Advanced Sciences and Technology Journal

ASTJ vol. 2, no. 2 (2025), P 1019
10.21608/astj.2025.343506.1019
https://astj.journals.ekb.eg/

Optimization Strategic Profiles of Solar PV System Operation

A. Mostafa[1,2*], B. H. El-Mahdy[2], B. M. Abd El-Magied[2], S. M. El-Moslmany[2], T. A. Shahin [2], G. T. Khalaf[2], A. Z. Bakir[2], Y. A. Kamel[2], M. H. Emara[2], H. H. Mostafa[2], N. H. Mostafa[3]

[1] Mechanical Power Engineering Department, Faculty of Engineering- at El-Mattaria, Helwan University, Egypt.
[2] Energy and Renewable Energy Engineering Department, Faculty of Engineering and Technology, Egyptian Chinese University, Cairo, Egypt
[3] Mechanical Power Engineering Department, Faculty of Engineering, Zagazig University, Egypt.
[*] amostafa@ecu.edu.eg

A R T I C L E I N F O

Article history:
Received 10 December 2024
Revised 7 April 2025
Accepted 20 April 2025
Available online 25 April 2025

Handling Editor: Prof. Dr. Mohamed Talaat Moustafa

Keywords:
Solar system trackers
On- and Off-grid solar systems
Hybrid solar system
Solar energy

A B S T R A C T

This review paper examines the optimization of solar photovoltaic (PV) systems for maximum efficiency and performance. It analyzes different PV system configurations, including on-grid and off-grid systems, and investigates the impact of various mounting structures, such as fixed, single-axis, and dual-axis tracking systems. By evaluating global case studies and conducting simulations, we aim to identify the most cost-effective and energy-efficient solutions for different applications and locations. The paper also explores the integration of optimal solar tracking systems to maximize power output and meet specific energy demands. While dual axis tracking systems exhibit higher energy capture, it is analyzed demonstrates that fixed structures offer a more economical and practical solution, particularly for large-scale installations with extensive land availability and a considerable number of solar PV.

Nomenclature:

A	Area of land
A_{pv}	Area of Photovoltaic Panels
N_{PV}	Number of Photovoltaic Panels
P_{Pv}	Power of single Photovoltaic Panels

Abbreviations:

REF	References
PV	Photovoltaic
EQ	Equation
Deg	Degree
DC	Direct Current
Fig	Figure
AC	Alternative Current
RE	Renewable Energy

1. Introduction

Worldwide is converting to Renewable Energy (RE) as the energy scenario according to forecasting shows that energy demand in 2050 will cover 86% of RE will be used and the highest share is solar power with 8519 GW **[1]** in 2022, solar energy was the fastest-growing RE source in recent years, generating 1,294 TWh, a year-on-year increase of more than one quarter (25.6%) **[2]** A PV solar power system is a RE system that converts sunlight energy into electricity. Nowadays, solar energy has the potential to satisfy the current and prospective energy requirements of the world **s**olar PV systems face a lot of challenges due to the availability of land and choosing the suitable system and component to present its aim besides choosing the suitable tracking system that is compatible with the area and the system capacity and that is by studying previous case studies and show options available.

1.1 Previous case studies:

By studying previous case studies, it is found that **Halabi et al. [3]** explored the PV grid system at the University of Malaya with three types of modules: Polycrystalline, Monocrystalline, and Thin Film, totaling 6.725 kW. Thin films perform better than others under the Malaysian climate. The study demonstrates the effectiveness of installing different PV technologies in similar climatic regions and highlights the role of environmental factors in increasing efficiency Also, performance analysis research conducted by **Apoorva et al. [4]** at a place called Belakawadi in Mandya district in the state of Karnataka, India established by Karnataka Power Corporation, a 5MW solar PV plant using PVWATT and PVsyst software.

Issues like fluctuating solar radiation and temperature changes may have interfered with energy production. Applying fixed mounting structures with polycrystalline modules to ensure better performance and consistent energy generation. 22560 PV modules were used in this project. Over a year, it produced 7.7 million kWh of electricity with a performance ratio of 77.3%. Another case study was conducted by **Ardiani et al. [5]** who used a Greentek Polycrystalline 250W PV module with ICA Solar 20kW Inverter On-Grid. 48 PV panels (250 W) and a 10kW Inverter were used for USD 19,734.79. In the scenario where the PV covered the whole building with an energy load of 240 kWh/m2/year, it could deliver a total energy of 65,957 kWh/year and still need to import 368,867 kWh from the grid.

After calculating the annual savings, the payback period of investing 224 PV panels is 15 years. If the PV only covered the energy load for lighting which is only 15% of the total building energy load (36 kWh/m2/year), it could deliver the same total energy load of 65,957 kWh/year and it would export 733 kWh/year to the grid. The payback period would be reduced to 12 years. The initial cost for investing in 224 PV panels was USD 91,997.43 while for 176 PV panels it was $72,283.69. while **Imam et al. [6]**discuss a 12.25 kW residential rooftop solar PV system in Jeddah, Saudi Arabia. The system utilizes 35 mono-crystalline silicon modules with a total area of 57 m², achieving an efficiency of 21.49%. It is mounted at an optimum tilt angle of 21° (fixed structure) to maximize solar energy capture. The system includes two inverters rated at 10 kW of maximum AC power. The system generates 23,589 kWh annually, fulfilling approximately 87% of the apartment's electricity needs. Despite high solar radiation in

Jeddah, efficiency is slightly reduced due to temperatures. Also, **Mac-Lean et al. [7]** evaluate grid-connected solar PV systems at two Chilean universities. The University of Magellan is planning a 94.1 kW system that will cover 10% of its energy needs. At the same time, the Faculty of Physical and Mathematical Sciences of the University of Chile has a small pilot system of 15 kW that will provide Campus Power.

In addition, **Kumar et al. [8]** discussed a rooftop solar PV system presented to meet the energy needs of an office in Bikaner, India. Using PVsyst software for simulations, the system showed the ability to deliver 1068.12 kWh of energy per year, which is close to meeting the department's needs. An off-grid configuration was chosen to provide a sustainable solution to ensure power availability during grid outages and reduce reliance on conventional grid power. The analysis includes system performance and loss metrics, focusing on storage optimization through battery integration. Off-site systems are ideal for remote locations or unstable networks, providing reliability and autonomy.

Escobedo et al. [9] studied the implementation of a solar PV system in the National School of Advanced Studies of Juriquilla in Mexico to reduce electricity consumption and power the CNC machine in its laboratory. The system consists of 50 API-M330 mono-Si panels, each producing 330W, with a total capacity of 17.25 kW, and a PV240-277V inverter is used. This system generates about 345 kWh per year. The CNC will have a peak load of 22.4kW. Building on the previous point Kerala State has been buying and importing power from outside the State to meet the increasing demand. More than 70% of power is being imported from Central Grid. Since only 30% of the power is being met by internal generation, it is natural for the State to tap the abundant RE sources to the maximum to meet its energy demands.

On a related note, Duke University Case Study conducted by **Zhang et al. [10]** has implemented solar PV systems as part of the university's goal to achieve carbon neutrality by 2024. The total technical potential of the system is 87.1 MW, with rooftop systems capable of supporting 51.5 MW and parking capable of 35.6 MW. Tools such as PVWATTS and HOMER are used to monitor system performance to predict energy production under different conditions. Also, **Krishna et al. [11]** have designed a simulated PV system for Taylor’s University, School of Computer Science and Engineering, Malaysia, consisting of 510.72 kW grid-connected rooftops using monocrystalline JKM380M-72-V solar panels each solar panel 380W and Context CL-60E inverters with 98.5% conversion efficiency.

The system is optimized at 0° in dry seasons and 19° in wet seasons adapted for Malaysia environment. With a performance ratio of 81.4%, it is expected to produce 555 MWh per year and have a payback of 7.4 years. Also, PV array losses 17.1%. In addition, **Anber [12]** investigates the efficiency of Building Integrated Photovoltaics (BIPV) into the skins of office buildings to reduce energy consumption and solar heat gain. It includes a comparative simulation of two types of BIPV systems and evaluates their feasibility, payback period, and energy-saving potential. The building of the case study is the National Bank of Egypt Headquarters, New Cairo, Egypt with an Annual energy consumption (base case): of 1,414,229 kWh.

A simulation using Design Builder software established the baseline energy consumption at 1,414,229 kWh, after which the BISOL XL Series multi-crystalline PV modules were integrated into 680.74 m² of the building’s skin, resulting in a 6.9% reduction in energy consumption to 1,317,745 kWh, annual savings of $9,648.4, and a payback period of 5.8 years; subsequently, the Jonsol JSM-72 PV modules were integrated into the same area, a 5.2% reduction in energy consumption to 1,339,501 kWh, annual savings of $7,472.8, and a payback period of 6.5 years. Shifting focus to **Wael et al. [13]** who focused on designing and simulating a grid-tied PV system for Pharos University in Alexandria.

The aim is to reduce electricity expenses by integrating a PV system while also minimizing noise and harmful emissions from diesel generators to support a cleaner. The study evaluates the economic and environmental benefits of installing rooftop PV systems on university buildings. The available roof area for implementing PV is 6165.5 m², total energy yield of 1654 kWh per year at optimal orientation, The PV system would produce a total power of 1366.3 kW. Also, the study by **Emeara et al. [14]** evaluates the feasibility and optimization of a PV plant at Cairo International Airport, focusing on maximizing energy production through optimal panel orientation using the PVsyst software.

An area of 500,000 m² has been identified for Terminal 3, with 100,000 m² allocated to PV cells comprising 48,750 units of 410 W panels arranged in 650 rows and 15 columns. The study explored two optimization scenarios: fixed annual slope angles and double-seasonal angles. Simulations have determined that the optimal annual fixed tilt angle is 30°, which produces 35 GWh per year. The optimization of the dual seasonal slope, with a summer tilt of 10° and a winter tilt of 50°, allowed further increase the energy production to 36.5 GWh per year. This optimization allows the PV system to save 50% of the annual electricity consumption of Terminal 3 and significantly contributes to the reduction of greenhouse gas emissions.

Evaluation of the energy performance and loss analysis of a 100-kW grid-connected rooftop solar PV system conducted by **KhareSaxena et al. [15]** installed at an institutional building in Bhopal, India. and comparing real data to simulated results. The system is composed of 339 polycrystalline PV panels with a total capacity of 100 kW meeting 80% of the building's daytime energy requirements, reducing reliance on the grid, saving 1,100,000 INR in electricity costs, and achieving a payback period of 5.9 years. It offsets 136 tons of CO_2 emissions per year.

During the summer, peak electricity demand becomes very high (93% increase) reaching a peak of 54 GW. To meet this increasing demand, The King Abdullah Center for Atomic and RE plans to boost capacity to 120 GW by 2032, While **Sher et al. [16]** evaluated the power of a 12 MW PV at Doncaster Sheffield Airport in the UK. The project will have 30,000 Mult-crystalline PV panels and generate 12,411.69 MWh of electricity per year, doubling the airport's power generation to 6,951.55 MWh. The plant has an average efficiency of 82.59% and a maximum capacity utilization of 21.67% during the dry season, demonstrating high efficiency. The panels are installed with adjustable tilt angles (14° in winter and 60° in summer) to maximize sunlight absorption. The system includes advanced inverters with an efficiency of up to 98.6% and will reduce CO_2 emissions by more than 10,562 tons per year.

In alignment with Saudi Arabia's Vision 2030, the Kingdom of Saudi Arabia is- undergoing various stages and working on projects to make their airports environment-friendly and pollution-free. On the Campus, the installed system has 774 modules connected to seven inverters, resulting in a total installed capacity of 219.78 kW Also, in the state of Kerala's case study by **Ajithgopi et al. [17]** reviewed the implementation model of solar PV micro-grids, 250 kW solar PV was utilized in the provision of electric supply to the countryside areas. The system consists of 300 panels, each one with 300 W capacity, connected to two 60 kW central inverters. A battery storage system with a capacity of 500 kWh provides energy supply during the absence of the sun.

This model increases energy security and lowers the electricity tariff of local self-governments. For the university, a similar system can reduce operational expenses and become a green energy solution for the micro-grid system. In addition, **Al Mehadi et al. [18]** Designed and simulated a PV system for The Islamic University of Technology is in Board-Bazar of Gazipur district of Dhaka division, The area is still quite underdeveloped, and load shedding is a common problem. Then **Algarni et al. [19]** studied the performance at the King Abdulaziz International Airport Solar PV Park, located in Jeddah, Saudi Arabia, with an installed capacity of 20 MW. PV modules used were Trina solar TSM–540DE19 540 WP and 2500 KW Sungrow inverter, Total PV modules used 925,925 and 158 inverters.

The panels installed in the solar plant are made of monocrystalline silicon, which enhances energy conversion. The cost analysis shows that the energy produced will cost $0.073/kWh. A detailed economic analysis of 25 years showed that the payback period of the system is 4.1 years. Also, Univali is a communitarian higher education institution located in the south of Brazil. It has seven campuses. One of those campuses is located in the city of Biguaçu and was the first university campus in Brazil to be 100% energy autonomous. Since 2018, the Biguaçu campus has operated with 596 solar panels which occupy an area of 1000 m². Such a structure produces 196 MWh/year **Santos et al. [20].**

In addition, an economic Feasibility Study was carried out by **Shafie et al. [21]** At the University Utara Malaysia to make electricity bills lower and boost sustainability. Crystalline silicon panels would be installed on campus buildings with roof sizes ranging from 4,523 to 24,596 m² using fixed mounts that require 9 m² per panel. These panels are 19% efficient. Depending on the size of the building, the system is projected to generate between 876,846 and 4,766,382 kWh annually, with any extra power sold to the grid under the NEM 3.0 program. Despite obstacles including high installation costs and roof suitability, the 20-year project is anticipated to save millions in electricity costs. The tracking system benefits from Basra's extended summer sun of 9.5 hours per day and an average annual solar radiation of 8.5 hours 50 kWh/m²/day.

Despite the higher operating costs, the increased efficiency of the tracking system and the environmental aesthetics make it favorable for RE projects. A study by **Kassem et al. [22]** at a residential building with a rooftop area of 100 m² in Baghdad, Iraq. A grid-connected PV system of the proposed 6.4 kW grid-connected observed the two-axis system has the maximum energy generation compared to vertical and include systems. In addition, this is another case in which **Eiva et al. [23]** focus on grid-connected PV systems designed for rural schools. The system uses single-sided PV modules with a capacity of 135 kW and two inverters (central and array).

The roof area is optimized for good panel installation. The average load is 357 kWh/day, and the peak time is during the university period. Adding **Duma [24]** aims to help startups save on electricity bills by using grid-connected PV power systems. This system is a game changer, reducing energy costs by 70%. This approach saves money and creates a practical and reliable solution. while **Nabil et al. [25]** focus on a grid-connected solar PV system in Bakaliya, Bangladesh, designed to produce 15 MW of electricity. The method of connecting to the grid was chosen because it is low maintenance, does not depend on batteries, and is suitable for transferring more energy to the grid. The system achieved a high efficiency of 84.03%, produced 21,510,186 MWh per year, and reduced CO_2 emissions by 252,168.5 tons during its lifetime.

Financially, it shows a competitive electricity price of $0.024/kWh and a payback period of 4.5 years, with a return on investment of up to 389%. The study shows the potential of the system in promoting local electricity generation and achieving sustainable energy goals. Also, **Navothna et al. [26]** studied the performance of a 1 MW solar PV array connected to the roof of GITAM University in Visakhapatnam, India. The system, which has been operational since 2018, has 3,078 PV modules and 23 inverters with capacities of 20 kW and 50 kW. It sends all the electricity generated to the national grid and is monitored for three years (2018-2021). In the first year, the annual energy production was 1,376.29 MWh, and in the third year, it decreased to 1,115.73 MWh, with a system efficiency of 11.39%.

Key performance indicators include efficiency ratios of 0.68, 0.62, and 0.58, and duty cycles ranging from 15.5% to 12.72%. The system reduced CO_2 emissions by approximately 2,145,406 tons CO_2. Adding a study by **Alfaoyzan et al. [27]** investigates the use of solar PV systems at Sulaiman Al- Rajhi University in Saudi Arabia to achieve a nearly zero-bill campus, and compares two scenarios: one covering only the roofs of buildings and another expanding to adjacent land; the systems, with capacities of 1.2 MW and 5.3 MW, respectively, produce annual energy outputs of 2.1 GWh and 10.1 GWh, covering 24% and 113% of the university's energy needs, with cost-effective increased energy costs of $0.026-$0.028/kWh, and achieving payback periods of 10 years for the smaller system and 8.1 years for the larger, while significantly reducing greenhouse gas emissions, such as CO_2 by 7,170 tons annually in the larger system.

Also, **Fallaha et al. [28]** Studied the design and installation of a PV system in the parking lots of King Faisal University to reduce dependence on the electricity grid and support sustainable development, covering approximately 6,500 m^2 in its initial phase with plans to extend it to 140,000 m^2. The financial analysis estimates an initial cost of SAR 3.37 million, with annual savings of SAR 520,000 and a payback period of seven years. Over 25 years, the system is expected to generate a cumulative revenue of more than SAR 11 million while reducing carbon emissions by 1,300 metric tons annually. While **Amekah [29]** at Islamabad, Pakistan solar project of 8.79MW. terrain elevation of 552 meters and tilt angle of 29.5^o with fixed structure for an on-grid solar system with a payback period of 12 years using a 14664 module of 600W.

In contrast, Studies show that using grid-tied solar power plants can improve power quality by reducing voltage fluctuations and harmonic distortion, resulting in more reliable power delivery. Also, **Ajagbe's [30]** study looked at grid-connected solar PV arrays for rural homes in Texas. This approach was chosen because it meets energy needs, especially during outages, and reduces electricity bills through net balancing and other financial incentives. It has proven to be a good and effective solution, providing a cost-effective solution. **Balat et al. [31]** study assesses the technical, and economic, of grid-connected PV systems in Egypt, focusing on a small 1.4 kW large-scale PV system in Dokii, Cairo, and a large 1 MW PV system in Ras El Hekma and Sohag.

This system consists of six 250 W solar panels and a 2-kW inverter. In addition, two large-scale 1 MW PV systems located in Ras El Hekma and Sohag were studied to assess the impacts of different weather conditions on performance. The results of the 1.4 kW small-scale PV system in Dokii showed an annual energy production of 2,507.69 kWh, with an average daily production of 6.87 kWh. Seasonal variations revealed the highest energy production in summer (789.4 kWh) and the lowest in winter (167.62 kWh).

The system cost was $0.3125/W for the modules and $0.146/W for the inverter, with a payback period of 6.4 years and an increased cost of energy (LCOE) of $0.04/kWh. For large-scale 1 MW PV systems, Sohag demonstrated the highest annual energy production at 1,805.8 MWh, with 5.43 kWh/kW/day, while Ras El Hekma generated 1,982.9 MWh annually at 4.93 kW/day.

Economically, Sohag achieved a payback period of 5.4 years and an LCOE of $0.03/kWh, while Ras El Hekma achieved a payback period of 6.1 years and an LCOE of $0.04/kWh. Sohag emerged as the most favorable location due to its higher solar irradiance and lower operating costs. On the other hand, a 6.9 MW rooftop solar PV system installed at University Tun Hussein On Malaysia as part of a self-consumption project program under a Supply Agreement for Renewable Energy (SARE) contract a performance study by **Batcha et al. [32]** Another study worked on analyzing its energy production, efficiency, financial benefits, and environmental impact over one year, reporting an average system efficiency of 11.86%, an annual performance ratio of 0.78, CO_2 emission reduction of 5450 tons annually, and potential savings of 25.1 million RM over 25 years.

While **Qamar et al. [33]** evaluated an 8.79 MW PV system for the National University of Science and Technology (NUST) in Islamabad, Pakistan, the system benefits from high solar radiation of 5.89 kWh/m² per day. The system was predicted to produce 11,270,771 kWh per year, achieving a maximum efficiency of 76.2% and an efficiency of 16%. The cost of generating electricity is $0.0141 per kWh, with significant environmental and economic benefits. Also, **Saddari et al. [34]** conducted a technical analysis of a PV system at Sunyani Teaching Hospital in Ghana using a benchmarking program. The proposed system can generate 9,418,145 kWh per year, powering the hospital and reducing its dependence on the national grid.

The research shows economic benefits such as a four-year payback period and CO_2 savings over the life of the project, demonstrating the power of solar energy in health facilities in developing regions. While a design that satisfies a 130 kW grid's electrical needs for a local factory in Al Obour City, Egypt (at Coordination 30.19373º, 31.44213º) stated using a fixed tilt mounting structure the system produces 212.7MWh each year they used 298 modules consists of 19 strings connected with 2 Huawei inverters inverter1 60kW and the other 50kW each has 6 MPPTs and 12 female input connectors with the optimum DC to AC and the estimated performance ratio is 80.04% **Mustafa et al. [35]**.

Tables 1. 1, 2, and 3 represent the most used system as the On-Grid. In the presence of the grid, two options were selected (On-Grid and Hybrid) there were several factors considered such as cost, energy requirements, and reliability. For cases mentioned above when the system was On-grid the payback average period was (5.6 years ~ 15 years) depending on the system capacity. In cases where the grid was not available, and there was not any electricity source, the Off-Grid system was the solution since it is self-dependent but one of the disadvantages is the cost since batteries increase the system cost.

The hybrid system was the second most used system since it does not rely on the availability of the grid and when the available area is not enough to generate the required capacity. It increases the reliability of the system even if it is combined with the grid or with another source of electricity, and it is more suitable for areas with unreliable energy grids or a high-cost tariff. Also, it is found that at locations of high irradiance, the fixed structure is the most used mounting structure, also it provides low cost compared to single and dual axis, it is also found that single and dual axis is commonly used in locations that have low irradiance to maximize the capture of sunlight.

Table 1.1: Summary of previous case studies (2019:2021).

2019:2021 REF. Cases	Available Area	Capacity	System Type	Mounting Structure
[7]	170 m²	12.25 kW	On- Grid	Fixed
[10]	96.7 m²	17.25 kW 345 kWh/year	Hybrid	Fixed
[11]	433,658 m²	87.1 MW	On-Grid	Fixed
[12]	2646 m²	510.72 kW	On-Grid	Fixed
[15]	500 km²	36.5 GWh/ year	On-Grid	Fixed
[16]	1980 m²	100 KW	On-Grid	Fixed
[17]	66,275 m²	12MW 12,4 MWh/year	Off-Grid	Fixed

Table 1.2: Summary of previous case studies (2022-2023)

2022:2023 REF. Cases	Available Area	Capacity	System Type	Mounting Structure
[23]	100 m2	6.4 kW	On- Grid	Dual axis
[24]	628 m²	135 KW	On-Grid	Fixed
[26]	73,793 m²	15 MW 21,510.186 MWh/year	On-Grid	Dual axis
[28]	10300 m²	1.2 MW	On-Grid	Fixed
[28]	49204 m²	5.3 MW	On-Grid	Fixed
[22]	54,916 m²	1,425,664 kWh/year	Hybrid	Fixed

Table 1.3: Summary of previous case studies (2024)

2024 REF. Cases	Available Area	Capacity	System Type	Mounting Structure
[30]	552 m²	8.79 MW	On-Grid	Fixed
[31]	175 m²	8.036 kW	Hybrid	Fixed
[33]	46,758 m²	6.9 MW	Off-Grid	Fixed

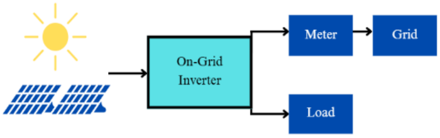
2. Scope and Modeling Configurations

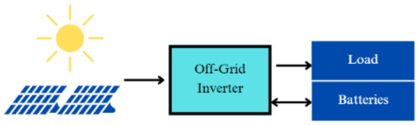
2.1. Solar PV Systems Configuration

To design and size a solar PV system, some parameters must be decided first, such as whether the system will be on-grid, off-grid, or hybrid based on the conditions of the project site. Each system type has specific components and considerations that must be addressed to ensure optimal performance.

Table 2.1. Comparison of PV systems configuration

System Type	Description	Components	Advantages	Figure
On-Grid System	Connected to the public electricity grid via a suitable inverter to convert DC power from PV modules to AC. Allows for electricity monitoring and excess energy selling using a Net Meter. **[36]**	PV modules, on-grid inverter, AC disconnect, main panel, and Net Meter. **[37]**	No dependency on storage systems. Excess energy can be sold to the grid. Suitable for urban areas with grid access.	**Figure 2.1** ON-Grid Systems
Off-Grid System	Independent of centralized grid infrastructures. Provides energy needs in remote areas using renewable resources like solar. **[38]**	PV modules, storage system (batteries), off-grid inverter. **[39]**	Reliable for areas without grid access. Full energy independence.	**Figure 2.2.** Off-Grid Systems
Hybrid System	Combines PV systems with energy storage to provide a stable power supply. Addresses solar energy intermittent using advanced storage technologies.	PV modules, PV-EES (photovoltaic-electric energy storage) system, hybrid inverter. **[40]**	Provides stable and reliable power. Suitable for grid regulation and resilience. Increasingly adopted for building applications.	**Figure 2.3** Hybrid Systems





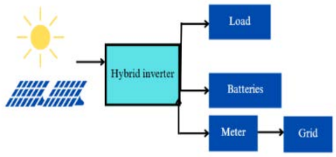


Figure 2.1 ON-Grid Systems [37] **Figure 2.2. Off-Grid Systems [38]** **Figure 2.3 Hybrid Systems [40]**

2.2. Mounting structures

Solar PV systems are installed using three main types of mounting structures—fixed, single-axis, and dual-axis. Fixed structures are cost-effective and suitable for static installations with minimal maintenance needs. Single-axis trackers rotate in one direction to follow the sun, boosting energy output, especially during sunrise and sunset. Dual-axis trackers adjust along two axes, offering the highest energy efficiency but are complex and expensive.

Table 2.2. Comparison of Mounting Structures.

System Type	Description	Advantages	Challenges	Control Technologies	Figure
Fixed Mounting Structures	Fixed systems optimize tilt angles based on location and materials like galvanized steel. Suitable for urban, rooftop, and all-terrain installations.	Energy-efficient, economical, easy to install and maintain.	Requires precise angle selection, lower performance in variable conditions, susceptible to high wind speeds.	Not applicable.	**Figure 2. 5.** Fixed structure side view.
Single-Axis Mounting	Rotates panels in one direction to track the sun, increasing energy yield by 20-30%. Popular for horizontal trackers due to power gain and reliability.	Cost-effective, easy to maintain, higher energy output than fixed systems.	Less effective in areas with significant sun angle variations.	**Time-Based:** Simple, cost-effective, pre-programmed algorithms. **Light-Sensor:** Responsive to sunlight, higher maintenance. **Hybrid:** Combines both, highly accurate but costly.	**Figure 2.6.** Single-Axis Tracker.
Dual-Axis Mounting	Tracks the sun along both vertical (north-south) and horizontal (east-west) axes for maximum energy capture.	Optimal energy production, effective in high and seasonal insulation areas.	High mechanical complexity, expensive maintenance, potential mechanical failures.	Microcontroller-Based: Low-cost, suitable for small to medium projects. **PLCs:** Industrial-grade, reliable for large-scale systems.	**Figure 2.7.** Dual-Axis Tracker.

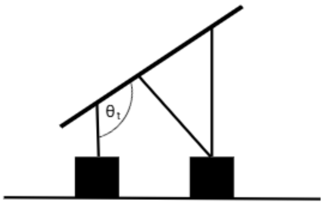


Figure 2. 5. Fixed structure side view [41]

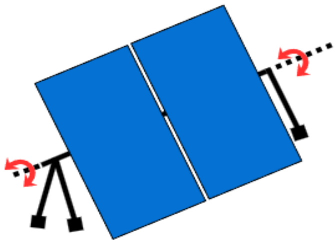


Figure 2.6. Single-Axis Tracker [41]

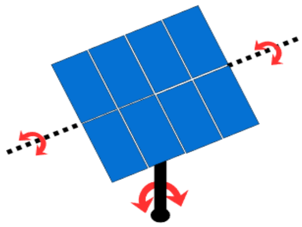


Figure 2.7. Dual-Axis Tracker [41]

2.3. Theoretical Comparison

This section shows the comparison between orientation systems (Fixed, Single-Axis and Dual-Axis) by Total energy produced and economically by the System Total cost.

Assuming a constant area of 100 m² for all orientation system conditions, the PV module used in this comparison is the Jinko Solar 610 Mono-Facial Module, (These conditions were simulated based on the Cairo, Egypt Location)

Table 2.3, Jinko Solar 610 Mono-Facial Module [42]

PV Module	
Model	JKM610-635N-66HL4M-(V)-F2-EN
Material	Mono-Crystalline
Module Area	2.67 m2
Module Capacity	610 Watt
Efficiency	22.58%

2.3.1. Calculations

Area of PV panel = 2.67 m²

The number of panels used $N_{PV} = A \div A_{PV}$ eq. (1)

Total output power of panels (W) = $P_{PV} \times N_{PV}$ eq. (2)

Table 2.4. Calculations Table

	For Constant Area (100 m²)	**For Constant Area (105 m²)**	**For Constant Area (115 m²)**	**For Constant Area (135 m²)**
The number of panels used	From **eq. (2)** 37.45 ~ 37 Panels	From **eq. (2)** 38.6 ~ 39 Panels	From **eq. (2)** 42.6 ~ 43 Panels	From **eq. (2)** 51 Panels
Power output of panels	From **eq. (3)** 22,570 watt = 22.57 kW	From **eq. (3)** 23,570 W= 23.57 kW	From **eq. (3)** 26,000 W= 26 kW	From **eq. (3)** 31,110 W= 31.11 kW

Table 2.5. Conditions system inputs

	Power output of PV (kW)	**Module Type**	**Array Type**	**Area (m^2)**	**System Losses (%)**	**Tilt angle (deg)**	**Azimuth angle (deg)**
Fixed Structure (First Condition)	22.57	Standard	Fixed (Roof Mounting)	100	14.08	25	180
1-Axis Tracking (Second Condition)	22.57	Standard	1-Axis Tracking	100	16.71	25	180
2-Axis Tracking (Third Condition)	22.57	Standard	2-Axis Tracking	100	16.71	N/A	180
Fixed Structure (Fourth Condition)	31	Standard	Fixed (Roof Mounting)	135	14.08	25	180
1-Axis Tracking (Fifth Condition)	26	Standard	1-Axis Tracking	115	16.71	25	180
2-Axis Tracking (Sixth Condition)	23.57	Standard	2-Axis Tracking	105	16.71	N/A	180

These conditions were simulated based on the Cairo, Egypt Location

2.3.2. First Condition Fixed Structure (Roof Mounting)

According to input data from Table 2.5, System condition Results from Figure 2.8, It shows that annual solar radiation is 6.55 and the annual AC Energy generation will be 40,180 kWh/year.

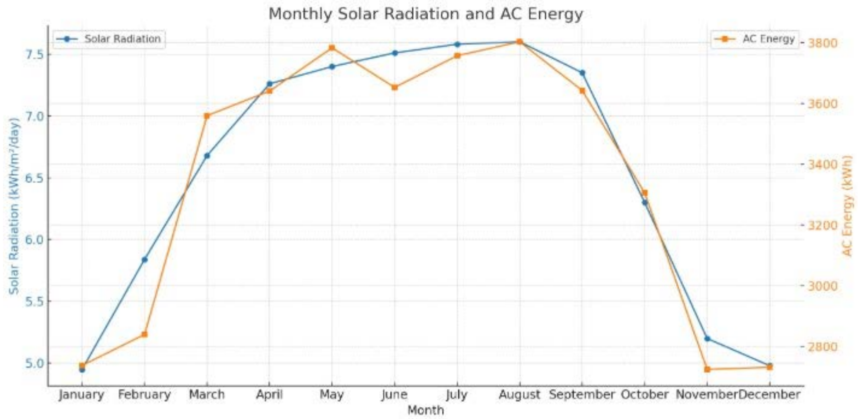


Figure 2.8 Fixed Structure Solar Radiation and AC Energy Relationship

2.3.3. Second Condition Single-axis Tracker

According to input data from Table 2.5, System condition Results from Figure 2.9, It shows that annual solar radiation is 7.97 and the annual AC Energy generation will be 48,106 kWh/year.

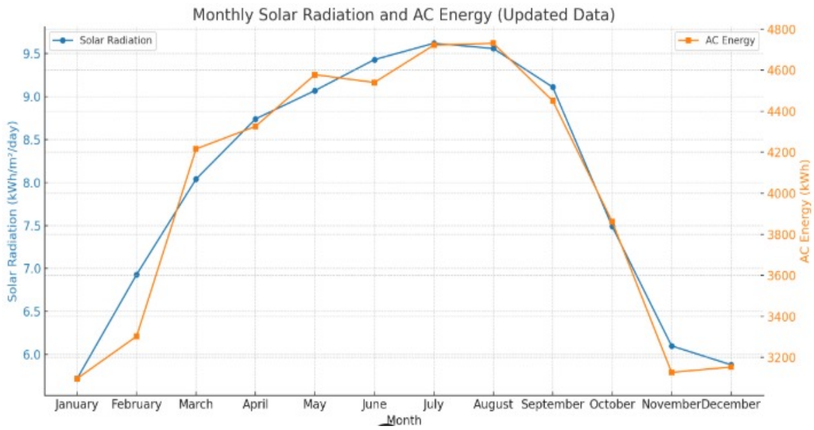


Figure 2.9 Single-Axis Tracker Solar Radiation and AC Energy Relationship

2.3.4. Third Condition Dual-axis Tracker

According to input data from Table 2.5, System condition Results from Figure 2.10, It shows that annual solar radiation is 8.83 and the annual AC Energy generation will be 53,062 kWh/year.

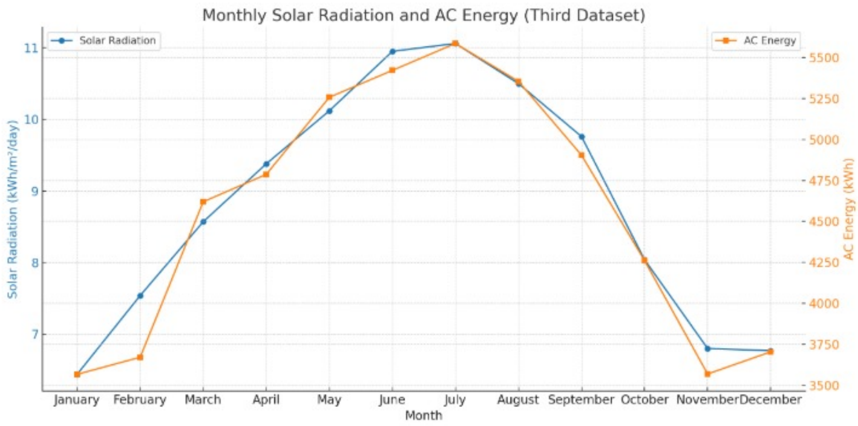


Figure 2.10 Dual-Axis Tracker Solar Radiation and AC Energy Relationship

2.3.5. Fourth Condition Fixed (Roof Mounting) Structure

In the earlier conditions the area was constant (100 m²) Conversely in this condition assume the area was changed to 135 m² for fixed mounting structure. Economically and Energy generation it would be the preferred solution. The panel used is the Jinko Solar 610 Mono-Facial Module, The Panel Area is 2.67 m². (These Scenarios were simulated based on Cairo, Egypt Location)

According to input data from Table 2.5, System condition Results from Figure 2.11, It shows that annual solar radiation is 6.55 and the annual AC Energy generation will be 55,188 kWh/year.

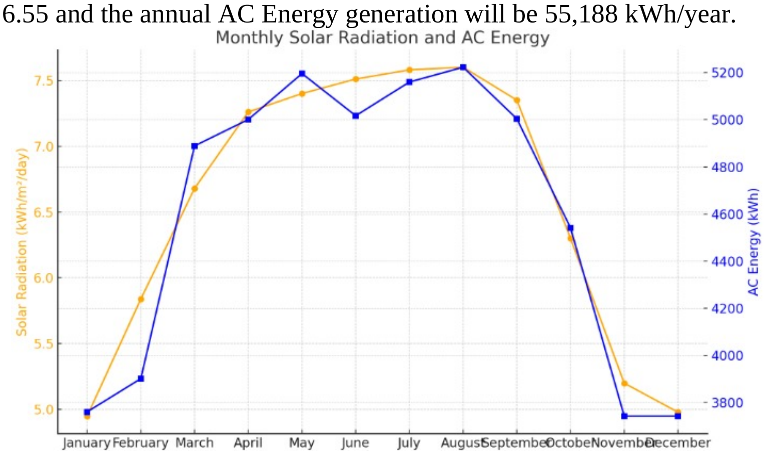


Figure 2.11 Fixed Structure Solar Radiation and AC Energy Relationship with more area availability

2.3.6. Fifth Condition Single-Axis Tracker

In the previous condition the area was (135 m²) however in this condition assume the area was changed to 115 m² for single axis tracker. With the same energy generation. The panel used is the Jinko Solar 610 Mono-Facial Module, The Panel Area is 2.67 m². (These Scenarios were simulated based on Cairo, Egypt Location)

According to input data from Table 2.5, System condition Results from Figure 2.12, It shows that annual solar radiation is 7.97 and the annual AC Energy generation will be 55,411 kWh/year.

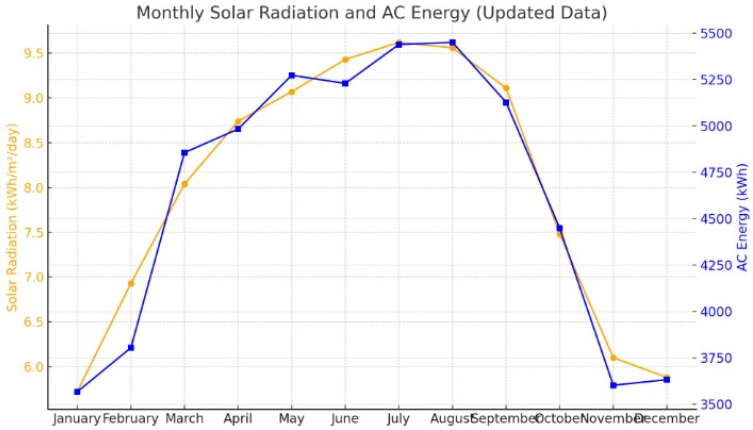


Figure 2.12 Single-Axis Tracker Solar Radiation and AC Energy Relationship with more area availability

2.3.7. Sixth Condition Dual-Axis Tracker

In the previous condition the area was 115 m² however in this condition assume the area was changed to 105 m² for the dual-axis tracker, with approximately the same energy generation. The panel used is the Jinko Solar 610 Mono-Facial Module, The Panel Area is 2.67 m². (These Scenarios were simulated based on Cairo, Egypt Location)

According to input data from Table 2.5, System condition Results from Figure 2.12, It shows that annual solar radiation is 8.83 and the annual AC Energy generation will be 55,369 kWh/year.

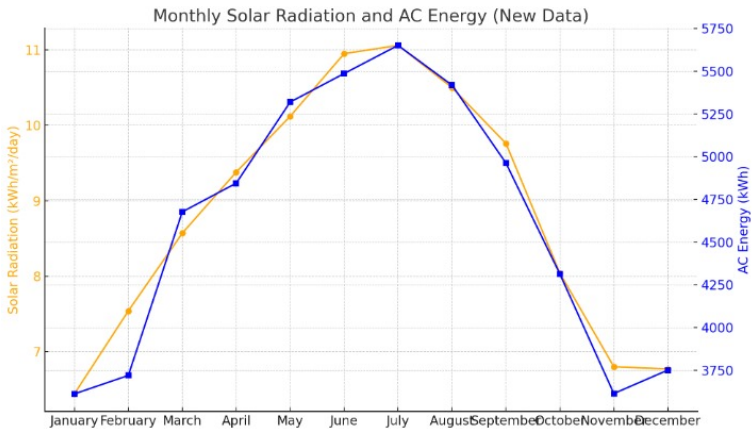


Figure 2.13 Dual-Axis Tracker Solar Radiation and AC Energy Relationship with more area availability

2.3.7. Comparing between orientation structures economically

After Comparing the Fixed Structure, Single Axis tracker, and Dual Axis tracker at the same installation area (100 m²), the Fixed structure (First Condition) generated 40,180 kWh/year, the Single Axis tracker (Second Condition) generated 48,106 kWh/year while the Dual-Axis Tracker (Third Condition) Generated 53,061 kWh/year which shows that dual axis (Third Condition) generates more energy when compared with the other systems.

Fixed Structurer (First condition) Costs (1450 EGP/kW) giving a Structure total cost of (32,726.5 EGP). The single-axis tracker (Second Condition) costs (4000 EGP/kW) giving a Structure total cost of (90,280 EGP), While the Dual-Axis (Third condition) structure costs (6000 EGP/kW) with a total Structure orientation cost of (135,420 EGP), the PV panels cost is constant for the three conditions (167,018 EGP). On the other hand, the dual-axis Tracker is more costly (302,438 EGP) than the Fixed structure and Single Axis tracker while the Fixed Structure is a more economical solution but less energy generation Table 2.7.

When Comparing Fixed (Fourth Condition), Single-Axis (Fifth Condition), and Dual-Axis (Sixth Condition) the annual energy produced is approximately the same when the area was changed from (105 m²) for the dual-axis tracker and (115 m²) for the single-axis tracker then to (135 m²) for fixed structure. The fixed structure (Fourth Condition) generated 55,188 kWh/year, and the single-axis tracker (Fifth Condition) generated 55,411 kWh/year. The dual-Axis Tracker (Sixth Condition) Generated 55,369 kWh/year which shows that the Fixed structure (Fourth condition) is more economical solution that cost (275,323.5 EGP) which is lower than the other systems. At the same time, the average solution is the single-axis tracker (298,102 EGP) in case of area availability. However, in case of unavailability of area, the Dual axis tracker would be the optimal solution for energy generation Table 2.7.

Table 2.6. Comparing Fixed Structure and Dual-Axis Tracker Economically assuming constant area.

	Fixed structure (First Condition)	**Single-Axis (Second Condition)**	**Dual-Axis (Third Condition)**
Power output of PV panel	22.57kW (37 Panels 610 W)	22.57 kW (37 Panels 610 W)	22.57 kW (37 Panels 610 W)
Total Energy per year Produced after losses	40,180 kWh/year	48,106 kWh/year	53,061 kWh/year
Cost of single structure / kW	1450 EGP	4000 EGP	6000 EGP
Total cost of structure	32,726.5 EGP	90,280 EGP	135,420 EGP
Total cost of PV panels (Price of wattage for each panel (7.4 EGP/Watt)	167,018 EGP	167,018 EGP	167,018 EGP
Total Cost (panels + structures)	199,744.5 EGP	257,298 EGP	302,438 EGP

Table 2.7. Comparing Fixed, Single and Dual Axis Tracker Economically

	Fixed structure (Fourth Condition)	Single-Axis (Fifth Condition)	Dual-Axis (Sixth Condition)
Power output of PV panel	31.11 kW (51 Panels 610 W)	26 kW (43 Panels 610 W)	23,57 kW (39 Panels 610 W)
Total Energy Produced per year after losses	55,188 kWh/year	55,411 kWh/year	55,369 kWh/year
Cost of single structure / kW	1450 EGP	4000 EGP	6000 EGP
Total cost of structure	45,109.5 EGP	104,000 EGP	141,420 EGP
Total cost of PV panels (Price of wattage for each panel (7.4 EGP/Watt)	230,214 EGP	194,102 EGP	176,046 EGP
Total Cost (panels + structures)	275,323.5 EGP	298,102 EGP	317,466 EGP

3. Conclusions

This paper collected data from previous case studies with authors point of view of installation of solar photovoltaics system according to area, choice of system configuration and structure

Also, it underlines the performance of different solar PV systems from worldwide case studies. Solar systems have shown considerable benefits by ensuring a reduction in CO_2 emissions, a reduction in energy costs, and meeting sustainability targets. Adopt the proper system is one of the important steps to ensure the optimum solution for energy production by studying the site specifications as the available area, the availability of the national grid and whether the system can be connected to it or not, and most importantly the load profile which the system is considered for. Those are the factors to consider when selecting a solar PV system.

After evaluating the previous cases most used system was the On-grid system because the system can feed its loads and selling the extra generation to the national electric grid and due to its payback average period (5.6 years ~ 15 years) depends on the system. When the available area is not enough to generate the required capacity, The hybrid system is the best choice hence it is the second most used system in addition it does not rely on the availability of the grid. Further sources can support covering the required consumption. Cases which the grid was not available, and there was not any electricity source the Off-Grid system was the solution achieving self-dependency, but one of the disadvantages is the cost since batteries increase the system cost. Also, it’s found that at locations of high irradiance, the fixed structure is the most used mounting structure, also it provides low cost compared to the single and dual axis, it is also found that single and dual axis is commonly used in locations that contain low irradiance to maximize the capture of sunlight.

The theoretical comparison results showed that when assuming constant area of (100 m²) in Cairo, Egypt location the fixed structure (First Condition) generates 40,180 kWh/year, while the single-axis tracker (Second Condition) captures 19.72% more energy than the fixed structure (First Condition) which is 48,106 kWh/year and the dual-axis tracker (Third Condition) captures 32.05% more energy than a fixed roof mounting structure which is 53,061 kWh/year. Therefore, the Dual axis (Third Condition) generates more energy when compared with the Single axis tracker (Second Condition) and with the Fixed structure (First Condition) at constant area (100 m²). Also, the fixed structure (First Condition) is more economical than the Dual-axis tracker (Third Condition) with a cost difference (102,693.5 EGP).

When the energy generated is constant at these three conditions and increasing the area for the fixed structure (Fourth Condition) to (135 m²), increasing the area for the Single axis tracker (Fifth Condition) to (115 m²) and increasing the area of Dual axis tracker (Sixth condition) to (105 m²), the fixed structure (Fourth Condition) system total cost is (275,323.5 EGP), the Single axis tracker system total cost is (298,102 EGP) and the Dual-axis tracker system total cost is (317,466 EGP). Therefore, the fixed structure (Fourth Condition) is the best economical option compared to the single axis tracker (Fifth Condition) and dual axis tracker (Sixth Condition) when there is area availability.

Although the dual axis tracking systems achieve greater energy capture, The result analysis reveals that fixed structures are a more cost-effective and practical choice, especially for large-scale installations requiring vast land areas and numerous solar panels.

References

[1] Outlook, G.R., Global Renewables Outlook: Energy Transformation 2050. Abu Dhabi, United Arab Emirates, 2020.

[2] Agency, I.R.E. Renewable energy highlights. 2024 21 December 2024]; Available from: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Jul/Renewable_energy_highlights_FINAL_July_2024.pdf.

[3] Halabi, L.M. and S. Mekhilef. Performance analysis of multi-photovoltaic (PV)-Grid tied plant in Malaysia. in IOP Conference Series: Earth and Environmental Science. 2018. IOP Publishing.

[4] Apoorva R, D.J.S.R., Dr. H. Naganagouda, Performance Analysis of 5MW Solar PV Grid connected Power plant. 2019.

[5] Ardiani, N., M. Koerniawan, and D. Naimah. Application of building integrated photovoltaic in hot humid climate. Case study: office building in Indonesia. in IOP Conference Series: Earth and Environmental Science. 2019. IOP Publishing.

[6] Imam, A.A. and Y.A. Al-Turki, Techno-economic feasibility assessment of grid-connected PV systems for residential buildings in Saudi Arabia—A case study. Sustainability, 2019. 12(1): p. 262.

[7] Mac-Lean, C., L. Vargas, and C. Reyes. Renewable Energy at Chilean Universities: Is it Possible? in IOP Conference Series: Earth and Environmental Science. 2020. IOP Publishing.

[8] Kumar, R., et al., Design and simulation of standalone solar PV system using PVsyst Software: A case study. Materials Today: Proceedings, 2021. 46: p. 5322-5328.

[9] Hernandez-Escobedo, Q., et al., sustainable solar energy in mexican universities. case study: The National School of Higher Studies Juriquilla (UNAM). Sustainability, 2020. 12(8): p. 3123.

[10] Zhang, J. and R. Zaragoza Castillo, Increasing the Electricity Generation Capacity from Solar Resources at Duke University. 2018, Master's project, Duke University. https://hdl. handle. net/10161/16573.

[11] Krishna, Y., M. Fauzan, and N.M.N. Gan. Design and simulation of a rooftop PV System in Taylor’s University Lakeside Campus. in Journal of Physics: Conference Series. 2021. IOP Publishing.

[12] Anber, M.F., The Efficiency of Using Building Integrated Photovoltaics in the Retrofitting of Office Buildings in Egypt. Port-Said Engineering Research Journal, 2021. 25(2): p. 53-59.

[13] Mohamed, A., et al., Roof Top PV Energy System in Pharos University: An Aggregated Approach to Economical Environmental Returns.

Journal of Environmental Studies and Researches, 2021. 11(4): p. 327-337.
[14] Emeara, M.S., A.F. AbdelGawad, and A. El Abgay, Orientation-Optimization Simulation for Solar Photovoltaic Plant of Cairo International Airport.
[15] KhareSaxena, A., S. Saxena, and K. Sudhakar, Energy performance and loss analysis of 100 kWp grid-connected rooftop solar photovoltaic system. Building Services Engineering Research and Technology, 2021. 42(4): p. 485-500.
[16] Sher, F., et al., Fully solar powered Doncaster Sheffield Airport: Energy evaluation, glare analysis and CO2 mitigation. Sustainable Energy Technologies and Assessments, 2021. 45: p. 101122.
[17] Sudhakar, K. and N.W. Keng. Solar PV Microgrids Implementation model: A case study of Local Self Governments in the Indian State of Kerala. in IOP Conference Series: Materials Science and Engineering. 2021. IOP Publishing.
[18] Al Mehadi, A., et al. Design, simulation and analysis of monofacial solar pv panel based energy system for university residence: a case study. in IOP Conference Series: Materials Science and Engineering. 2021. IOP Publishing.
[19] Algarni, A.H. and M.H. Mohamed, ON-GRID PERFORMANCE AND ECONOMIC ANALYSIS OF A SOLAR ENERGY PLANT FOR KING ABULAZIZ AIRPORT LOADS. 2022.
[20] Santos, C.M., J. Dadam, and A.P. da Rosa. Univali’s Biguaçu Campus: The first Campus in Brazil to generate 100% of its energy. in IOP Conference Series: Earth and Environmental Science. 2023. IOP Publishing.
[21] Shafie, S., et al., An economic feasibility study on solar installation for university campus: A case of universiti Utara Malaysia. International Journal of Energy Economics and Policy, 2022. 12(4): p. 54-60.
[22] Kassem, Y., H. Gökçekuş, and Q.A.S. Furaiji, Applicability of solar systems with various technologies and sun-tracking: A case study of Baghdad, Iraq. Future Energy, 2022. 1(2): p. 03-08.
[23] Eiva, U.R.J., et al., Design, performance, and techno-economic analysis of a rooftop grid-tied PV system for a remotely located building. IET Renewable Power Generation, 2023.
[24] Duma, T.C., Techno-Economic Comparative Study of a Grid-Tied Solar Pv Battery System and Demand-Side Management for a Foundry. 2023, University of Johannesburg (South Africa).
[25] Nabil, M.H., et al., Techno-economic analysis of commercial-scale 15 MW on-grid ground solar PV systems in Bakalia: A feasibility study proposed for BPDB. Energy Nexus, 2024. 14: p. 100286.
[26] Navothna, B. and S. Thotakura, Long-term performance of grid-integrated solar photovoltaic system on institutional buildings in tropical wet and dry climates of India—a practical study. Environmental Science and Pollution Research, 2023. 30(37): p. 88036-88048.
[27] Alfaoyzan, F.A. and R.A. Almasri, Utilizing solar photovoltaic systems in educational facilities to achieve a zero bill campus: The Sulaiman Al-Rajhi University case. Energy Exploration & Exploitation, 2023. 41(4): p. 1415-1438.
[28] FALLAHA, A.S., Design and Installation Photovoltaic system in Car Parks in King Faisal University and Study the Economic and Environmental Impact. Arab Journal for Scientific Publishing (AJSP) ISSN. 2663: p. 5798.
[29] Amekah, E.D., et al., Optimal Placement and Upgrade of Solar PV Integration in a Grid-Connected Solar Photovoltaic System. Solar Compass, 2024: p. 100099.
[30] Ajagbe, I.A., NREL's Sam-Based Simulation Model And Techno-Economic Evaluation Of A Grid-Connected, Building-Integrated Solar Pv-Battery Storage System For Rural Residential Application In El Paso, Texas. 2024, The University of North Dakota.
[31] Balat, A.E., et al., Techno-Economic Analysis of Grid-Connected PV Power Plants in Different Zones of Egypt. ERJ. Engineering Research Journal, 2024. 47(4): p. 473-484.
[32] Govindarajan, L., M.F.B.M. Batcha, and M.K.B. Abdullah, Discover Applied Sciences. Discover, 2024. 6: p. 328.
[33] Qamar, S.H., et al., Design, modeling and cost analysis of 8.79 MW solar photovoltaic power plant at National University of Sciences and Technology (NUST), Islamabad, Pakistan. Scientific Reports, 2024. 14(1): p. 25351.
[34] Saddari, N., N.S.A. Derkyi, and F. Peprah, Technical and Economic analysis of solar PV electricity generation under the net metering scheme at Sunyani Teaching Hospital (STH), Ghana. Renewable and Sustainable Energy Transition, 2025. 6: p. 100097.
[35] Moustafa, M., et al. Design and simulation analysis of 130 KWp grid-connected solar PV system using PVsyst: A case study in Egypt. in Journal of Physics: Conference Series. 2024. IOP Publishing.
[36] Mohanta, P.R., et al., A review on solar photovoltaics and roof top application of it. International Journal of Advanced Research in Science, Engineering and Technology, 2015. 2: p. 2394-2444.
[37] Usah, E.O., et al., Pvsyst Software-Based Comparative Techno-Economic Analysis Of PV Power Plant For Two Installation Sites With Different Climatic Conditions. International Multilingual Journal of Science and Technology (IMJST), 2020. 5(7).
[38] Mannan, A., S. Kirmani, and I. Akhtar. Design Methodology of Off-Grid PV System. in Journal of Physics: Conference Series. 2023. IOP Publishing.
[39] Pollock, E., et al. Off-Grid Systems. in IOP Conference Series: Earth and Environmental Science. 2019. IOP Publishing.
[40] Liu, J., et al., Overview on hybrid solar photovoltaic-electrical energy storage technologies for power supply to buildings. Energy conversion and management, 2019. 187: p. 103-121.
[41] Rooij, D.D. Single Axis Trackers. 2024 21 December 2024]; Available from: https://sinovoltaics.com/learning-center/csp/single-axis-trackers/.
[42] JinkoSolar, Jinko solar 610-watt mono-facial module N-Type, JinkoSolar, Editor. p. 2.