

Article

Experimental and Techno-Economic Analysis of Solar PV System for Sustainable Building and Greenhouse Gas Emission Mitigation in Harsh Climate: A Case Study of Aswan Educational Building

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Abstract: Climate change is a global issue that requires collective action to address. One of the most pressing concerns is reducing emissions resulting from combustion processes. The use of renewable energy sources and green energy has become a trend worldwide. Solar energy is one of the most promising sources due to its abundance and simplicity of implementation. The city of Aswan, located in the South of Egypt, has a high solar radiation that makes it ideal for utilizing solar power. The current study investigates the optimal design for a sustainable building electricity system at the Aswan Campus of the Arab Academy for Science, Technology & Maritime Transport (AASTMT) in Egypt. The campus has four electricity sources: a utility grid, PV panels, batteries, and a diesel generator, along with a weather station. Experimental investigations have been carried out in this research paper to study the performance characteristics of solar power. Moreover, HOMER pro software is used to model various configurations of the campus grid, including different photovoltaic (PV) panel types and tracking systems. The simulations are compared with real-world data collected from a weather station on campus. Additionally, CO₂ and NO₂ emissions are measured to assess the environmental impact of different scenarios. The total net cost over the life cycle is also calculated for different cases. The results demonstrate that the addition of a PV renewable system can reduce traditional grid usage by 38% and emissions by 50%. A decrease in the Levelized Cost of Energy (LOCE) from USD 0.0647 to USD 0.0535 is reported. Moreover, the difference in NCP cost between dual-axis tracking and fixed zero angle is USD 143,488. The dual degree tracker for PV panels can further enhance energy production by 30% more, compared with fixed panels, while reducing carbon dioxide emissions by more than 20%. The simulation results reveal that tracking systems provide greater energy generation, and that a cost–benefit analysis may prioritize fixed panels in some cases. The results from the HOMER software simulations closely match those of the experimental data, which is that the total presentation error does not exceed 8%, demonstrating the software’s effectiveness for optimizing renewable energy systems. This study demonstrates that a comprehensive analysis and optimization of a building’s energy sources can significantly reduce costs, lower emissions, and promote the use of renewable energy, particularly solar power.



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Keywords: experimental model; tracking system; solar energy; environmental sustainability; renewable energy

1. Introduction

1.1. Background and Motivation

Based on the study of policy, regulations, and practical implementation issues, the Egyptian Government supports large-scale projects, such as Fares and Banban, which are two of the largest solar energy plants in the Middle East. Apart from employing tactics, like financial rewards, public awareness drives, and technical support to surmount obstacles, the government hopes to encourage the use of renewable energy, improve energy stability, and lower carbon emissions in the area [1].

Building Applied Photovoltaic (BAPV), such as Solar PV, has received a lot of interest in recent years as a way to use renewable energy sources to their fullest potential. In a heavily populated urban residential neighborhood, however, there is not enough space for photovoltaics, and they can get in the way of the sun [2]. To meet the energy needs of urban economies and make communities sustainable, new ideas are needed. The most important trend in Net-Zero Energy Buildings (NZEBS) that are good for sustainable growth is the use of renewable energy systems. Standalone combination solar photovoltaic/thermal (PV/T) systems are highly sought after in the building industry due to their reliable electricity generation capabilities [3]. There is a need for a detailed study to understand if it is practical and reasonable to add renewable energy to the current energy system to support sustainable development [4].

In recent decades, global population growth, economic expansion, and fast industrialization have all led to significant rises in building energy consumption costs. The energy consumption of residential and commercial buildings is around 20–40% of the overall energy usage [2]. Heating, ventilation, and air conditioning (HVAC) account for the majority of the overall energy used in buildings. An HVAC system typically represents approximately 40% of the overall energy usage in a building [3]. Hence, it is important to alleviate the environmental issues stemming from the now used energy sources. There is an urgent need for dependable, environmentally friendly, and renewable energy sources. Near-zero-energy buildings offer a possible way to address these concerns. Constructing structures in severe climates, such as hot and humid locations, sometimes requires a significant amount of energy, especially for air conditioning, because of the increased thermal load [5].

Energy is essential for the progress of nations. Fossil fuels have traditionally been the predominant energy source on Earth. Nevertheless, due to the rapid increase in population, higher standards of living, and the widespread adoption of energy-intensive activities in developed and developing countries, there has been a substantial burden on global energy consumption. Two primary problems have arisen from this trend: the exhaustion of easily accessible energy sources and the issue of global warming caused by the increasing escalation of greenhouse gas emissions, such as carbon dioxide and methane. The primary objective on a worldwide scale is to address the issue of climate change and global warming by implementing efficient and affordable sources of Renewable Energy (RE), which must be controlled and utilized in an effective manner [6].

Improving public health and environmental quality requires reducing emissions. This entails improving nearby air quality and reducing more significant environmental effects. Emission reduction does not only support climate change mitigation by curbing greenhouse gas emissions but also plays a significant role in informing policy decisions to promote sustainability and environmental protection. Emphasizing the importance of emission reductions across various sectors can bring about tangible benefits for the environment, air quality, and public health, fostering a more sustainable and healthier future for all stakeholders [7]. An ingenious approach to combatting air pollution is proposed through a comprehensive optimization strategy that considers multiple factors to enhance air quality, reduce emissions, and optimize power system dispatch effectively [8]. This innovative model plays a crucial role in environmental conservation by enabling precise predictions of PM_{2.5} concentrations, thus facilitating proactive measures to mitigate pollution levels. By

doing so, it not only enhances air quality but also mitigates health risks associated with poor air quality [9,10].

1.2. Literature Survey

1.2.1. Tracking Systems

When designing tracking systems for photovoltaic panels, the primary objective is to enable the panels to follow the sun's path throughout the day to maximize energy generation. There are two main varieties of tracking systems: single-axis and dual-axis. Single-axis systems have a single rotational axis, typically tracking the sun's movement along an East to West path. Dual-axis systems feature both a vertical and horizontal rotational axis, allowing for a more precise tracking of the sun's position. The fundamental principle behind tracking systems is to optimize the exposure of solar panels to sunlight, enhancing their energy generation capacity. By aligning the panels perpendicular to incoming sunlight through continuous tracking, the system can maximize the absorption of solar radiation [11].

Compared with fixed-tilt systems that maintain a constant angle, tracking systems can significantly increase energy production by dynamically adjusting the panel orientation throughout the day. However, this enhanced performance comes at the cost of requiring more mechanical components and regular maintenance to ensure optimal functionality. Tracking systems can be operated using various tracking algorithms, such as clock-driven, sensor-based, and astronomical methods. These algorithms determine how the panels adjust their position to track the sun accurately and efficiently. The overarching goal of designing and operating tracking systems is to enhance the efficiency of solar energy capture and increase the output of photovoltaic systems. By continuously optimizing the panels' alignment with the sun's position, tracking systems aim to maximize energy generation potential and improve overall system performance [11].

Renewable energy is a type of energy that is obtained from naturally existing and replenishable sources, such as sunshine, waves, rain, wind, and geothermal heat. Renewable energy sources supply power for generating electricity, as well as for heating and cooling air and water, and for transportation purposes [12]. Solar photovoltaic (PV) cells are the predominant means of turning sunlight into electrical energy. In order to achieve optimal efficiency, it is necessary to position PV cells in a perpendicular manner to the sun. Nevertheless, photovoltaic cells that lack mobility are not highly efficient because of the sun's motion. Utilizing a tracking device to follow the movement of the sun will optimize the collection of solar cell energy and enhance power generation [13].

Abundant sunlight in Aswan makes solar PV systems highly effective and efficient. However, Aswan's location and weather have no high-performance wind conditions suitable for wind energy generation. Geothermal Energy needs high initial investment costs and the need for geothermal resources may pose challenges [14].

Due to the low efficiency of photovoltaic modules and the resulting drop in electricity production, photovoltaic tracking systems have been a common area of study for many years. Research has shown that adding tracking systems to regular photovoltaic systems can improve their output by a large amount. There are three kinds of systems that have been made to make traditional PV systems work better: tracking PV systems, concentrating mirror PV (CPV) systems, and mixed PV/thermal (PV/T) systems. Each of these systems has its own special parts that can help make more electricity [15].

While each system has its advantages, no advanced system containing the properties of all three systems has been found in old research papers. However, researchers continue to explore new and innovative ways to combine the best features of each system to create a more efficient and cost-effective photovoltaic tracking system. To encourage the wider use and installation of solar tracking systems, it may be necessary to provide additional state subsidies. Traditional fixed systems are easier to set up and are more popular around the world. Solar tracking systems offer significant advantages that justify their cost. One notable advantage is that buildings can accommodate the installation of solar tracking

systems which outperform fixed photovoltaic systems that are impractical for residential installations.

Photovoltaic panels can collect solar energy throughout the year and day. Dual-axis systems make sure panels are always oriented to receive the most sunlight by tracking the sun's movement both vertically and horizontally. Although this dynamic adjustment increases energy production, it also increases expenses and complexity. Contrarily, fixed-angle systems have a static tilt and orientation, which makes design easier and requires less maintenance, however it is possible that they will not catch as much energy as dual-axis systems. The latitude of the site, the intended energy production, the amount of space available, financial restraints, and operational concerns all have a role in the choice of particular angles or configurations.

Solar tracking systems can be categorized depending on different criteria, including the control system, drivers, tracking method, and the system's degree of freedom. This exemplifies the extensive array of arrangements that solar tracking systems can possess, emphasizing the possibility for additional progress in this field. Research on the development and deployment of photovoltaic tracking systems is crucial as they have the ability to greatly enhance the electrical energy output of standard PV systems. By amalgamating the most advantageous attributes of current systems and advocating for the broader implementation of solar tracking systems, we may strive towards a future that is more ecologically sound and operationally effective. Figure 1 illustrates the many classifications of solar tracking systems. The classification of the system might be based on the control system, drivers, tracking strategy, or the degree of freedom of the system [16,17].

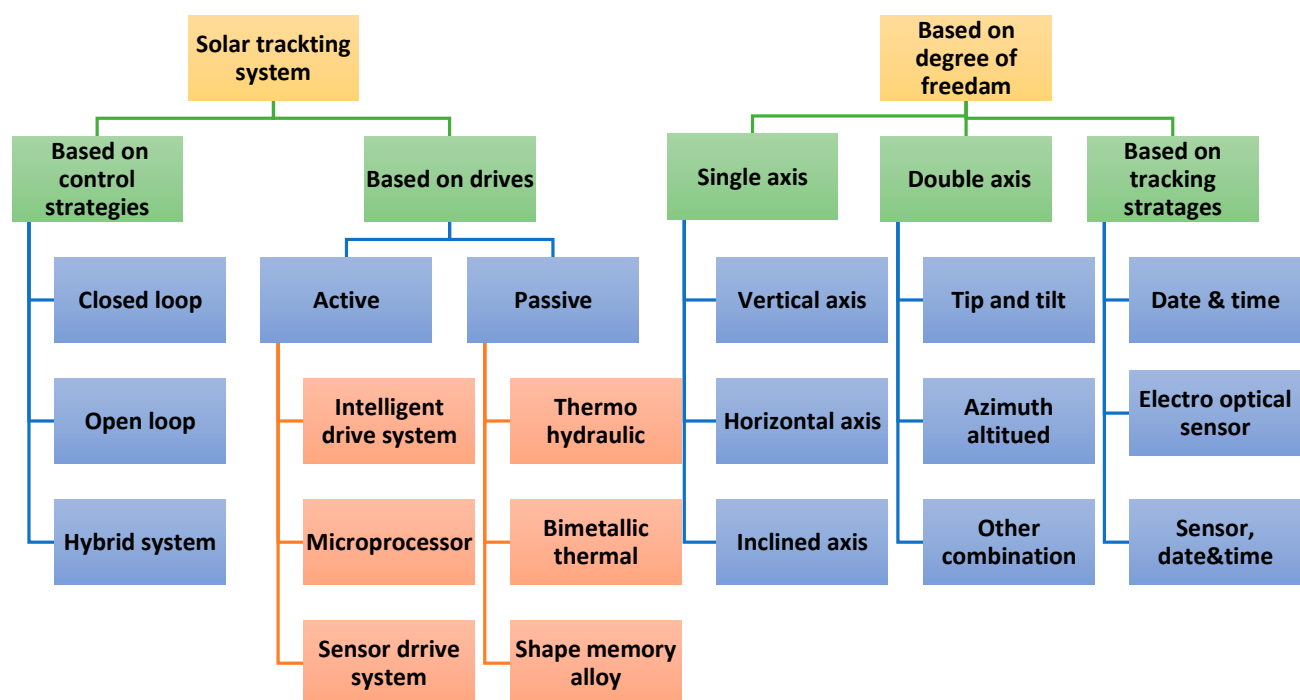


Figure 1. Classification of solar tracking systems.

Semi-continuous, single-axis solar tracker systems offer a favorable alternative to both traditional fixed-mounted and continuous tracking systems due to their ability to balance energy consumption and efficiency. Solar trackers enhance the efficiency of collecting solar energy, hence promoting a more environmentally friendly and sustainable approach of generating electricity [18]. This research proposes a novel sun-tracking method for photovoltaic systems that use numerical optimization and sensor technology to enhance energy output. The system uses UV and microelectromechanical sun sensors to accurately determine the positions of both the solar panel and the sun. The technology ensures the

optimal alignment of solar panels while minimizing power consumption by utilizing an arithmetic optimization and a proportional integral derivative controller in the control system. The MATLAB (R2018a) software is utilized for the purpose of system design and analysis, specifically in relation to energy input, output, and overall efficiency. The technology's enhanced ability to capture solar radiation and absorb solar energy makes it a practical alternative to dual-axis active solar tracking systems [11].

It can be seen that the classification of a photovoltaic tracking system is determined by the propulsion system, the degree of freedom, and the control system. Based on the preparatory work, it can be concentrated on the most crucial notes [19–27]. Single-axis and dual-axis photovoltaic tracking systems, with the proper control systems, can increase electrical energy by 22–56% compared with fixed PV systems. Combinations of microprocessor- and sensor-based control systems are the most popular and efficient control methods. Active tracking systems utilize electrical drives to move the axis, which, if improperly controlled, can devour a great deal of electrical energy. In order to optimize the power utilization of electrical drives, it is necessary to reduce the number of motor movements. Sensor-based photovoltaic tracking systems are more expensive due to the additional sensor devices, but they have a lower tracking error (0.14°) than that of sensorless systems (0.43°). Electric motors used in PV tracking applications are exposed to the elements and are therefore designed to withstand high winds, high temperatures, and high humidity. Permanent magnet brushless DC motors are the most common type of adopted electric motors because they are simple to maintain. Innovative new monitoring systems will incorporate dynamic weather forecasting and the cooling of PV systems with wind or water [28,29].

A unique approach to energy conversion, heating mechanisms, efficiency, control strategy, storage possibilities, day–night energy management, and adaptability to varying energy demands sets apart the multi-mode solar photovoltaic energy utilization system from typical solar thermal systems [30]. A multipurpose approach that combines photovoltaic power generation, radiative cooling power use, and overhang shade is the Rotatable Radiative Cooling-Photovoltaic (RRC-PV) system. This system breaks down the boundaries of building surface areas and makes a substantial contribution to the exploitation of renewable energy in high-density cities by enabling the continuous alternate use of solar energy and free cooling energy from space [31].

1.2.2. Simulation and Optimization Work

Due to its technological and economic efficacy, a modeling software called 'Hybrid Optimization Model of Multiple Resources' (HOMER) has been used to simulate hybrid energy sources all over the world. To correctly design and conduct feasibility studies and schedule and analyze system inputs to provide the most optimum solution that can maintain a sustainable energy environment, HOMER applications have been widely used in both off-grid and grid-connected systems [32]. Using the levelized Cost of Energy (COE) and the Net Present Cost (NPC) as primary economic outputs, different proposed or considered configurations are ranked. The statement also discusses the parameters of the HOMER Optimizer and the search spaces utilized for various designs [33,34].

A stand-alone solar PV power system with single-axis (horizontal and vertical) and dual-axis solar trackers and a diesel generator (DG) is examined in the solar PV system along with the performance and optimization results for any city. Based on the daily energy use in the study region, the HOMER program is used to develop, simulate, and optimize the hybrid energy system (HES). The simulation findings demonstrate that the optimal power system architecture, taking into account the renewable proportion and levelized cost of electricity, is an HES with dual-axis solar trackers [35]. The study investigates Iran's hybrid renewable energy systems which are sustainable and emphasizes how they can lower annual CO₂ emissions and support environmental sustainability [36].

Grid-connected PV system optimization is advantageous since it reduces the energy generated by traditional power plants and, consequently, the hazardous emissions dis-

charged as by-products. A Battery Storage System (BSS) supports a grid-connected PV system that is properly configured. The system components are first selected using the HOMER program while taking economic and electrical factors into account. Along with the in-depth technical analysis of the suggested systems, a comparison examination is conducted for three configuration systems. According to the simulation results, using a battery system and RES with a low energy cost is recommended (COE). The PV, converter, and battery system optimal size are calculated using HOMER and MATLAB, taking into account the Net Present Cost (NPC), COE, excess electricity and energy savings, emissions, and renewable penetration ratio to identify the most cost-effective and environmentally beneficial combination [37,38].

Soft Computing (SC) techniques have emerged as a feasible substitute for traditional methodologies in dealing with complex non-linearity problems in partially shaded solar systems. Several optimization algorithms have been proposed, such as Particle Swarm Optimization (PSO), Modified PSO, Artificial Bee Colony (ABC), Ant Colony Optimization (ACO), Simulated Annealing (SA), Bat Algorithm (BA), FireFly Algorithm (FFA), FireWork Algorithm (FWA), Glowworm Swarm Optimization (GSO), S-Jaya algorithm, Flower Pollination (FPA), Grey Wolf Optimization (GWO), and Human Psychology Optimization (HPO). These methods exhibit excellent efficiency in resolving the multi-peak Maximum Power Point Tracking (MPPT) problem, but their performance can be further enhanced when employed independently. Hybrid approaches, which integrate multiple methodologies, have recently been adopted to enhance performance.

Hybrid approaches in recent times have involved the integration of conventional algorithms with intelligent ones. Some examples of algorithms that might be mentioned include the Firefly Algorithm with Incremental Conductance (INC-FFA), P&O with Neural Network (P&O-ANN), Fireworks with P&O, Grey Wolf with P&O, Bat search algorithm with P&O (Bat-P&O), and Particle Swarm Optimization with P&O (PSO-P&O). Some hybrid approaches involve a combination of two or more intelligence algorithms, such as Simulated Annealing with Particle Swarm Optimization (PSO-SFLA), etc. Additional global Maximum Power Point Tracking (MPPT) techniques exist that specifically tackle the issue of tracking under partially darkened conditions, in addition to the ones previously discussed. These approaches encompass the transient evolution of series capacitors, curve fitting, the active bypassing of darkened cells, the recurrent scan and track method, the stepwise comparison search, and the beta algorithm [39–44].

This paper presents a stochastic and distributed energy management strategy for office buildings equipped with HVAC systems and EV charging stations. The model contains intricate building thermal dynamics and worker behaviors, and utilizes scenario-based stochastic programming to tackle uncertainties associated with photovoltaic electricity. An ADMM technique is employed for decentralized energy management. The problem is subdivided into network-side and building-side sub-problems to address privacy protection. The validity of the model is established by conducting numerical studies throughout the winter season and analyzing the comfort temperature range and expected state of charge [45].

The key distinctions between these techniques are their range of efficacy, speed of convergence, level of design complexity, sensor specifications, control parameters, and costs associated with hardware implementation. Therefore, while developing a PV system, a proper and appropriate algorithm selection is crucial, and it depends on the application in which it will be used [46].

1.3. Contribution and Novelty

This manuscript investigates the potential of utilizing solar energy for a specific building in question. This goes beyond simply measuring overall PV efficiency and delves into the building's unique energy needs. Additionally, by implementing a tracking system for the building's roof and side surfaces, this study optimizes solar energy capture based on the building's orientation and sun exposure throughout the day. This data can inform

future solar energy integration strategies for similar buildings. The total net cost over the life cycle can also be calculated for different cases.

The objective of this study is to address the identified gap in achieving energy sustainability and enabling decision-making for the transition to sustainable energy in buildings, such as that for higher education on the AASTMT Aswan Campus. After making a techno-economic analysis of the case study, it can be summarized that the integration of renewable energy sources is paramount in addressing climate change challenges, leading to benefits such as electricity bill savings and environmental preservation. While technologies, like PV panels and dual-axis tracking systems, offer significant advantages, their cost implications warrant careful evaluation when making decisions in sustainable energy deployment.

This manuscript presents two key points of innovation that contribute valuable new findings to the field of solar energy utilization:

1. This case study focuses on a unique location with specific parameters and climate conditions. This enables an analysis of the impact of solar energy (PV) in a previously under-represented context. By studying a less common location, one can gain valuable insights into how factors, like regional climate and geographic features, influence PV effectiveness.
2. This manuscript investigates the potential of utilizing solar energy for the specific building in question. This goes beyond simply measuring overall PV efficiency and delves into the building's unique energy needs.

Additionally, by implementing a tracking system for the building's roof and side surfaces, this study optimizes solar energy capture based on the building's orientation and sun exposure throughout the day. This data can inform future solar energy integration strategies for similar buildings.

A dual-axis tracking system is considered superior in terms of power generation and pollution reduction. However, several studies fail to consider its significant capital cost, which can greatly influence the decision-making process in favor of an alternative tracking system. These strategies aim to address the challenges and achieve a balanced approach towards emission reduction and sustainable development in the industry [47]. Despite considerable sector variation, one study's analysis of carbon emission efficiency across 28 Chinese industry sectors from 2005 to 2017 showed increasing embodied and direct emissions with a lesser opportunity for reduction than direct emissions [48]. A study involving 300 farmers of cotton and rice found that yields are positively impacted by farm machinery and biocides but negatively impacted by excessive fertilizer use [49].

The present paper is organized as follows: Section 2 is 'Methodology' which explains the experimental setup and mathematical model. Section 3 contains the 'Results and Discussion' which is divided into four subsections containing the following in order: the empirical data from the weather station, an overview of the simulation outcomes and software validation, the examination of power sources' impact on PV power generation and emissions, a comparison analysis between existing literature scenarios, and a proposed plan. Section 4 is the summarization of the work and future recommendations.

2. Methodologies

First, the methodology is outlined for the experimental case study, which is an educational building in Aswan, Egypt. Readings from a weather station are analyzed to determine the PV output and the amount of power that may be saved. In order to validate the program and give more comparative examples for the used parts, useable power, and tracking systems, a simulation model is subsequently developed for this case study in the HOMER software. This allows researchers to examine the impact of alternative approaches on output power and cost. The modeling of the numerical relationships for the PV panels, batteries, and economic models makes up the third section which provides the models and makes them more robust. Overall, the methodology is structured into two main sections: the first one focuses on the experimental setup detailing four electricity sources and envi-

ronmental parameters, while the second delves into the Homer simulation, examining the effects of varying energy system components, angles, and tracking systems.

2.1. Experimental Setup

The present campus has four electricity sources: a utility grid, PV panels, and batteries, in addition to a diesel generator used as a backup for emergency shutdown, which is connected to the lighting of the building, fire pumps, and drinking water pumps. The PV panels are installed vertically on one side of the building and on the rooftop. The vertical installation consists of twenty-five panels, arranged in five rows and five columns, as depicted in Figure 2. The Google micro-scale mapping in Figure 3A clearly shows the location of the building.

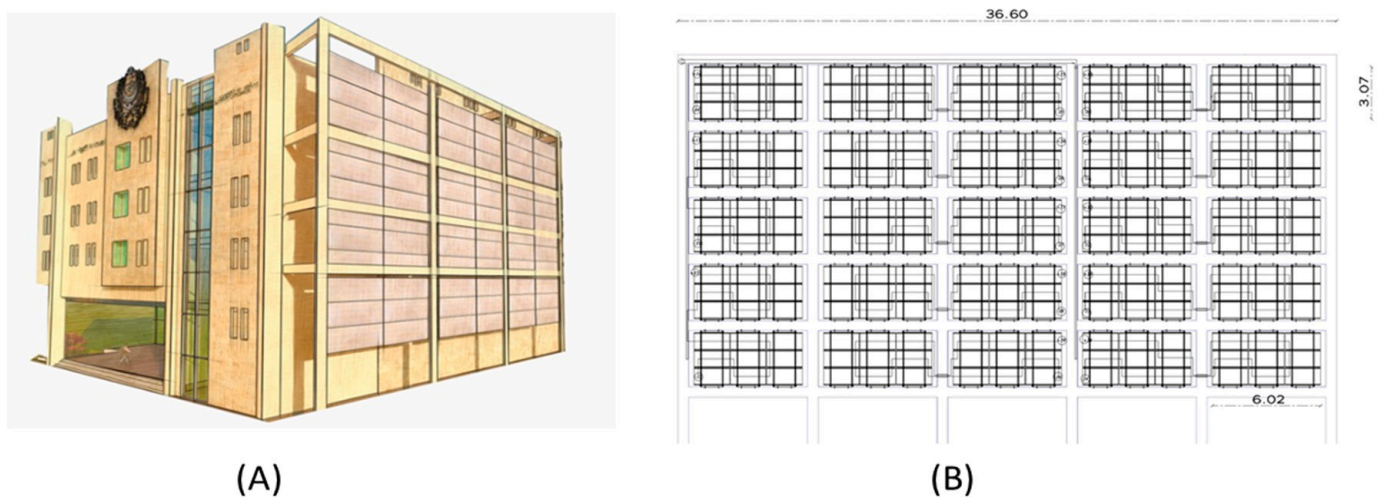


Figure 2. (A) Building design shows Vertical PV panels, and (B) the division of Vertical PV panels of campus building.

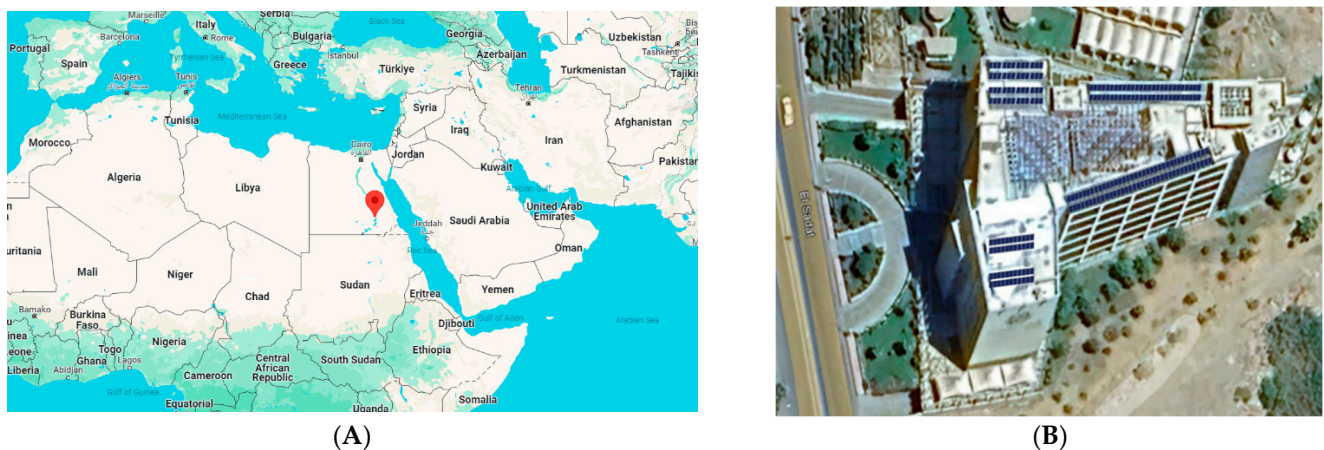


Figure 3. (A) A macro-scale map (Google Maps) of the location case study, and (B) Google earth campus building roof showing PV panels.

The rooftop is segmented into four sections, as shown in Figure 3B, with all PV panels linked to five inverters. Each inverter is connected to the grid, except for one located in the southwest corner, which operates off-grid and is linked to the battery storage room supplying lighting for the building facade. The inverters used are SMA models (SB5.0-1AV-41 and Sunny Island 8.0H, Germany) with a total nominal capacity of 9.60 kWh (equivalent to 200 Ah at C10) using lead batteries. The PV panels utilized are JA Solar Technology's JAM72S09 390/PR (1500V, China). The configuration of series and parallel connections

among the panels and the allocation of panels to specific inverters are optimized for maximum power output.

Figure 4A shows the load curve profile of the campus. It is illustrated that the load curve is increased in the summer time because of the hot climate in Aswan, and it is noticed that the load is also increased in morning time because this is an educational campus. The load curve profile is taken from the actual readings of the campus from July 2021 to June 2022. The average power is (29,107.75 KW), which is taken as input to the HOMER software simulation. The sun radiation can be obtained from the weather stations and also from HOMER by inserting a specific location from which the solar radiation and temperature can be taken using NASA predictions of worldwide energy resources or using the National Renewable Energy Laboratory. Furthermore, there are two electrical meters installed to calculate the net electricity consumption by deducing the PV output power, as illustrated in Figure 4B. Environmental parameters, such as ambient temperature, relative humidity, solar irradiance, air pressure, wind direction, and wind speed, are monitored by a weather station. Integration with a Meteocontrol data recorder facilitates easy data collection. Meteocontrol energy and weather stations offer various modules to enable users to select the most suitable configuration for their needs. The building consists of four floors, divided into educational floors containing classrooms and laboratories, and administrative floors containing the offices of the teaching staff, financial management, and assistants. The building roof area is 1715 m², and the PV represents about 50% of the area. The side area is about 828 m², and the area of PV covers about 70% of this area.

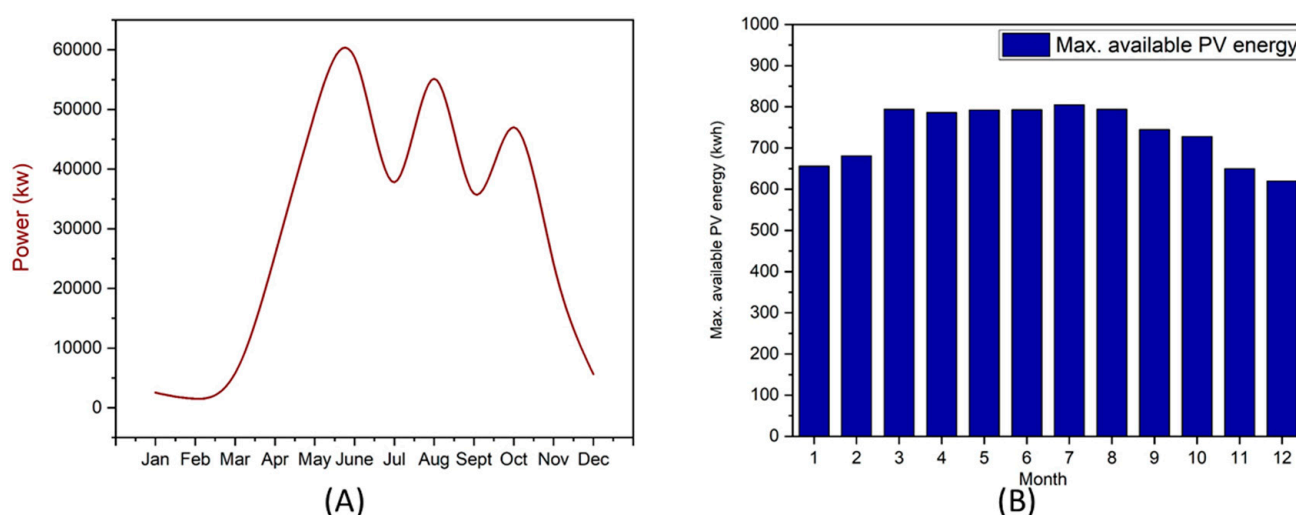


Figure 4. (A) The electricity output from PV panels, (B) The daily load curve profile of campus.

2.2. HOMER Simulation

The simulation phase is separated into two segments: the initial segment aims to investigate the impact of altering the constituents of the energy system. The second component involves examining the influence of different angles and tracking technologies, which are presented below.

The next stage of the ongoing investigation involves utilizing the HOMER energy simulation program to simulate the PV panels. HOMER is a software program that models and evaluates the impacts of renewable energy systems. The program [50] is used to undertake simulation, optimization, and analysis of the system's sensitivity. Furthermore, it offers analytical data concerning the economic feasibility of the suggested renewable energy system. It then models the functioning of the grid, comprising diverse electrical apparatus such as generators, converters, storage systems, and loads. The hybrid system essentially comprises diverse components, including renewable and nonrenewable energy sources, storage devices, AC/DC converters, and the grid [51]. This device can be collectively

simulated under different limitations and situations. Table 1 shows the costs of the hybrid solar system components.

Table 1. Components' description of solar hybrid energy system which clarifies the cost and efficiency of each case.

System Component	Grid	Solar PV	Battery	Converter
Type	Sample rate	Jinko Eagle PERC60 300W	Generic 1kWh Lead Acid	Generic
Cost Capital	Power price	500	200	400
Replacement	USD/kWh 0.15	500	200	400
Operation and Maintenance	Net accesses prices 0.05	10	10	10
Efficiency		18.33%	8 strings	
Remark		- Operation temperature (45 °C) - Temperature coefficient for power (−0.39) - Derating factor 88% - lifetime (25)	- Lifetime (10) battery - Nominal voltage 12 V - Charge current 16.7 A - Maximal discharge current 24.7 A - Weight 11.5 kg	- Functions as inverter to convert DC to AC - Functions as rectifier to convert AC to DC

Conducting a sensitivity analysis in HOMER software is crucial for evaluating the impact of changes in input parameters on simulation results. A sensitivity analysis aids users in comprehending the impact of alterations in crucial variables, such as fuel prices, system sizes, or the accessibility of renewable resources, on the overall effectiveness and feasibility of their energy system designs. Utilizing a sensitivity analysis allows users to enhance decision-making and optimize designs by identifying the parameters that exert the most significant influence on the outcomes.

Figure 5 is a flowchart illustrating the operational procedure of the planning process for utilizing the HOMER program. At each selected location, the four input data points are utilized. The factors influencing the system are the daily load demand, weather conditions, economics, component size, and project limits. The Graham Algorithm is employed to determine the optimal configurations for HOMER by minimizing the objective function while considering the predefined constraints. Optimal configuration is achieved when the system successfully satisfies the load demand. Sensitivity analysis is employed for each system built to determine the impact of uncertain parameters on the optimal outcomes. The prior procedure is reapplied to each location in order to facilitate a comparison of the final outcomes. To assess and enhance the scale of the grid-connected hybrid renewable energy systems (HRES) for their practical application, the following procedures are employed.

1. Get the necessary weather data and load profile for the selected universities. This includes solar radiation, wind speed, temperature, and daily load demand.
2. Explain what it means for the goal function to be limited.
3. Set each component's economic trait and search number.
4. Use the HOMER software to solve the goal function by minimizing NPC.
5. Show the best output device which can handle the load.
6. Use the sensitivity analysis on the system you have built by changing the payback period, the load, and the rate.

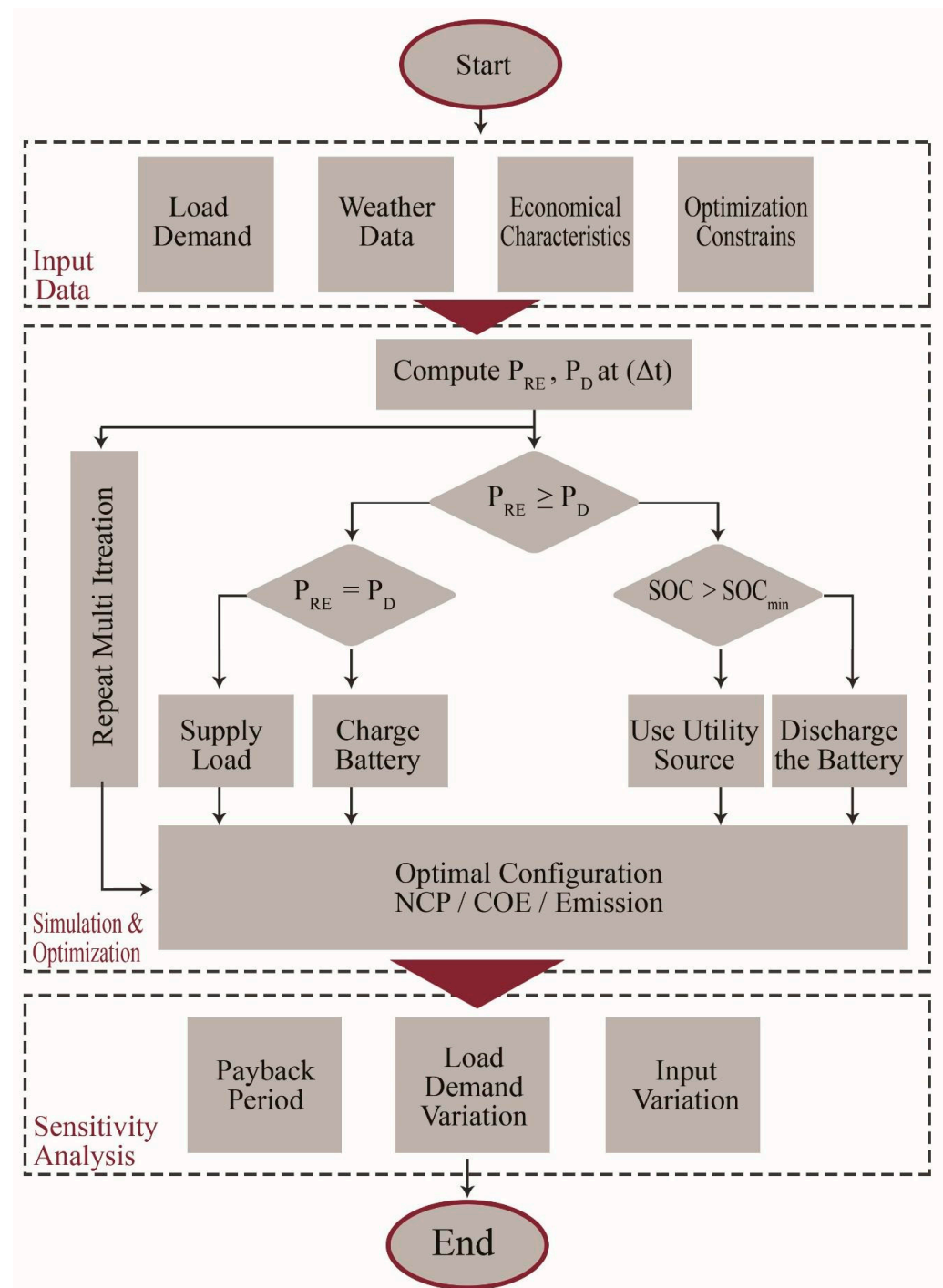


Figure 5. Schematic representation of the HOMER simulation-based optimization procedure.

2.2.1. Varying of Different Components

To study the effect of adding renewable energy sources, firstly the conventional way (grid) should be studied. Obviously, adding renewable resources reduces energy cost and also reduces gas emissions, but the percentage of availability of using these renewable sources and their auxiliary components, such as batteries and converters, should be studied in the simulation program.

Validation of Experimental Data

The first section is presented to validate the actual solar module at AASTMT Campus in Aswan. The application of renewable energy is implemented using the HOMER simulation

software, and it shows promising results. The simulated schematic diagram is illustrated in Figure 6. It consists of the conventional grid, solar PV sources, converter, batteries, and electrical load. Hybrid solar sources are simulated in the current work to investigate the possibility of applying a green and sustainable campus. Four cases have been simulated, shown in Table 2, which are (1) only a grid; (2) a grid with batteries and a converter; (3) a grid with PV and a converter; and (4) a grid with PV a converter and batteries. The schematics illustrate the campus's conventional grid system, the grid with the batteries system, the grid with a solar system, and the hybrid solar with the grid and batteries, and they are also all compared. NASA's projections of global energy resources or the National Renewable Energy Laboratory are used since they contain the solar GHI renewable energy resource. Figure 7 illustrates NASA clearance and solar radiation.

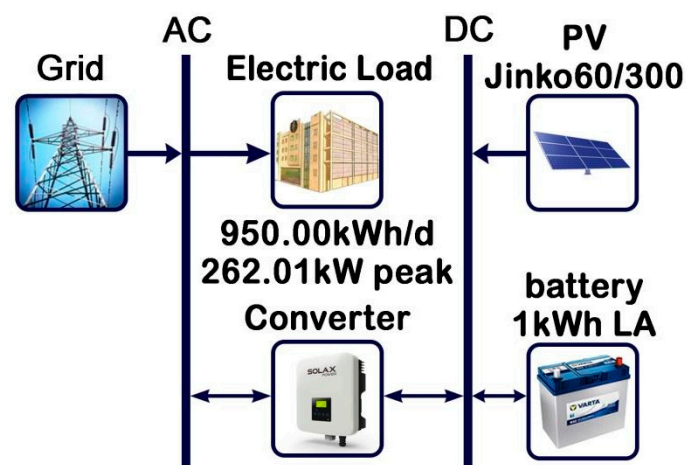


Figure 6. Schematic diagram of the proposed system.

Table 2. Four cases specifications.

Parameter	Grid Only	Grid with Batteries and Converter	Grid with PV and Converter	Grid with PV, Converter and Batteries
Hours of Operation of Converter (h/yr)	0	804	4380	4385
PV Capacity	0	0	150 kw	150 kw
System Converter	0	2.05 Kw	109 Kw	105 Kw

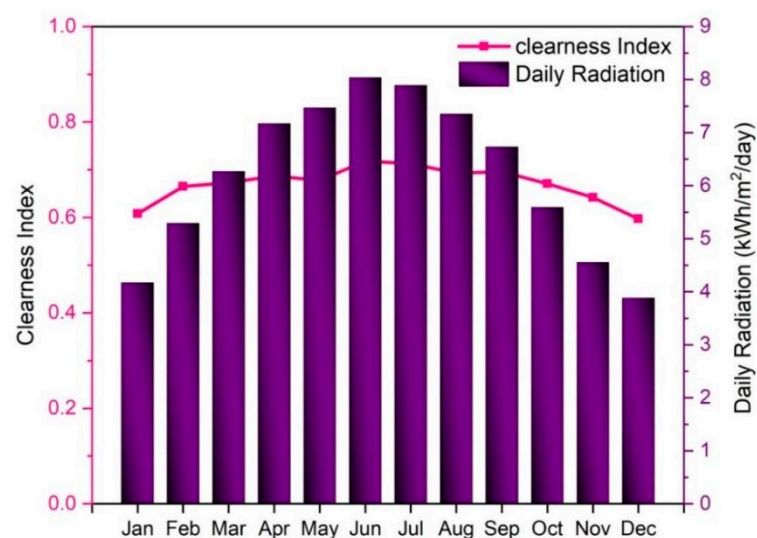


Figure 7. NASA predictions for worldwide energy resources for solar radiation and clearance.

2.2.2. Impact of Varying Angles and Tracking System

Six distinct tracking technologies are utilized to enhance the electrical output power of the solar photovoltaic (PV) panels. The tracking configurations utilized are outlined below:

1. The Absence of Tracking Fixed Slope (0°): Panels are arranged at a constant incline with no inclination.
2. The Absence of Tracking Fixed Slope (20°): Panels are positioned at a constant incline of twenty degrees.
3. Non-Traceable Fixed Slope (35°): Panels are positioned at a constant angle of 35 degrees.
4. Continuous Horizontal Axis (CHA): The CHA involves rotating around the east–west axis while adjusting the slope angle to maximize the angle at which sunlight hits the surface.
5. Continuous Vertical Axis (CVA): The CVA involves rotating around a vertical axis while maintaining a fixed slope angle and allowing for the continuous adjustment of the azimuth angle.

Dual-axis tracking refers to the simultaneous horizontal and vertical tracking of a solar panel system in order to optimize power production.

Furthermore, a sensitivity analysis is conducted to enhance the efficiency of the PV panels in Aswan city, a desert region, by taking into account the environmental parameters, such as temperature and dust deposition, which affect power production. The purpose of this analysis is to examine the impact of different environmental variables on the performance of the PV panels in a specific location and determine the optimal design of a tracking system to maximize energy output in these settings.

2.3. Modeling and Numerical Relation of Energy System

This paper proposes an optimum design for a hybrid solar photovoltaic (PV) battery power system. The system comprises solar photovoltaic (PV) panels, batteries, and a converter and a controller for the purpose of charging and discharging the batteries [52,53].

2.3.1. Photovoltaic Array

The power (PPV) generated by the PV panel is determined using both irradiance and temperature [54].

$$P_{PV} = Y_{PV} \times F_{PV} \times \frac{G_T}{G_{T,STC}} [1 + \alpha_P (T_c - T_{c,STC})] \quad (1)$$

where G_T represents the current level of irradiance during the simulation, while $G_{T,STC}$ refers to the irradiance under standard test conditions (STC), which is 1000 W/m^2 and 25°C . T_c represents the temperature of the PV panel, and α_P and F_{PV} represent the power temperature coefficient and derating factor of the PV panel, respectively. Y_{PV} refers to the rated capacity of the photovoltaic (PV) array, which represents its power production when tested under standard conditions in kW.

The configuration of the PV array based on the PV panels is expressed as follows:

$$P_{PV,STC} = (N_s + N_p) P_{mSTC} \quad (2)$$

where N_s is the number of series connections, and N_p is the number of parallel connections.

The PV panel efficiency is calculated as follows:

$$\eta_{mp,STC} = \frac{PV}{A_{PV} \times G_{T,STC}} \quad (3)$$

where PV refers to the rated capacity of the PV panel, which represents its power output under standard test conditions in kW. A_{PV} , on the other hand, represents the surface area of the PV panel in m^2 . The coefficient of the renewable fraction (f_{ren}) is a crucial parameter

for evaluating the substitution of conventional fuel (diesel) energy with renewable energy in a hybrid energy system (HES):

$$f_{ren} = 1 - \frac{E_{nonren}}{E_{cons}} \quad (4)$$

where E_{nonren} represents the nonrenewable energy production, and E_{con} is the total energy used by the load.

2.3.2. Battery Storage System

The Battery Storage System (BSS) plays a crucial role in autonomous solar PV-based hybrid energy systems (HES). The Battery Storage System (BSS) is employed in situations where there is insufficient power generated by photovoltaic (PV) systems or in the event of a grid outage. During each time step, the kinetic battery model is used to compute the maximum power charge limit ($P_{bat,c}^{lim}$) and the maximum power discharge limit ($P_{bat,d}^{lim}$). This kinetic model incorporates the voltage losses, depth of discharge (DOD), serial resistance, cycle-by-cycle degradation, and impact of temperature on the battery's capacity and rate of deterioration. The kinetic battery model enables the determination of the power output of the battery, which is subsequently utilized to ascertain the current output of the battery.

$$P_{out} = I V_{output} = V_o I - R_o I^2 \quad (5)$$

The battery capacity is determined based on its current (Ah) or the amount of charge (state of charge (SOC)) during one round trip. The SOC is calculated as follows:

$$SOC(t + \Delta t) = \min \{ SOC(t)(1 - \delta) + \eta_{ch} (P_{gen} - P_L) \Delta t, SOC_{max} \} \quad (6)$$

where t represents the current time, Δt represents the time interval in hours, δ represents the coefficient of self-discharge, η_{ch} represents the battery efficiency, P_L represents the essential load power, and SOC_{max} represents the maximum permitted state of charge.

2.3.3. Economical Model

The economic modeler within the HOMER software is utilized to assess the expenses associated with all scenarios, and the Net Present Cost (NPC) is computed in the following manner:

$$NPC = \frac{C_{ann,tot}}{CRF_{(i,N)}} \quad (7)$$

The equation represents the total yearly cost ($C_{ann,tot}$) in terms of the annual real interest rate (i), the project duration (N), and the capital recovery factor (CRF).

$$CRF_{(i,N)} = \frac{I(1+i)^N}{I \times (1+i)^N - 1} \quad (8)$$

The cost $C_{ann,tot}$ is determined by considering the impact of the capital investment, operational expenses, replacement costs, resource costs, and maintenance expenses. This analysis finds that solar PV systems do not incur replacement and resource costs, while the converter and BSS only incur replacement costs. The salvage value (SV) is determined using HOMER and Equation (9):

$$SV = C_{rep} \times \frac{R_{rem}}{R_{comp}} \quad (9)$$

where C_{rep} , R_{rem} , and R_{comp} are the cost of replacing the part, how long it has left, and how long it will last. The LCOE and COE are worked out as follows:

$$COE = \frac{C_{ann,tot}}{(E_{prim} + E_{def} + E_{grid\ sales})} \quad (10)$$

where E_{prim} , E_{def} , and $E_{grid\ sales}$ are made up of the amounts of the main, deferrable, and electrical energy sold to the utility grid. According to this analysis, both the quantity of energy that can be postponed and the quantity of electrical energy that is sold to the grid are considered to be zero.

3. Results and Discussion

This section's analysis comprises two main studies. First, an experiment is conducted on a hybrid system consisting of both fixed vertical PV and roof solar panels. In Aswan, this model is applied to parametric conditions. Meanwhile, the solar PV panel is being tested, and its efficiency is being evaluated in preparation for integration with a grid system. The simulations are conducted using the HOMER software to execute a numerical investigation in the second stage. To determine the efficacy of the hybrid system, two scenarios with numerous cases are utilized. Initially, a scenario analysis and analyses of system components, such as an electrical grid, a grid with a solar system, a grid with batteries, and a grid hybrid solar system with a converter, are conducted. Six cases are utilized for a comparative analysis with regard to the second scenario of the azimuth angle and tracking system variations. The scenarios are proposed in order to facilitate a meaningful comparison between the simulation results and the experimental prototype. The PV capacity is then changed to 150 (actual or rated power) or 175 (maximum power) before comparisons are made. Finally, the results are compared with those of other recent academic studies.

3.1. Experimental Results

The energy yields (monthly/annual/total) are displayed, along with the performance data (daily/weekly), based on the feed-in meter values. Any manual meter reading changes are taken into account and reflected in the monthly, annual, and total views. In case the daily or monthly yields are exceptionally high, they will be highlighted using color.

This scenario may arise, especially when meter readings undergo manual adjustments to bridge data gaps spanning extended periods. For daily and weekly assessments, the focus shifts towards converting the values into power units or aggregating AC power readings. Notably, the analysis includes AC power in correlation with the feed-in meter. When an irradiance sensor is accessible, adjustments are made to ensure alignment between the system's installed power and an irradiance of 1000 W/m². This alignment aids in promptly identifying any decline in power output. Figure 8 illustrates the solar radiation from the weather station Meteocontrol (Si-RS485TC-2T-MB, China) and the inverter sensor (KippZonen SMP10, China). Figure 8A shows the daily output generation as an example day of August for this year, and the results are found in Table 3. Figure 8B also describes the output power of PV for one week. Table 4 summarizes the data of yearly generation. In outcome, the annual generation is depicted in Figure 8C. It is noticed that the maximum solar irradiance takes place in August and April at 12:00 p.m.; however, the maximum power can be obtained in August. In the daily load curve, it is found that the PV generation starts from 6 a.m. to 6 p.m. and reaches its peak at 12 a.m. In the weekly generation curve, the power generations are actually the summation of the daily generation of power. By surveying the annual output, one finds that the summer generation is the best, especially in August; on the other hand, it reaches its minimum value in December.

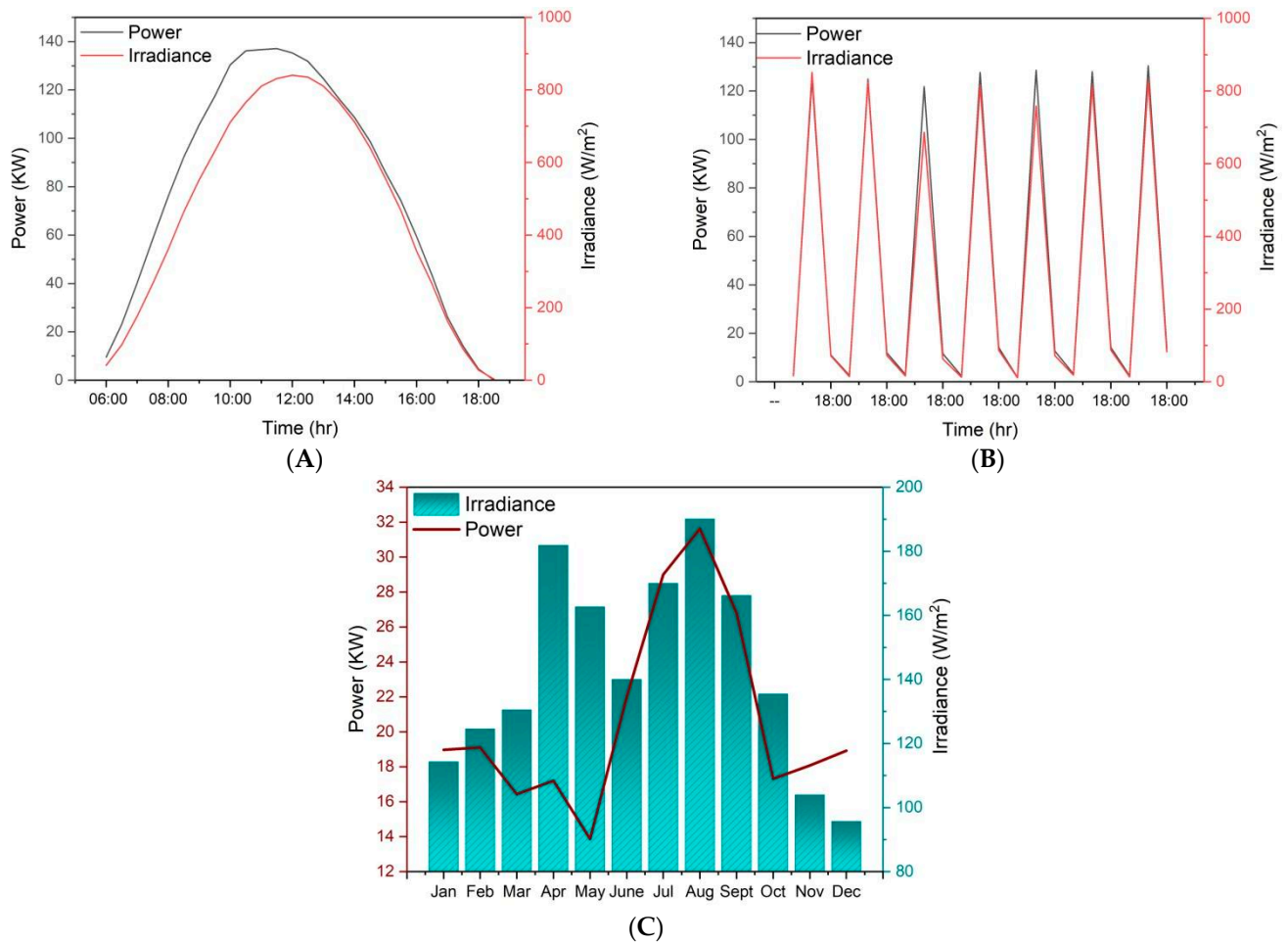


Figure 8. (A) the daily output power generation from PV measured from weather station, (B) the output power of PV but for one week, and (C) the annual power generation compared with irradiation.

Table 3. The summary data of daily generation.

	Daily Values Unit	Maximum Value Unit
Sum of global radiation	6.45 kwh/m ²	884.47 W/m ²
Energy	1089.60 kwh	154.10 kw
Specific energy	6.22 kwh/kwp	-
Nominal output	175.11 kwp	-

Table 4. Summary of the data of yearly generation.

	Annual Values Unit	Total Values Unit
Sum of global radiation	1071.32 Kwh/m ³	1545.02 Kwh/m ²
Energy (measurement technique)	154,557.40 kwh	167,351.51 kwh
Energy (METER reading)	154,557.40 kwh	167,375.86 kwh
Specific energy	882.63 kwh/kwp	953.54 kwh/kwp
Nominal output	175.11 Kwp	-

It is clear that the irradiance and power are directly proportional, and the different clear curves depend on the temperature and the cleaning of PV panels. The variations of input/output power of the plant depending on the irradiance are cleared in Figure 9A. It

is noted that the maximum power can be reached to around 140–160 kW for the month and day selected at 800–900 (W/m^2) of irradiance. The total efficiency of the system with regard to irradiation is shown in Figure 9B. The main consideration is that the generated AC power depends on the irradiance over the plant area. It is found that the maximum efficiency is around 20% for both the day and month selected.

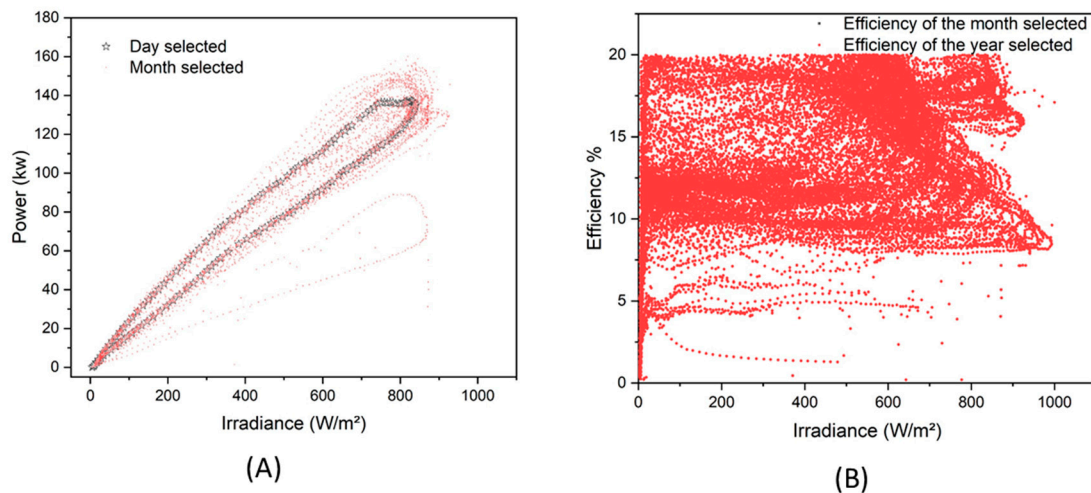


Figure 9. (A) The power versus irradiation, and (B) the system efficiency.

Figure 10 shows the inverter heat map of the normalized power of all inverters for an installation during the day. The color scale is determined relative to the daily maximum value. Intervals for which no data are available are shown in dark red. The yellow color indicates the high power.

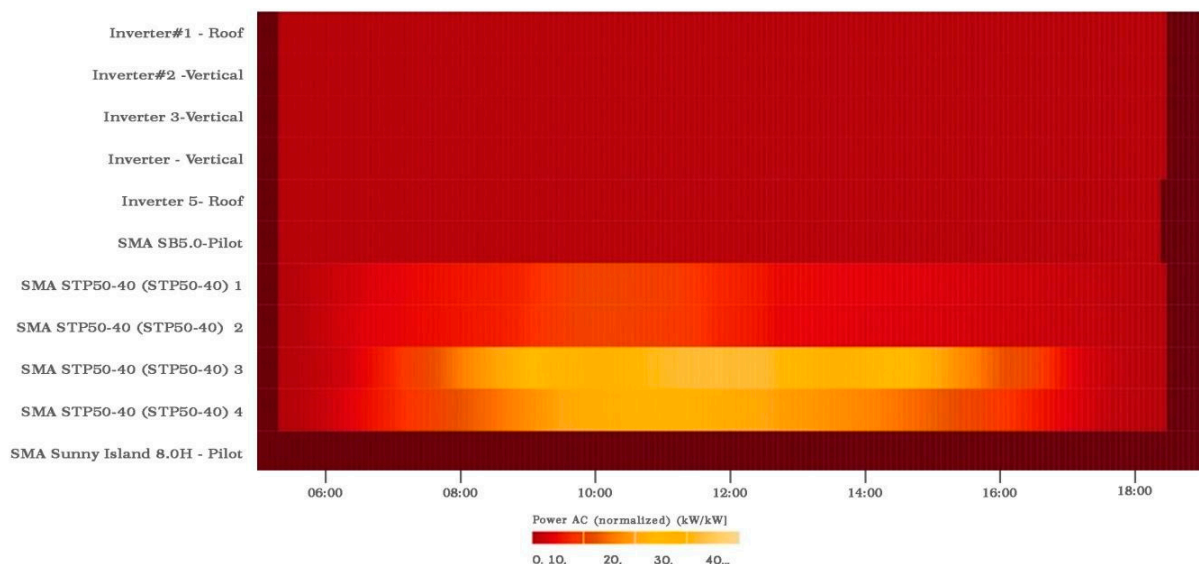


Figure 10. The AC power output power of inverter.

3.2. Simulation HOMER Results

The simulation section is divided into two parts: the first part is to study the effect of varying the components of the energy system. The second part studies the impact of varying angles and tracking systems, and those parts are shown below.

3.2.1. Validation of Experimental Data

Over the course of a full year, data from both experimental and simulation studies are analyzed. Validation is performed based on key parameters in the PV solar systems,

namely solar irradiance and PV output power. Actual irradiance data are sourced from the weather station, while simulation data are obtained from NASA. Power generation data are collected from the inverter, and simulation data are fine-tuned post-optimization. The comparison between experimental and simulation results depicted in Figure 11 reveals a close alignment, affirming the validity of the simulation model for broader applications.

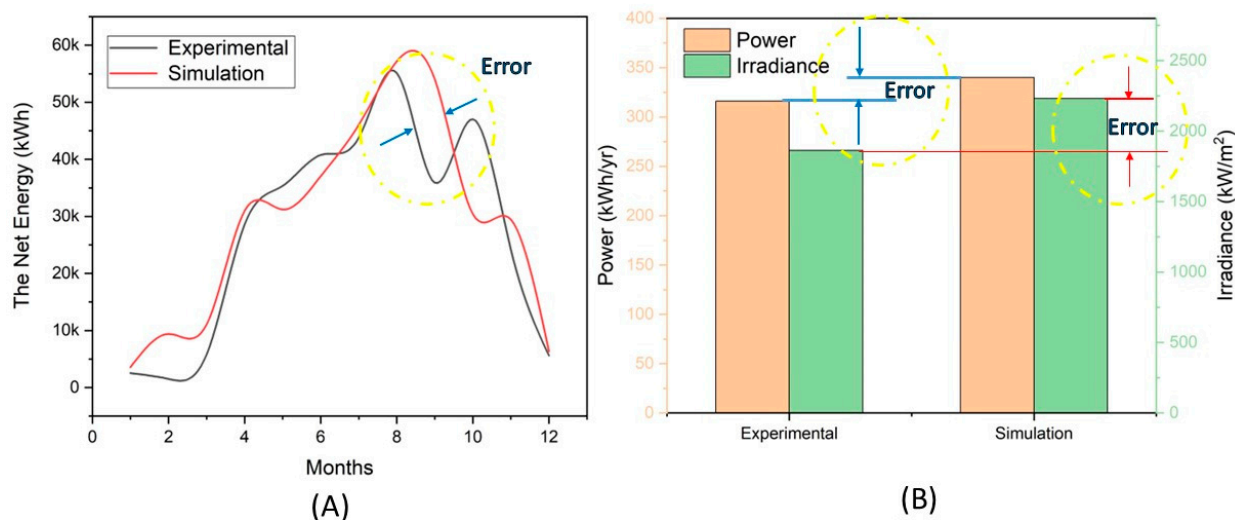


Figure 11. The comparison between the experimental and the simulation results (A) Annual total energy and (B) Total power and irradiance for both cases (with error difference).

In Figure 11A, the energy output in kWh over a year is examined, indicating an acceptable error margin between simulation and experimental data. Figure 11B delves into the total PV generation power in kWh/year and irradiance in kW/m², showcasing a negligible difference within 8% between the experimental and simulation results, with the experimental power output at 316 kWh/year. Notably, the error in generation power is found to be lower than that in irradiance.

In conclusion, the simulations exhibit slightly higher, but more consistent, results compared with the experimental findings, which can be attributed to various environmental factors affecting experimental efficiency, such as temperature variations, shading effects, and panel cleanliness. The quality of sensors, data collection methods, system upkeep, and environmental influences are among the factors influencing the reliability of the data gathered from the PV solar systems. Generally, with proper calibration and maintenance, the data from the PV solar systems can be deemed highly reliable. Comparing the data of the current year (21/22) with the following year (22/23) highlights the stability and high reliability of the collected data over time.

3.2.2. Varying of Different Components Results

To begin with, the project is estimated to last for a lifetime cycle of 25 years. The simulation results for the four cases of grid only, grid with batteries and a converter, grid with PV and a converter, and grid with PV, a converter, and batteries have been illustrated in the current section. Consequently, Table 5 illustrates the comparisons of the four cases with their total costs. The first case of the conventional grid shows a cost of USD 466.8 thousand, while the levelized energy cost is 0.150 USD/kWh. The campus purchases almost 350 kWh/year of power from the main electrical grid. This amount of power produces 219,146 Kg/year in CO₂ emissions. The conventional system incurs operating expenses amounting to USD 52,000, the highest among all four cases. In the second scenario where batteries are integrated into the grid, the total operational cost remains close to that of the first case. However, the addition of batteries enhances system stability during shutdowns. The newly introduced solar PV system boasts an annual production of 340.8 kWh, with a capacity of 175 kW. This solar power generation slashes

grid power purchases by 68%. Nevertheless, the new PV system necessitates a system converter costing USD 138.5 thousand to handle 127 kW. Despite this capital expenditure, the new system operates at a lower cost of USD 14.8 thousand compared with the first case. In the fourth case, a hybrid solar system coupled with the conventional grid is analyzed to assess the impact of battery integration. The results indicate stable PV productivity, albeit with a slight increase in costs. The overall addition of green sources exhibits a greater cost reduction than that of the conventional grid system throughout the project's lifetime, where the CAPEX is capital cost and the OPEX is operation cost.

Table 5. A comparison of the 4 cases with their total cost (when PV MAX power 150 KW).

Parameter	Grid Only	Grid with Batteries and Converter	Grid with PV and Converter	Grid with PV, Converter, and Batteries
Total Net Present COST	USD 664,894.30	USD 668,751.60	USD 368,443.30	USD 370,063
Levelized Cost of Energy	USD 0.150	USD 0.151	USD 0.0647	USD 0.0653
Converter Losses (KWh/yr)	0	0.215	14.352	14.212
Grid Purchases (KWh/yr)	346,750	346,750	172,709	173,008
PV Production (KWh/yr)	0	0	292.109	340.79
CAPEX	0	USD 1621	USD 118,504	USD 117,111
OPEX	USD 52,013	USD 52,187	USD 19,552	USD 19,788
CO ₂ Emitted (kg/yr)	219,146	219,143	109,152	101,449

Figure 12 illustrates the comparison of operational costs and capital investments between the primary grid and a grid equipped with PV systems. Among the four scenarios, the grid has the highest operational cost. The overall projected cost of the grid amounts to USD 664,000. However, the analysis does not include the capital expenditures of the main grid, as they have already been accounted for and paid. By gaining a deeper comprehension of the solar PV system implementation at the AASTMT Campus, the new system effectively decreases its operating expenses by 60%. This figure also includes the solar PV operating expenses, which are negligible in comparison with the operating costs of the main grid system. Conversely, the cost encompasses capital expenditures. The initial expenses associated with the solar PV system encompass the acquisition of the solar panels, the frame construction, and the battery cells. Included are the present converters utilized for transforming direct current into alternating current, enabling its connection to the primary power grid.

The amount of electricity that is purchased from the main grid for the four simulated cases is depicted as follows:

In Case 1, as shown in Figure 13A, the amount of power delivered from the primary grid is raised all year long. The amount of power that is pulled from the grid increases throughout the summer and reaches its maximum. These months always experience higher peaks in electricity consumption as a result of rising temperatures and rising air conditioning usage. On the other hand, the solar PV system provides electricity and lowers the overall amount of power purchased from the main grid, as shown in Case 2's illustration (Figure 13B). As the sun is at its strongest in the middle of the day, solar PV electricity is concentrated during that time. As a result, during certain times, less power is acquired from the main grid. As was previously noted in Table 4, the solar system illuminates the majority of the day throughout the entire year, with the summer months experiencing its peak.

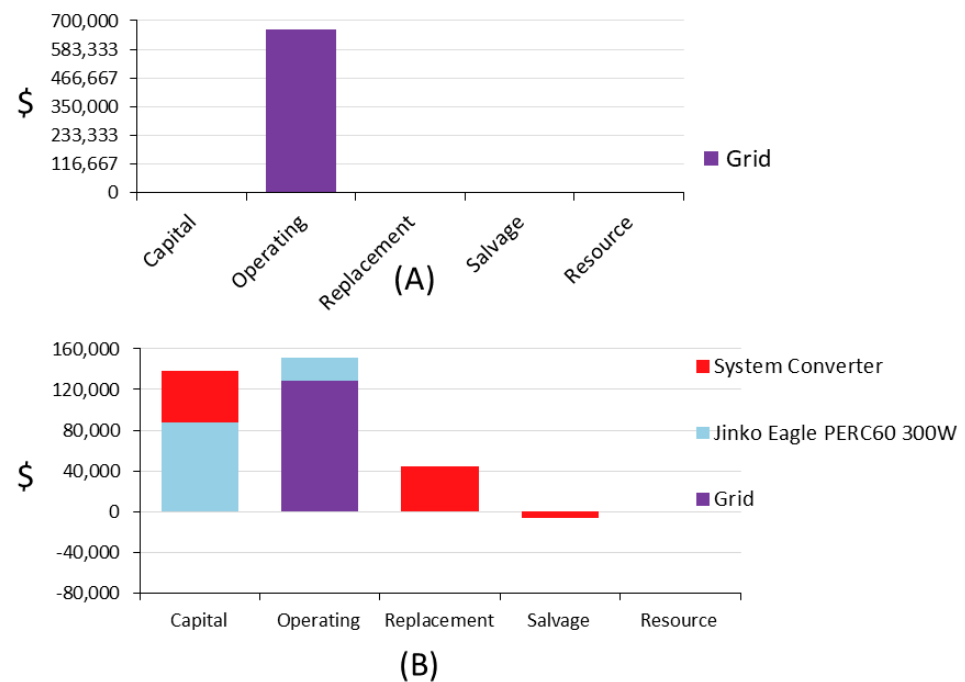


Figure 12. (A) Comparison of the main conventional grid's operational costs and capital investments and (B) the main grid using a solar PV system.

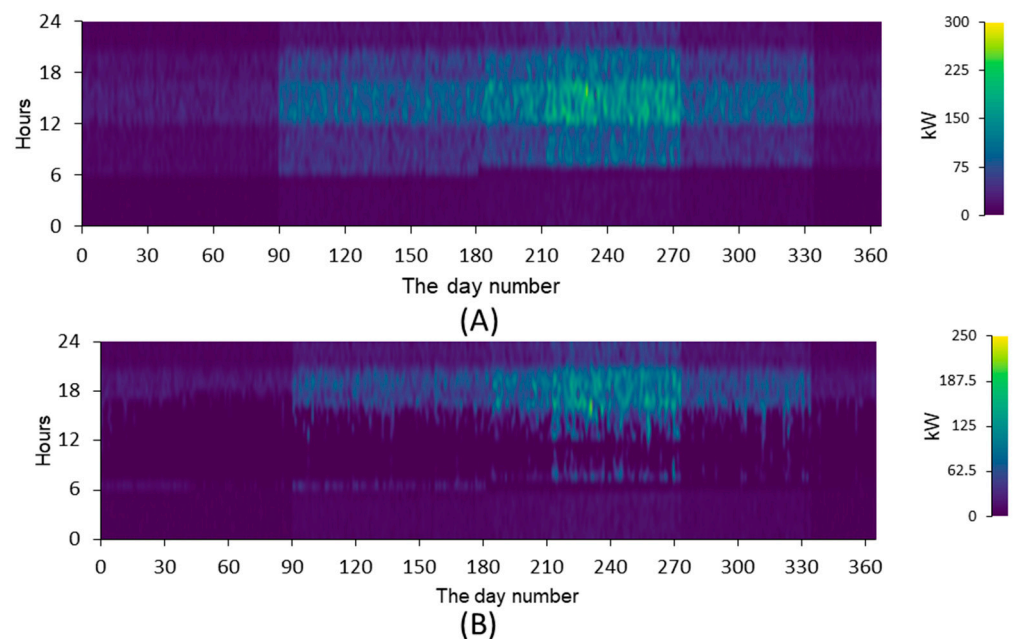


Figure 13. Daily consumption of electricity from the traditional main grid system during the course of a full year, expressed in kW in (A) Grid only, and (B) Grid with solar.

Figure 14A illustrates the fluctuation in purchased power throughout the course of the year, showing a significant rise from June to September as a result of the increasing electricity demand. Figure 14B emphasizes the smooth integration of the solar PV system with the main grid, demonstrating the efficiency of the recently installed solar PV system which is connected to the grid. The system is projected to have an overall performance efficiency of 60%, resulting in an average yearly electricity generation of 460 kW and a total of 15 MW over the course of a year. Furthermore, in order to meet the needs of port operations, supplementary power acquisitions are made throughout the summer season.

Considering the significant increase in solar power output at this time, it is advisable to utilize this hybrid system.

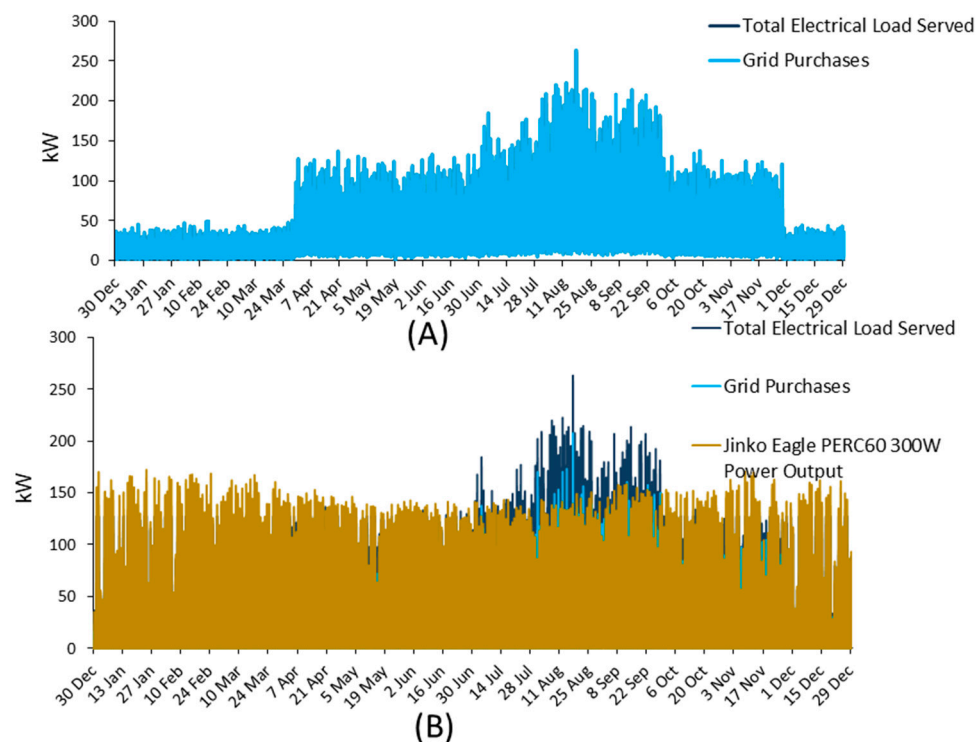


Figure 14. (A) Purchased electricity from the primary conventional grid for a year, and (B) Electricity produced from all renewable energy sources.

3.2.3. Impact of Varying Angles and Tracking System Results

The results are obtained by using the standard daily AC load of 950 kWh/day, as specified in Table 1 (component specifications).

Upon reviewing the daily and weekly power production profiles depicted in Figure 8, it is clear that all the examined cases exhibit unique values, while also displaying similar attributes in terms of their electrical output power. Solar photovoltaic (PV) systems achieve their maximum electricity production during solar noon, with an average of 800 watts per square meter (W/m^2). The dual-axis tracking system demonstrates the longest period of peak power output, whereas both the fixed system and the CHA tracking system have relatively shorter durations.

Figure 14 illustrates the electrical balance of the HES. The total electrical power generation is around 480 kWh/year, with the PV system generating between 460 and 495 kWh/year, and the other system generating between 289 and 400 kWh/year. The surplus electrical power produced by the HES varies from 480 to 490 kWh per year for the CHA and CVA tracking scenarios, respectively. Furthermore, the converter experiences a 10% electrical power loss in all examined scenarios, as the simulations take into account its efficiency.

3.2.4. Economic Analysis

The comparison of Net Present Cost (NPC) and yearly costs across all Hybrid Energy System (HES) case components, displayed in Figure 15 and Tables 6–12, provides valuable insights into the economic and operational considerations of different system configurations. The NPC encompasses various costs, such as capital, operation, maintenance, replacement, and means costs. It serves as a critical metric for evaluating the economic feasibility of HES configurations. Among the cases examined, the fixed zero-angle system exhibits the highest NPC at USD 371,155, indicating higher initial investment requirements. In contrast,

the dual-axis monitoring system boasts the lowest NPC of USD 227,667, reflecting a more cost-effective solution in terms of total lifetime expenses.

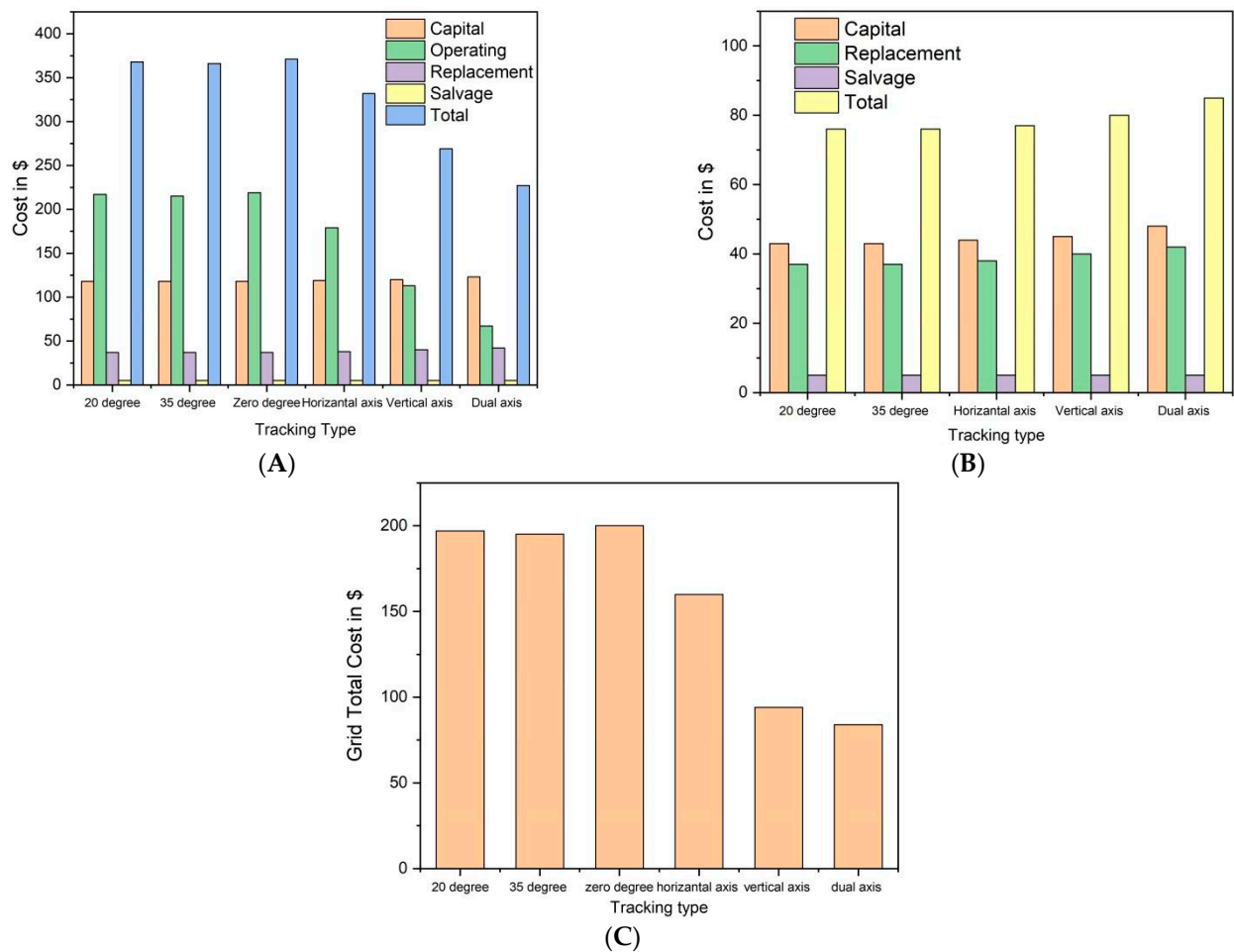


Figure 15. (A) Summary of NPC for the system in USD (\$) for all tracking cases, (B) the Converter NPC in USD (\$) for all cases, and (C) the grid total cost for different tracking system.

Table 6. Comparison of all tracking system types (when PV Max 150).

Tracking System		Fixed (No Tracking)			Single-Axis		Double-Axis
		Zero Degree	20 Degrees	35 Degrees	Horizontal	Vertical	
Cost	NPC	371,155	368,443	366,486	332,550	269,117	227,667
	COE	0.06534	0.0647	0.0642	0.0568	0.0437	0.0348
	Operation	19,764	19,552	19,395	16,680	11,589	8143
	Initial	118,504	118,504	118,504	119,325	120,967	123,575
Renewable friction		61.0	61.2	61.4	64.5	69.9	73.3
PV productivity		289,909	292,109	293,756	317,551	358,639	400,467
Emission (kg/yr)	Carbon Dioxide	109,562	109,152	108,849	102,778	91,482	86,308
	Sulfur Dioxide	475	473	472	446	397	374
	Nitrogen Oxides	223	231	231	218	194	183

Table 7. Net Present Costs at zero degree with no tracking system.

Name	Capital	Operating	Replacement	Salvage	Total
Grid	USD 0.00	USD 200,688	USD 0.00	USD 0.00	USD 200,688
Solar PV	USD 75,000	USD 19,175	USD 0.00	USD 0.00	USD 94,175
System Converter	USD 43,504	USD 0.00	USD 37,857	−USD 5068	USD 76,293
System	USD 118,504	USD 219,863	USD 37,857	−USD 5068	USD 35,118.156

Table 8. Net Present Costs at 20 degrees with no tracking system.

Name	Capital	Operating	Replacement	Salvage	Total
Grid	USD 0.00	USD 197,975	USD 0.00	USD 0.00	USD 197,975
Solar PV	USD 75,000	USD 19,175	USD 0.00	USD 0.00	USD 94,175
System Converter	USD 43,504	USD 0.00	USD 37,857	−USD 5068	USD 76,293
System	USD 118,504	USD 217,150	USD 37,857	−USD 5068	USD 368,443

Table 9. Net Present Costs at 35 degrees with no tracking system.

Name	Capital	Operating	Replacement	Salvage	Total
Grid	USD 0.00	USD 195,967	USD 0.00	USD 0.00	USD 195,967
Solar PV	USD 75,000	USD 19,175	USD 0.00	USD 0.00	USD 94,175
System Converter	USD 43,504	USD 0.00	USD 37,857	−USD 5068	USD 76,293
System	USD 118,504	USD 215,142	USD 37,857	−USD 5068	USD 366,436

Table 10. Net Present Costs single-axis horizontal tracking.

Name	Capital	Operating	Replacement	Salvage	Total
Grid	USD 0.00	USD 160,642	USD 0.00	USD 0.00	USD 160,642
Solar PV	USD 75,000	USD 19,175	USD 0.00	USD 0.00	USD 94,175
System Converter	USD 44,325	USD 0.00	USD 38,572	−USD 5164	USD 77,733
System	USD 119,325	USD 179,817	USD 38,572	−USD 5164	USD 332,550

Table 11. Net Present Costs single-axis vertical tracking.

Name	Capital	Operating	Replacement	Salvage	Total
Grid	USD 0.00	USD 94,330	USD 0.00	USD 0.00	USD 94,330
Solar PV	USD 75,000	USD 19,175	USD 0.00	USD 0.00	USD 94,175
System Converter	USD 45,967	USD 0.00	USD 40,000	−USD 5355	USD 80,612
System	USD 120,967	USD 113,505	USD 40,000	−USD 5355	USD 269,117

Despite requiring additional tracking instruments, the dual-axis tracking system features the lowest PV array capacity at 289.909 kW compared with other systems. This lower capacity is contrasted with the system's ability to generate more electricity, reaching 400,467 kWh/year, largely driven by efficient incident angle control for optimal solar radiation absorption.

Table 12. Net Present Costs dual tracking.

Name	Capital	Operating	Replacement	Salvage	Total
Grid	USD 0.00	USD 48,305	USD 0.00	USD 0.00	USD 48,305
Solar PV	USD 75,000	USD 19,175	USD 0.00	USD 0.00	USD 94,175
System Converter	USD 48,575	USD 0.00	USD 42,270	–USD 5659	USD 85,187
System	USD 123,575	USD 67,480	USD 42,270	–USD 5659	USD 227,667

The fixed zero-angle PV system incurs the highest annual resource costs due to its relatively lower renewable fraction compared with other systems. In contrast, the dual-axis tracking case achieves a renewable fraction of 69.2% while meeting demand with its higher electricity generation capacity. Notably, the dual-axis tracking system demonstrates reasonable annual replacement costs, contributing to its long-term operational efficiency and economic viability. The battery component within the dual-axis system incurs the highest annual replacement cost, underscoring the significance of proper maintenance and lifecycle management.

The dual-axis tracking case surpasses other configurations in terms of performance and longevity, leveraging its sophisticated tracking mechanism. Despite its advantages, the operation and maintenance costs associated with Battery Storage Systems (BSS) are notably higher, nearly double those of solar PV arrays across all scenarios, highlighting the importance of efficient BSS management.

Figure 15 provides a detailed breakdown of converter and grid costs associated with different tracking systems, offering additional insights into the operational expenses and infrastructural requirements of each configuration. It is concluded that the comprehensive analysis of NPC, yearly costs, capacity, renewable fraction, and operational considerations underscores the importance of selecting the most cost-effective and efficient HES configuration tailored to specific energy generation and demand requirements.

During the life of the system, the batteries will need more upkeep and will need to be replaced at least twice. Also, since the price of diesel fuel has been going up for the last two years, using solar photovoltaic (PV) in the HES is a possible way to lower the LCOE and GHG emissions. Figure 16 illustrates the electrical output power of the solar PV system, the overall system power, and the proportion of renewable energy for all the tracking systems. The renewable fractions for the fixed (0, 20, 35) degree, CHA, CVA, and dual-axis situations are 61.4%, 61.25%, 61.5%, 64.5%, 69.9%, and 73.3%, respectively. The photovoltaic power production of the dual-axis tracking system is 27.75% higher compared with that of the fixed zero-degree system.

Table 6 clearly compares different tracking systems, starting from fixed or no tracking to dual-axis tracking systems. It can be seen that the dual-axis tracking system has the highest PV production with a renewable friction of up to three-quarters of the load, and relatedly, the emission produced is decreased by more than twenty per cent of the fixed system. The low power generation of this type is notable when compared with other variants. For instance, the dual-axis configuration stands out for its superior power output, coupled with relatively low operational costs. However, the drawback of a double-axis after a complex control system is the higher installation cost, which rises to fifty per cent for a fixed system. Comparing such types of tracking separately, it is found that the best angle of a fixed system is 35°, with a fixed initial cost, having more PV production and less emissions. Therefore, this angle is recommended for the South of Egypt, especially in Aswan and other cities located at the same geographical latitude. In the single-axis tracking system, it is found that the vertical is better in costs and emissions, except for the initial cost with few increases.

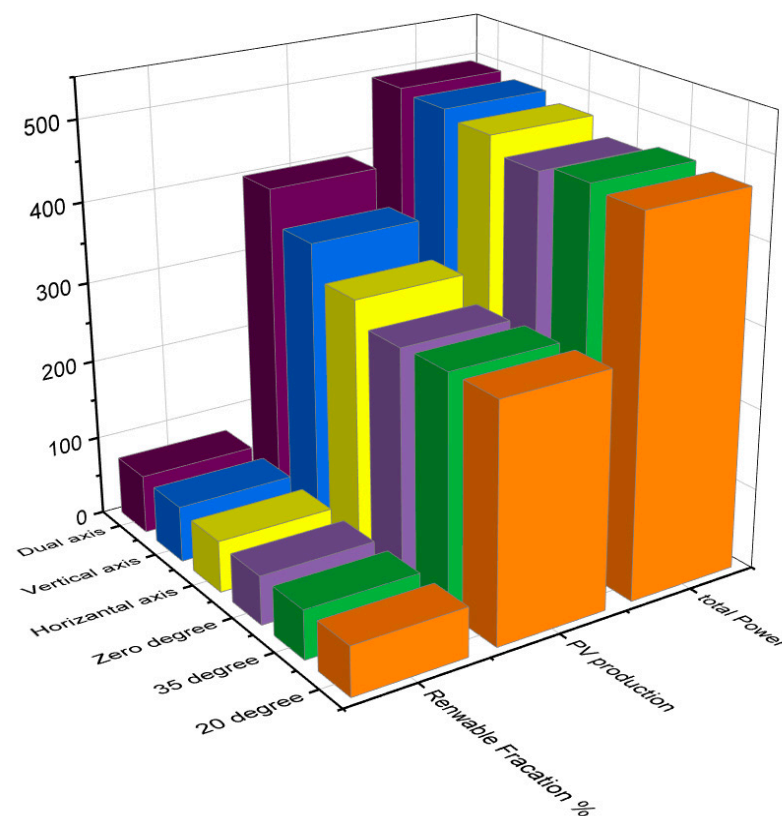


Figure 16. Total power, PV production, and renewable fraction of all cases studied.

This optimization study was performed to find the best way to combine the powers of the PV, the BSS, and the converter. In the optimization study, the LCOE as well as the share of renewable energy are both used as goals. The LCOE is changed from USD 1/kWh to USD 0.25/kWh for all probable combinations. The best PV, grid, and converter capacities for the AC main loads in the Aswan Campus are 150 kW, 172.7 kW/yr, and 109 kW, respectively. The converter costs are independent of the output power side for its capacity (capital cost) and maintenance (running or operation cost). Hence, the single-axis tracking is higher than the fixed in terms of converter cost.

3.2.5. Emission and Pollution Analyse

The impact of HES diversity on air emissions is a critical determinant in the establishment of a clean energy system. The system with the lowest greenhouse gas emissions during its lifespan has the least significant environmental impact. Table 6 indicates that the HES with dual-axis has the most minimal carbon footprint. The reduction in the number of different pollutants is directly proportional to the increase in the proportion of renewable energy in each scenario. This decrease in pollutants helps to mitigate the impact of the carbon footprint on the atmosphere of the city. Consequently, the health standards of the city are improved. Furthermore, the dual-axis tracking system exhibits the lowest NO_x emissions among all scenarios. The dual-axis tracking system has the lowest levels of SO₂ and Particulate Matter (PM) emissions, as described earlier. All pollutants and greenhouse gas emissions are quantified in kilos per year. According to Figure 17, the CHA, CVA, and dual-axis tracking systems, with the fixed angles of 0°, 20°, and 35°, respectively, result in reductions of CO₂ emissions by 51%, 51.5%, 54%, 59%, and 61%. For all the examined cases, the levels of other emission gases, such as CO, SO₂, and NO_x, as well as UHC and PM, show reductions of a similar extent as the ones of the CO₂ emissions.

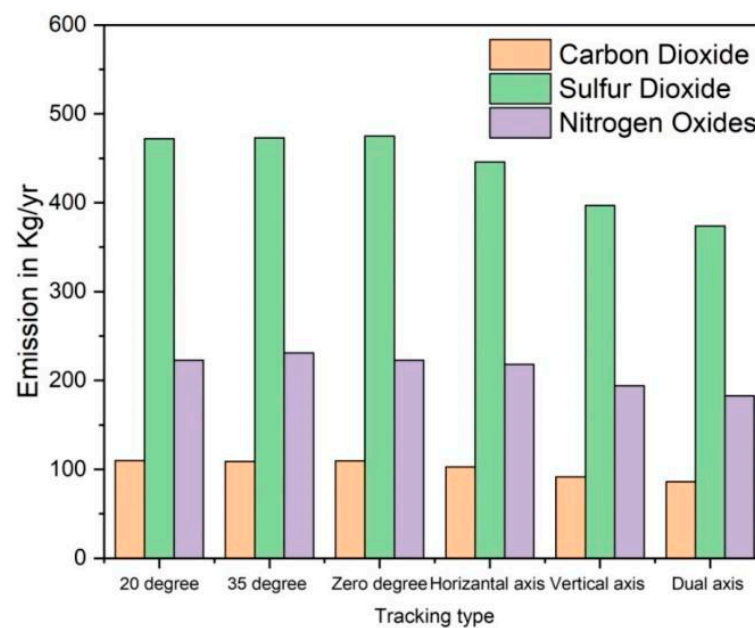


Figure 17. Summary of emissions produced from all tracking cases.

3.3. Compression between Max and Actual Power

When the PV capacity is set to 175 kW in HOMER simulations, the PV output is maximized. A thorough examination of the results reveals that this specific arrangement of resources not only leads to reduced expenses but also improves the proportion of renewable energy all the while decreasing environmental pollution. A comparison of Tables 5 and 13, which are identical save for the PV maximum capacity, reveals noteworthy enhancements in several parameters. In Case 3, which represents the best possible situation, there is a rise in photovoltaic (PV) production from 60% to 68%, a decrease in the Levelized Cost of Energy (LOCE) from 0.0647 to 0.0535, and an 8% reduction in carbon dioxide (CO₂) emissions. In addition, a comparison between Tables 5 and 14 highlights other advantages. When using dual-axis tracking, the Cost of Energy (COE) drops from 0.0348 to 0.0267. At the same time, the renewable percentage increases from 73% to 77%, resulting in a decrease in emissions. These findings highlight the benefits of maximizing PV capacity, not just in terms of cost-effectiveness but also in terms of achieving greater sustainability and environmental performance.

Table 13. Comparison of the 4 cases with their total cost (when PV MAX power 175 KW).

Parameter	Grid Only	Grid with Batteries	Grid with PV and Converter	Grid with PV, Converter, and Batteries
Total Net Present Cost	USD 664,894.30	USD 668,751.60	USD 327,848.50	USD 329,671.10
Levelized Cost of Energy	USD 0.150	USD 0.151	USD 0.0535	USD 0.0539
PV Capacity	0	0	175 KW	175 KW
System Converter	0	2.05 KW	127 KW	127 KW
Grid Purchases (Kwh/yr)	346,750	346,750	160,510	160,510
PV Production (Kwh/yr)	0	0	340.79	340.79
CAPEX	0	USD 1621	USD 138,487	USD 138,933
OPEX	USD 52,013	USD 52,187	USD 14,813	USD 14,921
Co ₂ Emitted (kg/yr)	219,146	219,143	101,442	101,449

Table 14. Comparison of all tracking system types (when PV Max 175).

Tracking System		Fixed (NO Tracking)			Single-Axis		Double-Axis
		Zero Degree	20 Degrees	35 Degrees	Horizontal	Vertical	
Cost	NPC	331,055	327,893	325,486	289,550	232,511	192,467
	COE	0.0542	0.0535	0.0531	0.0458	0.0346	0.0268
	Operation	15,070	14,813	14,628	11,762	7170	3923
	Initial	118,504	118,504	118,504	119,325	120,967	123,575
Renewable Friction		66.3	66.5	66.7	69.6	74.6	77.4
PV Productivity		338,209	340,109	342,756	370,551	418,412	467,212
Emission (kg/yr)	Carbon Dioxide	101,846	101,442	101,148	94,959	84,295	80,027
	Sulfur Dioxide	442	440	439	412	365	347
	Nitrogen Oxides	216	215	214	201	179	170

3.4. Comparison Results with Other References

Table 15 shows how the current study compares against others like it. First, switching to renewable energy sources, like solar and wind, will always result in lower energy bills. Second, using a combination of the various renewable energy sources accessible has been shown to be the most effective strategy. It is concluded that the current study's energy system stands out for its cost-effectiveness, environmental sustainability, reliability, technological advancements, and scalability compared with the other systems discussed. It showcases a balanced mix of renewable energy sources, storage capacity, grid connectivity, and technological innovation to provide efficient and effective energy solutions. The use of renewable energy sources, like PV, in the current study's system reduces the reliance on fossil fuels, leading to a lower carbon footprint and environmental impact compared with systems that use diesel generators or bio-gen sources (Tareq Salameh [35] and Abdulla Al Wahedi [55]). Furthermore, the Cost of Energy in the current study's system (PV/Battery/Grid/Converter) is significantly lower at USD 0.0348 per kWh compared with other systems, such as PV/Battery/Diesel/Grid at USD 0.25 per kWh and PV/Battery/Wind/Bio-Gen/Electrolier at USD 0.285–0.329 per kWh. This indicates that the current study's system is more cost-effective.

Table 15. Comparison of energy cost results with those of other similar studies.

Reference	System	Cost of Energy (USD/KWH)	Case Study
Hisham M. and A.H. Elbatran [52]	PV/Wind/Battery/Grid	0.0750	Jabel Ali Port in UAE
Tareq Salameh [35]	PV/Battery/Diesel/Grid	0.25	in Khorfakkan, United
Abdulla Al Wahedi [55]	PV/Battery/Wind/Bio-Gen/Electrolier	0.285–0.329	Qatar
Mustafa M.A. [37]	Utility/Battery/PV/Converter	0.11	Makkah in Saudi Arabia
Current	PV/Battery/Grid/Converter	0.0348	AASTMT Aswan campus

4. Conclusions and Future Work

This study sets out to explore the viability of solar PV systems as a means to curb carbon emissions and foster energy sustainability. Focused on maximizing solar PV generation at the examined educational facility, the investigation delves into the renewable energy potential of the AASTMT Aswan Campus. Initially, the study examines the campus' energy demand before delving into the impact of integrating PV panels, converters, and batteries on both cost and environmental factors.

The subsequent phase employs HOMER simulation software to validate and refine the findings. Conducting a comprehensive techno-economic analysis of the campus, this study is bifurcated into two main segments. The first segment scrutinizes the effect of varying component usage percentages, while the second segment compares different tracking systems. This study reveals that, across all the tracking systems considered, a fixed experimental model falls short of harnessing the full solar potential of the region. The results indicate that implementing a solar PV system leads to a significant reduction in total costs, halving them in comparison with traditional systems, along with notable emission reductions. Moreover, adopting tracking systems, particularly the dual-axis configuration, demonstrate a remarkable 20% decrease in emissions compared with fixed models. These findings underscore the compelling economic and environmental benefits of embracing solar PV technologies within educational facilities. The inclusion of a PV renewable system can lower traditional grid demand by 38% and emissions by 50%, based on the results. In addition to increasing energy production by 30% over fixed panels, the dual degree tracker for PV panels can lower carbon dioxide emissions by over 20%.

Reducing energy costs in Egypt and the surrounding region could have several significant effects, such as economic growth, a living standards increase, development, energy security, environmental benefits, and government budget relief [56].

A discussion of the effects of particular actions is included, emphasizing how rebound effects might reduce energy and carbon reductions. It suggests that reducing working hours and income should have a greater impact on reducing energy use and emissions than that of downshifting [57].

4.1. Recommendations for Future Work

- Applying the dual tracking system to the experimental model for the campus and verifying all the simulation results, and adding more renewable resources to both the simulation and experimental work.
- Using an experimental model adopting an Artificial Intelligent system to predict the best position of PV panels.
- Using high temperatures in cooling systems for future study, and in circuits that combine cooling the panels with the heat cycle.

4.2. The Work Limitations

- The area available to the project (the area of the side and roof, which restricts the quantity of PV panels utilized and the electricity generated)
- Weather conditions (high temperature and dusty weather of Aswan also affect PV efficiency)
- The availability of components and their cost (high inflation rate of exportation system)

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Abbreviations

PV	Photovoltaic
BAPV	Building Applied Photovoltaic
NZEBs	Net-Zero Energy Buildings
PV/T	Photovoltaic/Thermal
HVAC	Heating, Ventilation, and Air Conditioning
RE	Renewable Energy
CPV	Concentrating Mirror PV
HOMER	Hybrid Optimization Model of Multiple Resources
ACO	Ant Colony Optimization
SA	Simulated Annealing
FFA	Firefly Algorithm
FWA	Firework Algorithm
GSO	Glowworm Swarm Optimization
NASA	National Aeronautics and Space Administration.
CHA	Continuous Horizontal Axis
COE	Cost Of Energy
NPC	Net Present Cost
DG	Diesel Generator
HES	Hybrid Energy System
BSS	Battery Storage System
SC	Soft Computing
PSO	Particle Swarm Optimization
ABC	Artificial Bee Colony
FPA	Flower Pollination
GWO	Grey Wolf Optimization
HPO	Human Psychology Optimization
GMPPT	Maximum Power Point Tracking
GHI	Global Horizontal Irradiance
CVA	Continuous Vertical Axis
GHG	Greenhouse Gases

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