty of engineering. This maximizes the benefit of this a grid-connected system. Figure 4(b) shows the sun's path on the horizon in Summer and Winter, typical for northern-hemisphere installations. Figure 5(a) shows the monthly averaged solar irradiance at the site. The strongest solar radiation occurs during the summer months (Jun-Aug). Again, this matches the increased demand in summer months due to the high cooling load demand required in summer months. Figure 5(b) shows the inter-annual variation of solar irradiance in the period 2010-2020. This historical solar irradiance pattern ensures future fixed performance and reduces the system's uncertainty, as will be shown later.



(a) (b)

Fig. 4. Site Solar Resource (a) Daily Irradiance Profile (b) Outline of Horizon [44]



(a) (b)

Fig. 5. (a) Site Monthly Solar Irradiance (b) Inter-annual Solar Irradiation Estimates (2010-2020) [44]

2.3 Site Electricity Demand

The purpose of the installation of the PV system is to cover part of the electricity demand of the school of engineering. Figure 6 shows the electricity payments for the previous year.

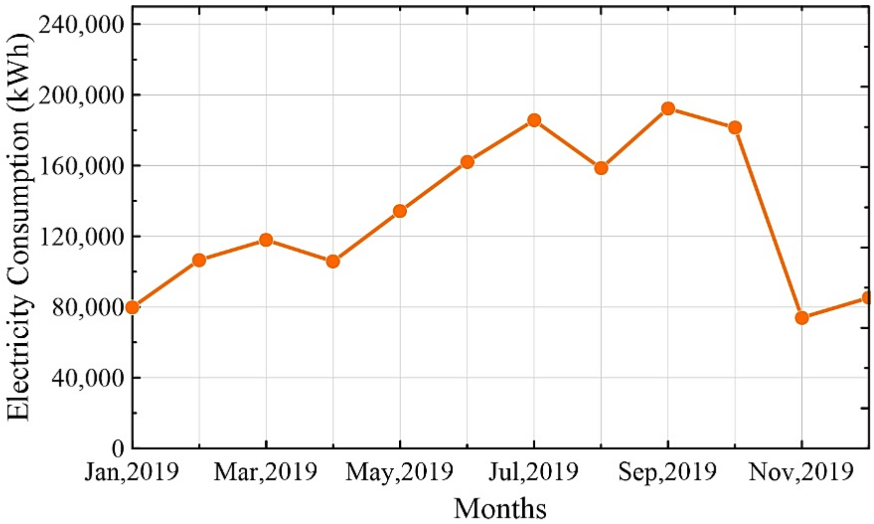


Fig. 6. Consumption of the Engineering School (meter readings)

3. Detailed PV System Modeling

3.1 Technical Parameters

This section covers information about the technical parameters of PV systems those, are the effect of ambient temperature, annual production to the grid, Yield Factor, and Capacity Factor.

3.1.1 Effect of temperature

It is important to study the effect of ambient temperature on the performance of PV systems. As the temperature rises, the output of the PV system decreases due to the impact of temperature on the solar cell's efficiency. High temperatures can cause the solar cells to operate at a lower efficiency level, which can result in a reduced amount of energy being produced. Therefore, it is important to consider the impact of temperature when designing and installing a PV system. The Mean ambient temperature gets from the following Eq. (1) [45,46].

$$T_c = \frac{NOCT * G_t}{800} + T_a \tag{1}$$

where NOCT: Nominal operating cell temperature, $\mathrm{G_t}$: Average daily solar radiation $\mathrm{G_t} = \mathrm{H}/7$, H: Solar radiation (kWh / m^2), and $\mathrm{T_a}$: average air temperature.

The corrected PV module efficiency can be calculated as the Eq. (2):

$$\eta_m = \eta_r \left[1 - \mu \left(T_c - T_r \right)\right] \tag{2}$$

where η_r: Reference efficiency, T_r: Reference temperature, μ : Temperature coefficient, T_c: Mean ambient temperature. Some researchers integrated the PV panel in a cooling loop to reduce the impact of temperature of the module efficiency [47].

3.1.2 Annual production of a PV system

The annual production is a critical parameter that determines the generated electric energy from the PV system. The annual production depends on various factors such as the size of the PV system, the efficiency of the solar cells, and the amount of sunlight received by the system. Accurately estimating the annual production is important in determining the effectiveness and profitability of the system. The performance ratio and the total annual production of a PV system can be calculated as follows [45,46]:

$$PR = \eta_e (1 - Lm)(1 - Lc) * (1 - L_s) \quad (3)$$

$$E_g = \eta_m * PR * A * H \quad (4)$$

Where PR: system performance ratio, η_e : inverter efficiency, Lm: Panel capture losses, Lc: Soiling losses, E_g: annual generation (kWh), Ls: System losses, η_m: Corrected PV Module Efficiency, A: Area of PV Modules (m^2), H: Solar radiation (kWh / m^2).

The yield factor and the capacity factor of the PV system is expressed as follows [48].

$$YF = \frac{E_g}{PV\ Capacity\ (kWp)} \quad (5)$$

$$CF = \frac{YF}{8760} \quad (6)$$

3.2 System Advisor Model (SAM)

The following section outlines the step-by-step design process of the system. The design and optimization of the PV system are carried out using System Advisor Model (SAM), a software tool that enables the selection of suitable modules, inverters, and configurations that best match the site conditions and maximize the system's output while minimizing costs [49]. Furthermore, an uncertainty analysis is conducted to examine potential variations in the system's output throughout its lifespan.

3.3 Solar Resources and Weather Data

All the required data for the PV system simulation has been downloaded from PVGIS as recommended by SAM software [44]. The data is related to Lat:30.586 Long:31.483 which is our location’s coordinates for the period 2010 – 2020. More accurate commercial and creditable data sources will result in more accurate simulations.

3.4 PV System Optimization

To ensure the PV system is optimized for the chosen site, a three-step process is employed. The first step involves the selection of appropriate modules and inverters that are best suited for the site's characteristics. This step takes into account factors such as the available sunlight, temperature, and wind conditions to determine which module and inverter combination will provide optimal performance and efficiency. The second step involves the selection of an appropriate tracking system and mounting configuration. This step considers the orientation of the modules relative to the sun and the positioning of the tracking system to maximize energy production. The mounting configuration must also be designed to withstand the environmental conditions of the site, such as wind, rain, and snow. The final step in the optimization process is the DC-AC ratio optimization. This step involves determining the optimal ratio of DC to AC power output to maximize the system's efficiency. The DC-AC ratio is influenced by various factors such as module efficiency, inverter efficiency, and the site's climate conditions. By performing these three steps, the PV system can be optimized to provide the maximum energy yield for the selected site while minimizing costs.

3.4.1 PV modules and inverters

The process of selecting the most appropriate PV module for the system involves several steps. Firstly, a range of PV modules are nominated and evaluated based on their power output, efficiency, and temperature coefficient. This evaluation is carried out using System Advisor Model (SAM 2018) [49]. SAM's parametric optimizer then searches through its extensive database of inverters to identify the best match for the selected PV modules that are available in the local market. The inverter selection is based on the best module that yields the highest capacity factor, which is a measure of the module's ability to convert sunlight into electricity. By selecting the optimal combination of PV module and inverter, the system can be designed to achieve maximum energy output and efficiency, while also taking into account the specific characteristics of the site and environmental factors. The key specifications for the simulated module are presented in Table 1.

Table 1
Specifications of the module used in the proposed simulation

Module	Nominal Power	Power Tolerance	Efficiency	Vmpp	Impp	Voc	Isc
	[W]	[%]	[%]	[V]	[A]	[V]	[A]
SUNTECH STP435S-B72/Vnh	435	5	20	40.8	10.67	48.6	11.4

The purpose of this study is to implement a PV system that will provide renewable energy to six buildings associated with the Faculty of Engineering at Zagazig University. To achieve this, the PV system will be divided into six separate sections, one for each building. The design will require the installation of six inverters, with three having a maximum capacity of 20 kWp and the remaining three with a maximum capacity of 15 kWp. The specifications of the two selected inverter models are shown in Table 2. Figure 7 showcases a real representation of the installed inverter and module, along with their respective nameplates.

Table 2
Specifications of the inverter used in the proposed simulation

Model	Max input power	Max input voltage	MPPT voltage range	Max input current	Max SC current	MPP trackers	Efficiency
	[kWpk]	[V]	[V]	[A]	[A]		[%]
SUNGROW SG20KTL-M	20	1000	480-850	44	60	2	98.3
SUNGROW SG15KTL-M	15	1000	380-850	44	60	2	98.3

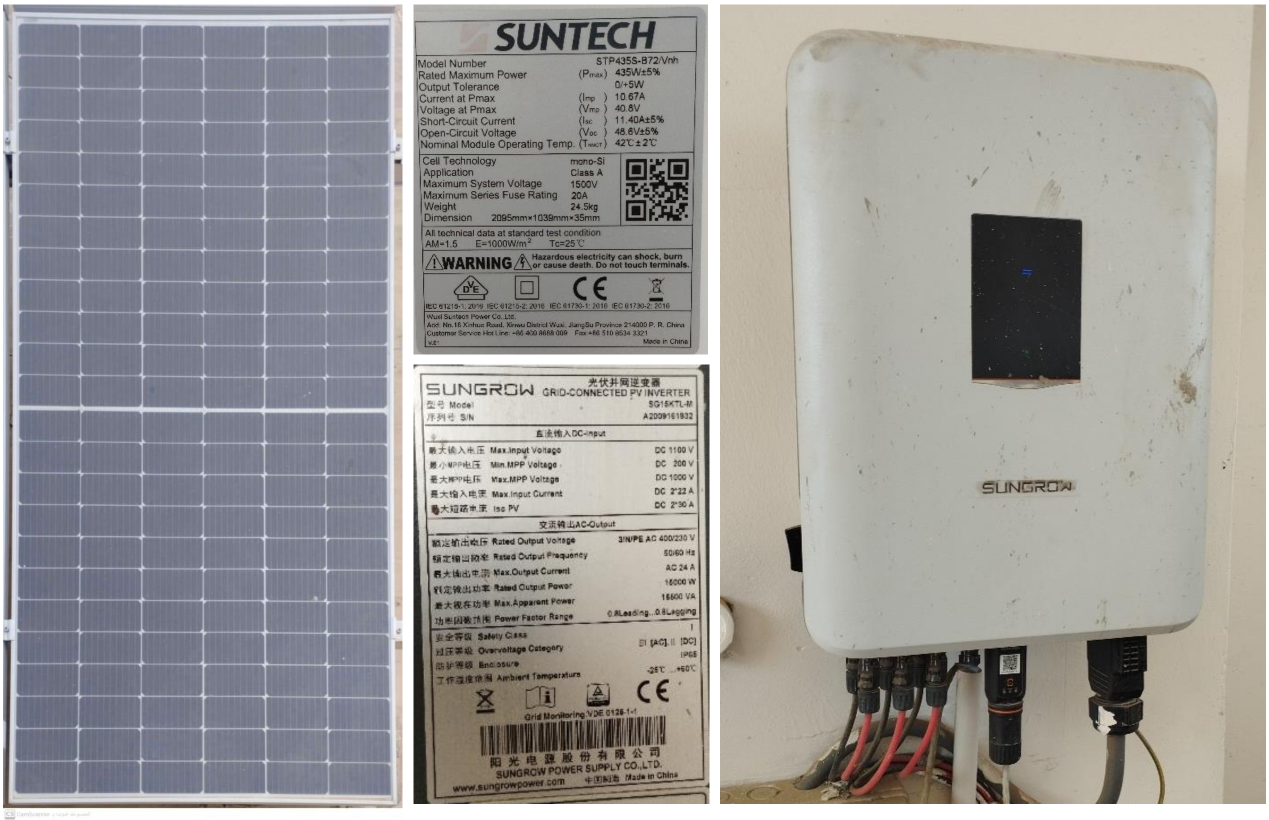
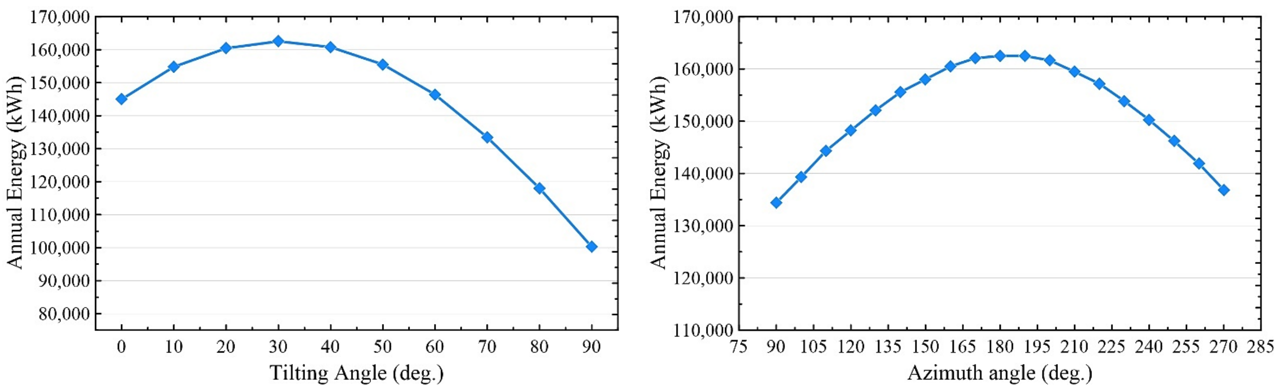


Fig. 7. Actual installed inverter and module and their nameplate

3.4.2 Tracking system

PV tracking systems are a type of technology used to optimize the PV system's performance by aligning the panels to the sun throughout the day. There are three options for the tracking system: Fixed tilt, 1-Axis tracking and 2-Axis tracking. The fixed tilt PV system is considered for these plants. Using SAM's parametric simulation, the PV system is designed and optimized to achieve higher output/ capacity factor. To avoid an increase in initial cost as well as adding O&M costs, a fixed array is to be used. Figure 8 obtained from SAM parametric simulation- show the effect of module tilt and azimuth angles on the electricity produced from 75kW PV array.



(a) (b)

Fig. 8. The effect of (a) Tilt angle (b) Azimuth angle on the production of 75 kW PV array

Optimum row spacing between subarrays is calculated based on a solar window from 9:00AM to 3:00 PM on December 21st (winter solstice). The minimum row spacing is calculated when azimuth angle is considered. Increasing the spacing will increase the generated power. These row spacings are function of the subarray dimensions used in this proposal, if any change occurs in the subarray, spacings will change. For this purpose, the online sun path chart program provided by the University of Oregon is used. Figure 9 shows the Sun path diagram for Zagazig University.

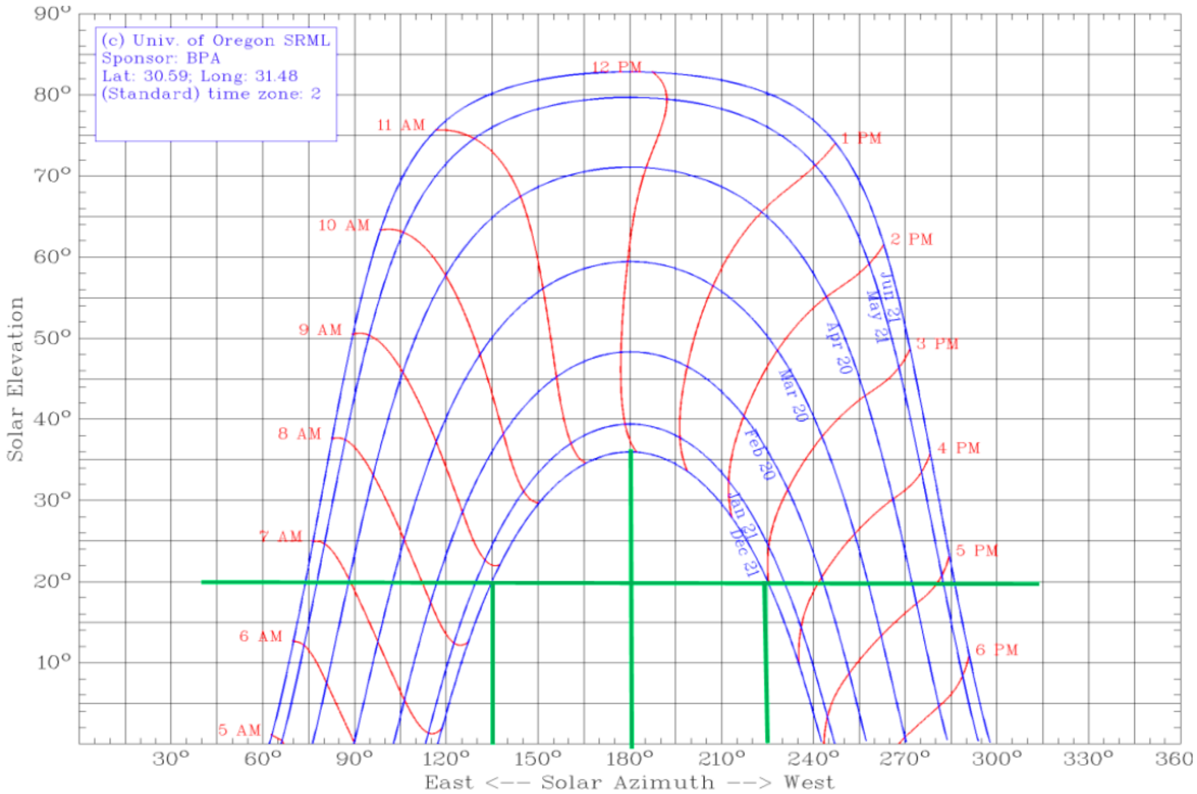


Fig. 9. Sun path diagram for Zagazig University which is generated from University of Oregon online tool [50]

3.4.3 DC-AC ratio optimization

After the selection of module and the system configuration, it is important to determine how much the system should be oversized to get a certain AC capacity. The system must be oversized by a certain ratio because the modules don't produce their rated power unless they are operating at standard conditions (Temperature 25 °C and Irradiance 1000W/m^2). Thus, the system needs to be oversized to get the required power. For oversized systems, we will gain power from the additional PV modules and lose power clipped by the inverter. We can observe this from the LCOE which will be quite constant until a certain DC/AC ratio is reached, then it will start to increase rapidly. This is because after this point we will add more investment, but we will get less power (money) in return. We should oversize until this point. SAM's parametric simulation is used and both annual energy and LCOE will be used to determine the optimum DC/AC ratio. DC/AC Ratio is selected based on SAM parametric simulation. Oversizing the system produces more energy. However, the energy gain to installed capacity is reduced after a 1.2 ratio, having a negative effect on both the capacity factor and project economics as shown in Figure 10. Also, it was found that beyond the optimum DC/AC ratio of 1.2, the LCoE significantly increases without significant increase in the system output.

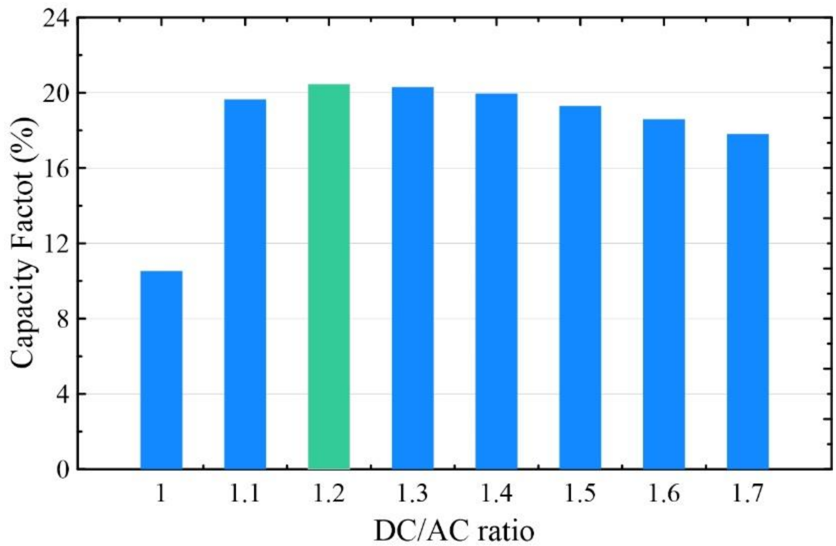


Fig. 10. DC/AC ratio effect on the capacity factor % of kW_{AC} PV system

3.5 System Design

System design step is where PV modules and inverters are arranged to best suit the specified site. The basic two parts of the system design are to make the AC sizing which represents the output of the system going to the grid and the DC sizing and configuration that represents the input side of the system.

3.5.1 AC and DC sizing

An easy way to size an AC system is to let SAM estimate the sub array configuration. All the inputs needed to be specified are the DC capacity and the DC-AC ratio. SAM then calculates the number of modules required to output such DC power. The number of modules in a string is then automatically calculated based on the inverter's rated voltage, and then it calculates the number of strings based on Eq. (7) as follows:

$$\text{No. of Strings} = \frac{\text{Total No.of Modules}}{\text{No.of Modules in a String}} \tag{7}$$

The AC capacity of the system is calculated based on Eq. (8) as follows:

$$\text{System AC capacity} = \frac{\text{System DC capcity}}{\text{DC−AC ratio}} \tag{8}$$

3.5.2 Shading and Ground Coverage Ratio (GCR)

GCR is the ratio of the PV system array area to the total ground area. It can be also expressed as the side length of a row divided by the bottom distance between two consecutive rows (row spacing). SAM's self-shading model estimates losses produced by shading of panels by other panels in neighboring rows based on the Ground Coverage Ratio specified. The next figure shows the length of the side, row spacing, and number of modules in the side and bottom of the row, see Figure 11.

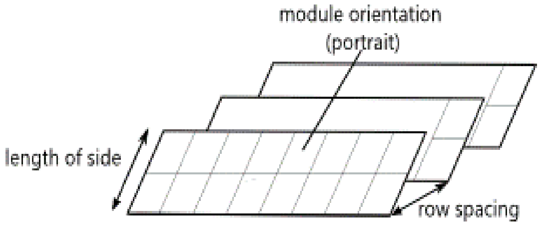


Fig. 11. Module layout parameters

3.5.3 Losses

There are several potential losses that can occur during the design of a photovoltaic (PV) system, including: Shading losses, Wiring losses, Inverter losses, Module mismatch losses, and Temperature losses. The default standing and shading models are used with the recommended tested value of losses. Table 3 shows typical values of these input losses.

Table 3
Typical values of input losses

Shading losses (%)	3
Soiling losses (%)	2
Mismatch losses (%)	2
Wiring losses (%)	2
Connections (%)	0.5
Light-Induced Degradation (%)	1.5
Nameplate Rating (%):	1
Availability (%):	3

Figure 12 shows the monthly production from the system analyzed using the SAM (System Advisor Model) software. The system exhibits varying energy production levels throughout the year, with higher outputs during the summer months and relatively lower outputs during the winter months. The capacity factor, which represents the actual energy output as a percentage of the maximum possible output, is presented monthly in Figure 12(a) as an indication of the plant's operational efficiency. The figure illustrates that the capacity factor varies from 15.5% to 21.5%, indicating consistent and reliable energy generation. Additionally, Figure 12(b) shows the distribution of losses within the PV system such as shading, module soiling, and system inefficiencies. By analyzing and addressing these loss factors, the PV plant can optimize its overall performance and maximize energy production.

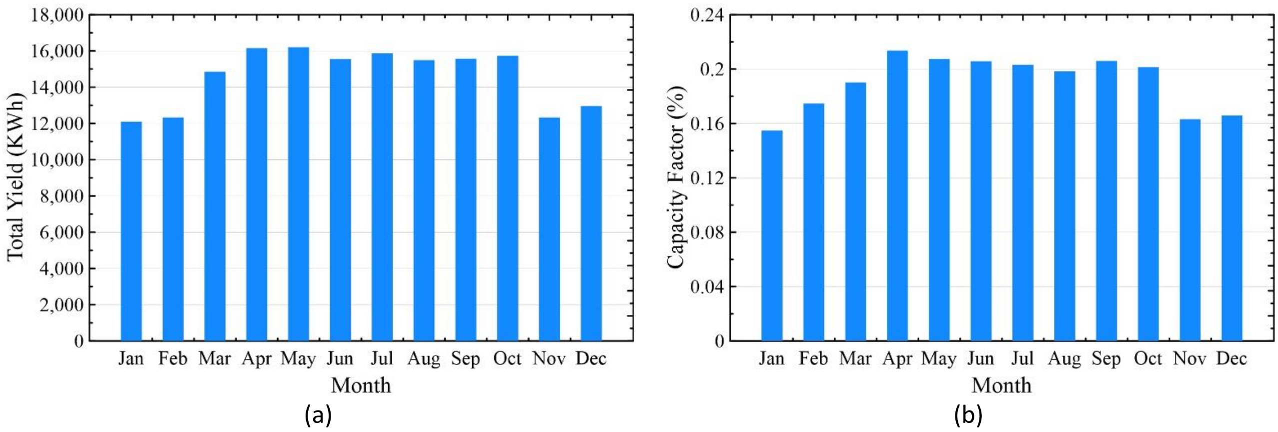


Fig. 12. Monthly (a) energy yield and (b) Capacity factor of the considered PV system

Figure 13 depicts the loss diagram generated using the SAM for the overall PV system. The losses are categorized in the sequence of their occurrence, commencing with optical losses at the plane-of-array (POA) and concluding with AC losses. In our specific PV system, the most significant source of loss was attributed to module deviation from standard test conditions (STC), which encompasses the impact of module temperature. Following this, the subsequent major losses, in order, were soiling, wiring, availability, and inverter efficiency loss, and the cumulative energy loss amounted to 30.32%. These findings serve as a valuable resource for evaluating the economic considerations associated with PV system design.

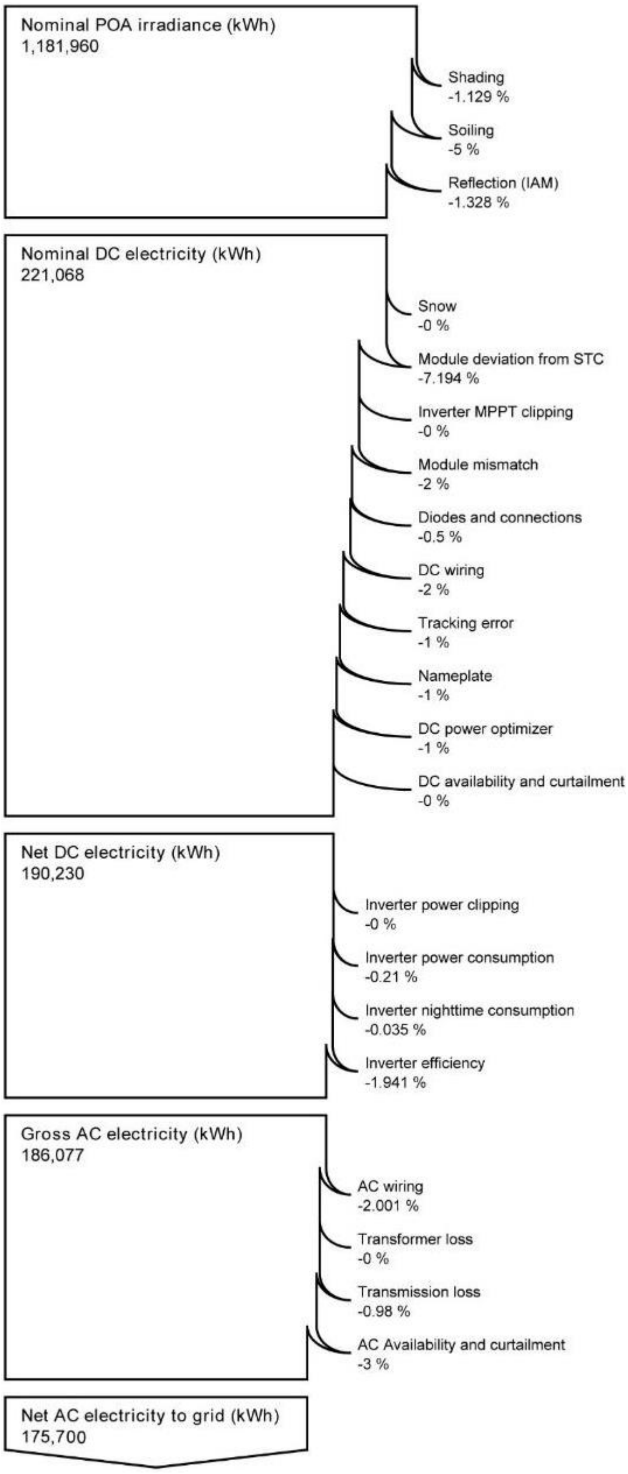


Fig. 13. Losses distribution

4. Financial Model and Feasibility Study

It is crucial to conduct a comprehensive financial model and feasibility study to understand the financial implications and practicality of such rooftop solar systems. A financial model is a forecasting tool that considers various factors such as initial investment, operating costs, revenue streams, and financing options to determine the financial viability of a project. In the context of a rooftop PV system, a financial model can help estimate the payback period, return on investment, and net present value of the project. Meanwhile, a feasibility study assesses the technical, environmental, and economic factors that may affect the success of the project. For a rooftop PV system, a feasibility study would evaluate factors such as roof size and orientation, availability of sunlight, local regulations and incentives, and potential impacts on the building's structural integrity. The combination of a financial model and feasibility study provides a comprehensive analysis of the costs, benefits, and risks associated with a rooftop PV system. This information is crucial for making informed decisions about investing in such projects and developing a feasible plan for their implementation.

4.1 Economic Parameters

Internal Rate of Return (IRR) and Net Present Value (NPV) are important measures of the profitability and financial feasibility of a photovoltaic (PV) system.

4.1.1 Net Present Value (NPV)

NPV is the difference between the present values of cash inflows and outflows over a specific time period. In the case of a PV system, the NPV is calculated by estimating the costs associated with installing and operating the system and the revenue generated by the system over its lifetime. The cash inflows include the revenue of exporting surplus electricity to the grid, while the cash outflows include the installation and operation costs of the system, including maintenance costs and parts replacement costs. A system is profitable if its net present value (NPV) is positive; otherwise, it is unprofitable. NPV is calculated using Eq. (9) [48,51,52]

$$NPV = \sum_{t=0}^{N} \frac{(Cash\ flow)t}{(1+i)^t} \tag{9}$$

4.1.2 Internal Rate of Return (IRR)

IRR is the discount rate at which the net present value is zero. In the case of a PV system, the IRR is calculated by estimating the costs associated with installing and operating the system and the revenue generated by the system over its lifetime. SAM software provides the IRR value based on the above-mentioned parameters and also, IRR tool in Excel or other software can be used to determine the IRR of an investment.

4.1.3 Life Cycle Cost (LCC)

LCC of a PV system is the total cost of owning and operating the system over its entire lifetime. The LCC includes the initial installation costs, maintenance costs, replacement costs, salvage costs, and any other costs associated with the system. The LCC is an important parameter to estimate the cost-effectiveness of the system over its lifetime. LCC is calculated using Eq. (10) [48,52]

$$LCC = Capital\ Cost + \sum C_{O\&M} + \sum C_{replacement} - C_{salvages} \tag{10}$$

4.1.4 Levelized Cost of Energy (LCOE)

LCOE is the unit of electricity cost as generated from the PV system. The LCOE is calculated by dividing the LCC by the total energy produced by the system over its lifetime. To calculate the LCOE, use equation. LCOE is calculated using Eq. (11) [48].

$$LCOE(real) = \frac{-Co - \frac{\sum_{n=1}^{N} Cn}{(1+d_{nominal})^{n}}}{\frac{\sum_{n=1}^{N} Qn}{(1+d_{real})^{n}}} \tag{11}$$

where Co represents the plant's equity investment in dollars, Cn represents the project's cost in n years, d_{real} represents the real discount rate in percentages, $d_{nominal}$ represents the nominal discount rate in percentages (i.e., the discount rate with inflation), N represents the analysis period in years, and Qn represents the amount of electricity generated by the plant in year in (kWh). Nominal Discount Rate is calculated using Eq. (12) [48]

$$NominalDiscountRate = \left[\left(1 + \frac{RealDiscountRate}{100}\right) \times \left(1 + \frac{InfilationRate}{100}\right) - 1\right] \times 100 \tag{12}$$

4.2 Techno-Economic Results

Table 4 presents the system design data for overall PV system including technical inputs and outputs in addition to economic inputs and indicators.

Table 4
Techno-Economic Inputs and Financial Indicators

System design	
No. of PV panels	242
Panel Capacity	435 W
PV System Capacity	105.270 KW
Technical Outputs	
Annual Production	175,700 kWh
Capacity factor	19.1 %
Annual CO_2 Reduction	78871.7 kg
Economic Inputs	
Capital Investment	1,158,465
Project Lifetime	25 years
Electricity Cost	1.15 EGP/kWh
deterioration rate	0.5 %
Annual maintenance cost	2.5 %
Annual material cost	5 %
Discount Rate	9 %
Inflation rate	7 %
Electricity Escalation Rate	5 %
Maintenance Price Index	1 %
Material Price Index	1 %
Economic Indicators	
Annual Savings	202,034 EGP/yr
Simple Pay-back Period	6.6 years
Discounted Pay-back Period	7.9 years
LCOE	0.55 EGP/kWh
NPV	1,571,171 EGP
IRR	20.06 %

Figure 14 and 15 illustrate the annual cash flow and the discounted cumulative cash flow over the project lifetime. From both figures, one can notice the value of the simple and discounted payback periods, respectively.

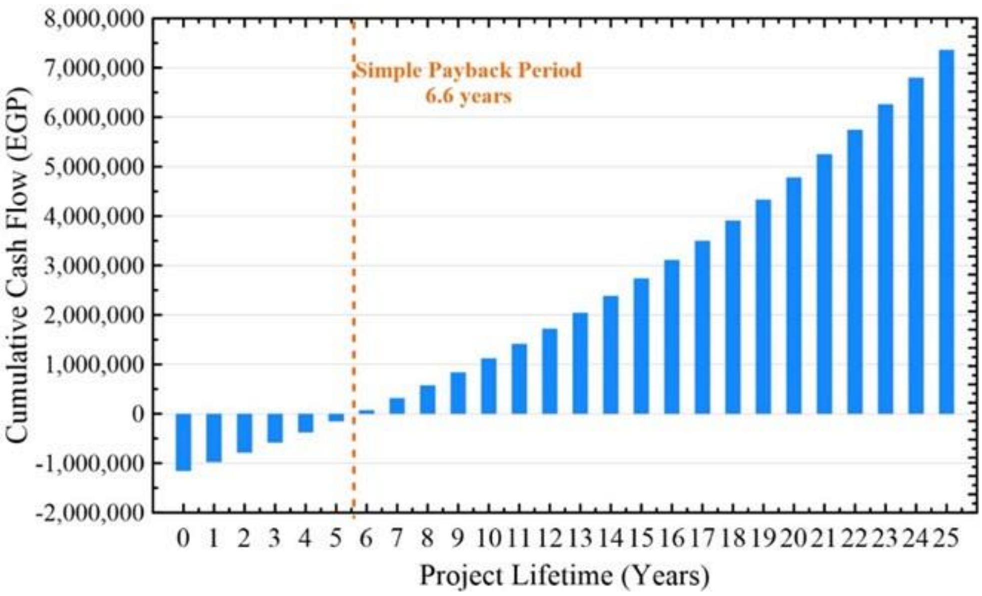


Fig. 14. Annual cumulative cash flow

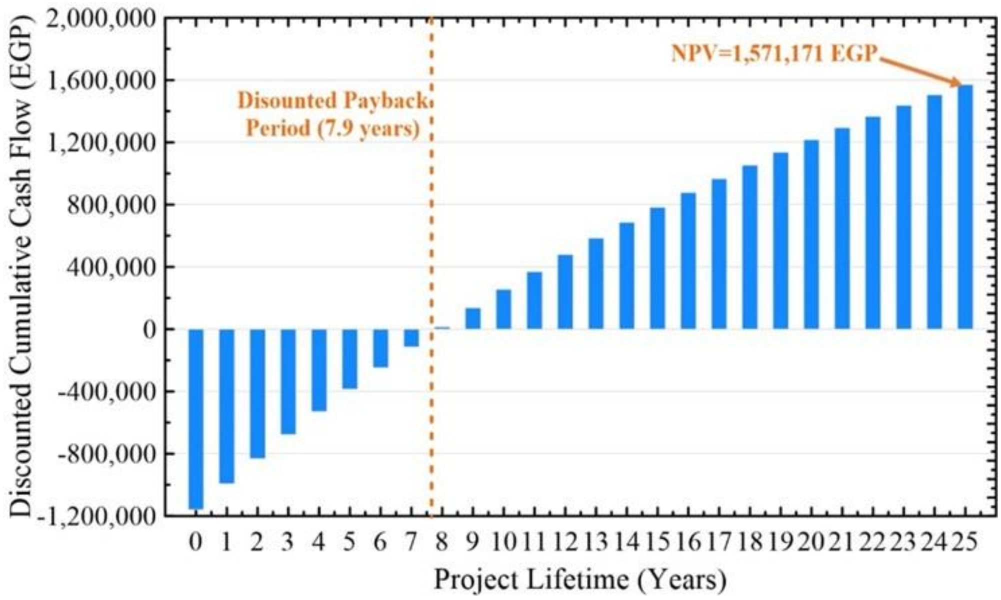


Fig. 15. Annual discounted cumulative cash flow

Given that the project has obtained financial funding by Industry Modernization Center [53] equivalent to 50% of the total project cost, with the university institution shouldering the remaining half, it greatly enhances the economic viability. As an illustration, the provided support has effectively reduced the discounted payback period to a mere 4.6 years, compared to the initial 7.9 years. Furthermore, it has successfully lowered the levelized cost of electricity (LCOE) to approximately 0.28 EGP/kWh, as opposed to the previous 0.55 EGP/kWh. This underscores the paramount significance of financial support in bolstering small-scale projects.

4.3 Sensitivity Analysis

Sensitivity analysis can be used to identify the key drivers of the LCOE and their impact on the overall energy cost. By conducting a sensitivity analysis on discount rate and the electricity escalation rate, we gain a better understanding of their impact on the LCOE and identify the level at which they become significant cost drivers. This information can help to make more informed decisions about the feasibility and cost-effectiveness of the project and can ultimately contribute to the development of a more sustainable and affordable energy system. Table 5 and Figure 16 show the effect of changing the discount rate and electricity escalation rate on LCOE. Since the grid electricity cost is 1.15 EGP/kWh, any LCOE above this value does not achieve the grid parity and the project will not be financially attractive at these values of LCOE as marked red in Table 6.

Table 5
Sensitivity analysis of changing the discount rate and electricity escalation rate on LCOE

		Discount rate (%)						
		9	10	11	12	13	14	15
Electricity Escalation Rate (%)	0	0.89	0.96	1.02	1.09	1.16	1.23	1.31
	1	0.81	0.88	0.94	1.00	1.06	1.13	1.20
	2	0.74	0.80	0.86	0.91	0.97	1.03	1.09
	3	0.68	0.73	0.78	0.83	0.88	0.94	0.99
	4	0.61	0.66	0.71	0.75	0.80	0.85	0.90
	5	0.55	0.60	0.64	0.68	0.72	0.77	0.81

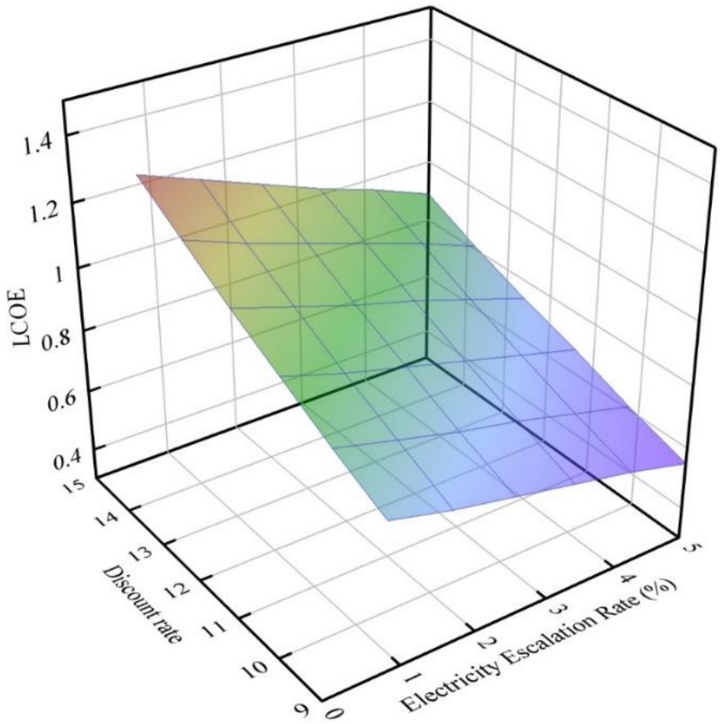


Fig. 16. Sensitivity of LCOE to changes in the discount rate and the electricity escalation rate

5. Environmental Impact [CO_2 Reduction]

By reducing CO_2 emissions, we can help to slow down or reverse the negative impacts of climate change. Considering the current generation mix in Egypt (85% Natural Gas, 15% heavy oil), the grid emission factor is estimated as 0.4489 kg CO_2/kWh [54]. The annual CO_2 avoided is calculated as follows:

$$CO_2\ Reduction\ = E_g \times 0.4489 \tag{13}$$

The total amount of CO_2 reduction over the project's 25-year lifetime is estimated to be 1882.3 Ton of CO_2 taking into consideration the PV system deterioration rate.

6. System Installation and Performance Evaluation

6.1 Overview

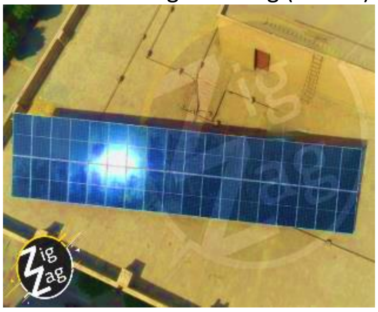
Figure 17 is taken by a drone flying over the installation sites of the system and it shows the six buildings with the rooftop PV panels. The system is installed above six engineering buildings, namely: Basic science, mechanical engineering, civil engineering, electrical engineering, architectural engineering, and workshop buildings. Figure 17 also shows the assigned installed capacity for each building.


Basic Science building (20 kW)


Mechanical Eng. Building (20 kW)


Civil Eng. Building (20 kW)


Electrical Eng. Building (15 kW)


Architecture Eng. Building (15 kW)


Workshop Building (15 kW)

Fig. 17. Installed PV System on Six Buildings of the Faculty of Engineering

6.2 Performance Evaluation

The system was commissioned and installed by SES, Inc. in October 2021 and it started actual operation by the end of November on the same year [55]. An online monitoring portal, proposed by SUNGREW, have been utilized in order to monitor system performance remotely as shown in Figure 18 [56]. Figure 19(a) Compares the actual energy production (kWh), as read from the online monitoring portal, compared to the theoretical production calculated by SAM, for the first year of operation (2022). It is manifest that the performance was close to the prediction in the first two months of operation with differences 4.2% and 4%, respectively. The performance started to have large variances later with worst performance in May 2022 (around 36% off-design) followed by July 2022 (19% off-design). It is speculated that the deviation comes from two sources, the dust accumulation over the panels and the interruptions in supply due to the system disconnections. In order to better understand and analyze the performance, the individual building's performance is analyzed in Figure 19(b) and in Table 6. Table 6 and Figure 19(b) show the commutative production from each building in the period (Jan 2022 – Dec. 2022) compared to the theoretical simulated cumulative yield. The civil engineering building's system showed the worst performance (38.6% off-design) followed by the workshop building over the monitored year.

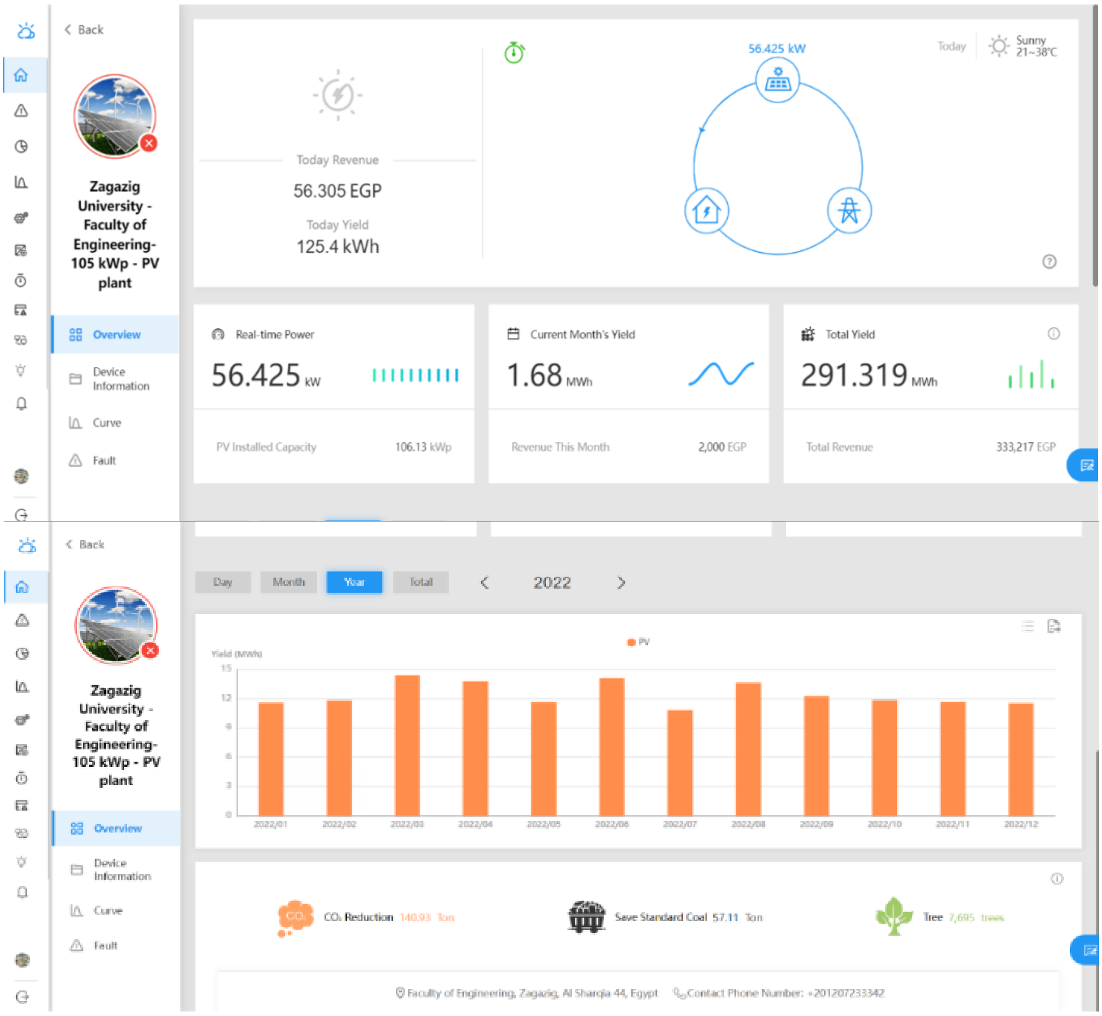


Fig. 18. Online monitoring portal [56]

Table 6
Commutative Production from each building (Jan 2022 – Dec 2022)

	Capacity (kW)	Annual Theoretical Yield (kWh)	Annual Actual Yield (kWh)	Diff. (off-design) %
Basic science	20	32652.5	30868.7	5.4%
Mechanical	20	32652.5	30816.7	5.6%
Civil	20	32652.5	23479.3	38.6%
Architecture	15	25922.8	25375.1	1.8%
Electrical	15	25922.8	24705.0	4.6%
Workshop	15	25922.8	22549.1	14.6%
Overall System	105	175725.8	157793.9	11.2 %

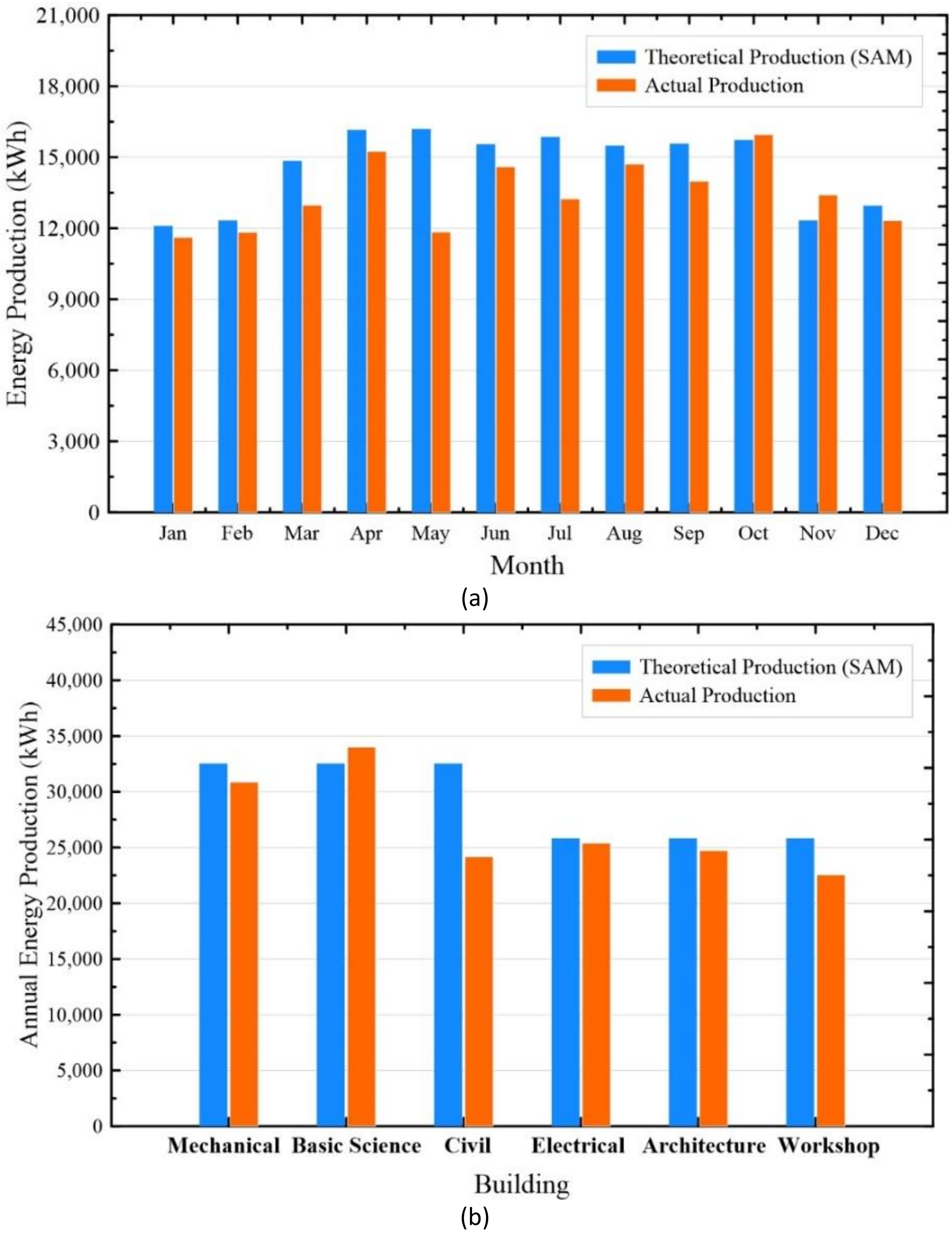


Fig. 19. Annual Performance of the Pilot 105 kW system (Jan 2022 – Dec. 2022)
(a) Month-by-month, (b) Commutative Production from each building

Figure 20 shows the individual buildings' performance month-by-month to accurately pin the reasons, locations, and periods of losses. The figure clearly shows a clear decline in Civil Engineering's system in April 2022, followed by workshops' systems in July 2022 and Basic science system in September and October 2022. By investigating the system performance log, it was discovered that Civil's system was disconnected in April 2022 for 14 days. In addition, all systems were disconnected in May for almost 8 days, due to national holidays. The workshop's system suffers 50% reduction in performance in June and July due to similar disconnections and dust accumulation (far and less used building). The overall system is also disconnected in July 2022 for a continues week during a national holiday. The basic science's system suffers from a 40% to 45% reduction in performance in September and October, respectively due to the disconnections resulting from a technical failure which took about a month to be fixed.

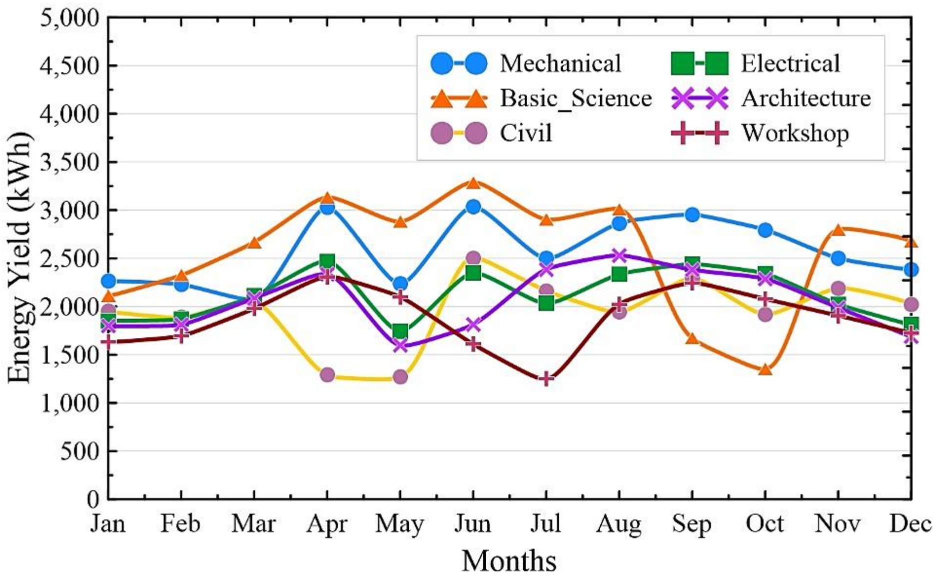


Fig. 20. Monthly Individual Building Performance for the year 2022

Overall, the system did fairly well in the first year of operation with an overall production of 157793.9 kWh. This saves the University 181,463 EGP bill payment annually and with additional annual CO_2 avoided of 70.8 ton. Unfortunately, 20,622 kWh was lost during this period partially due to system unintentional disconnections (45 %) and partially due to the deviation from optimum conditions (dust accumulation, other miscellaneous loss sources). The projected performance for the first year is outlined in Table 7 below. If correction measures were taken to prevent unintentional system disconnections, the capacity factor would increase to 18% and the system annual production would be 94.3% from the theoretical design conditions (165,640 kWh) as shown in the last column in Table 7.

Table 7
Projected Annual Yield of the 105 kW PV System

	THEORETICAL (SAM)	ACTUAL (SAME STATUS) *	ACTUAL (NO DISCONNECTIONS) **
Annual Yield (kWh)	175,700	157,793.9	165,640
Capacity Factor (%)	19.1%	17.2%	18.0%
CO_2 Reduction (Ton)	78.9	70.8	74.4
Revenue (EGP)	202,085	181,463	190,486
Energy Losses (kWh)	-	20,622	11,599
% Annual Target (Theoretical)	-	89.8%	94.3%

*Actual annual yield from the system.
**Estimated annual yield if system disconnection were avoided.

Based on the monitoring and running experience, the following recommendations help to improve the system's performance:

i. The issue of disconnecting the buildings' energy during the holidays must be considered. Separate switches must be specified to the PV system away from the normal building circuitry.
ii. Continuous cleaning of solar cells improves system efficiency (at least once a week). The instances where the system was cleaned yielded the theoretical design energy output.
iii. Monitor the system performance, continuously, in order to solve issues as they emerge.
iv. Avoid interruptions to the internet connection to be aware of the system's status.

7. Conclusions and Future Work

A 105 kWp pilot solar PV system was designed, operated, and monitored at the faculty of engineering, Zagazig University. The system is grid-connected and is designed to partially cover the electric demand of the engineering school at ZU. A full detailed design was performed which showed that the system is capable of producing 175,700 kWh per year with an annual capacity factor of 19.1 %. A full monitoring report on the first year of operation of the system showed that the system performed fairly well compared to the theoretical design. Financial analysis showed that the project is profitable with a discounted payback period of 7.9 years and LCOE of 0.55 EGP/kWh with no subsidy. Sensitivity analysis showed that the LCOE is very sensitive to electricity escalation rate and discount rate. In addition to the financial benefits, the project saves 1882.3 tons CO_2 emissions through its 25-year lifetime. The following few conclusions may be drawn from the current results:

i. Under the Egyptian solar resource and financial status, the current rooftop PV system seems feasible and financially attractive, even without any subsidies. Subsidies will greatly enhance the economics.
ii. Fortunately, designing and assessment of rooftop PV systems is made possible thanks to the publicly available professional software packages. The current project was designed using the professional software package SAM which is freely provided by NERL.
iii. Performance monitoring is very important to evaluate the system's performance and to solve issues as they emerge to ensure the maximum possible recovered energy.
iv. Cleaning of the system (at least once a week) is crucial to achieve the theoretical yield and maximize the financial gain. In fact, with cleaning, the system may perform better than the theoretical prediction.
v. The acquired system's running experience will ensure the sustainability and operability of the PV system during the 25-year lifetime of the project.

Regarding the future work, there is a great need to solve the dust accumulation problem as it greatly degrades the system performance. A Solar Panel Automated Cleaning (SPAC) System is under investigation to be implemented in the cleaning process.

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