PERFORMANCE ANALYSIS, CARBON OFFSET, AND AIR POLLUTION IMPACT FOR A GRID-CONNECTED SOLAR PV PLANT: A CASE STUDY AT AMU ALIGARH

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ABSTRACT: This study examines the performance and carbon offset of a 175 kWp grid-connected solar photovoltaic (PV) plant at Aligarh Muslim University's car parking facility. Key metrics, performance ratio (PR), and annual energy yield are analyzed to assess efficiency under local climate conditions. Carbon offset potential is evaluated through estimated CO_2 emission reductions, highlighting the plant's role in supporting carbon neutrality. Results indicate substantial energy savings and the reduction in air pollution, thereby contributing to cleaner air and a healthier environment, demonstrating the benefits of PV integration in institutional infrastructure and providing insights for optimizing similar PV installations.

Keywords: Photovoltaic; Capacity utilization factor; performance ratio; Carbon credit; Carbon offset

1. Introduction:

The shift towards renewable energy sources is essential in the global mission to reduce greenhouse gas emissions and combat climate change: Solar photovoltaic (PV) systems have proven to be a highly effective solution for generating clean, sustainable energy. Grid-connected PV systems are increasingly implemented in various settings, offering economic and environmental advantages. This paper presents a performance analysis and carbon offset evaluation for a grid-connected 175 kWp solar photovoltaic power plant installed at a university car parking facility in Aligarh, India. This installation meets a significant portion of the institution's power requirements and reflects a strong commitment to sustainability by substantially reducing its carbon footprint.

Through a thorough performance analysis, this study assesses the energy yield, efficiency, and reliability of the 175 kWp PV system under Aligarh's specific climatic conditions. The analysis includes data on energy production, system losses, and operating parameters, providing insight into the plant's efficiency, capacity factor, and overall performance. Additionally, the study quantifies the carbon offset achieved by the PV system, emphasizing its role in lowering institutional carbon emissions and supporting global carbon reduction goals [2, 9].

This research also highlights the benefits of the PV system. The findings offer a comprehensive view of how grid-connected PV installations can contribute to sustainable development goals, reduce reliance on fossil fuels, and set a precedent for similar projects across educational and commercial settings [3]. By documenting this PV system's operational performance and environmental impact, the study aims to provide valuable insights for stakeholders in academia, industry, and policy-making, encouraging the broader adoption of renewable energy systems.

Carbon Footprint: A carbon footprint is the total amount of greenhouse gases, primarily carbon dioxide, emitted directly or indirectly by human activities. This measure, usually expressed in tons of CO_2 equivalent (CO_2e), accounts for emissions from activities such as energy use, transportation, production, and waste, and is used to understand the environmental impact of these activities.

Carbon Credit: A carbon credit is a generic term for any tradable certificate or permit representing the right to emit one tonne of carbon dioxide or the mass of another greenhouse gas with a carbon dioxide equivalent ($tCO2e$) equivalent to one tonne of carbon dioxide.

Carbon Credit Trading (Emission Trading) is an administrative approach used to control pollution by providing economic incentives for achieving reductions in the emissions of pollutants. There are currently two exchanges for carbon credits: (i) The Chicago Climate Exchange (ii) the European Climate Exchange. ICE Futures Europe currently offers derivatives contracts on four types of carbon units: EU Allowances (EUAs), EU Aviation Allowances (EUAAs), Certified Emission Reductions (CERs) and Emissions Reductions Units (ERUs). The present market rate is fluctuating at €20–22 in the European Climate Exchange.

2. On-Grid Solar Photovoltaic System

This ON-Grid solar PV system is connected to the utility grid. In this if excess power is generated it is fed to the grid when the power isn't sufficient, the load capacity is served by drawing the power from the grid. It is comparatively cheaper than the OFF-Grid solar system because the battery is not included in it.[4,11,12]. The major components in a standard grid-connected PV system are: PV Module / Panel, Module Mounting Structure, Cables, Array Junction Box, Solar Grid connects Inverter, AC Distribution Box, Earthing Kit & Lightning Arrestor

A. Solar Panel: A solar panel is also called a solar module, photovoltaic module, or photovoltaic panel. A stack of PV cells forms a solar panel or PV module. These cells use sunlight as a source of energy and produce direct current electricity. In this solar panel, arrays are connected in series to achieve the desired output voltage and/or parallel to achieve the desired current. These solar panels range from 30 to 400 watts. The efficiency of a solar panel ranges between 15% to 20%, only a high-quality solar panel can exceed up to 22%. A single solar cell only produces about 0.5 volts.

B. Structure: The intensity of sunlight will be maximized when incident irradiation is perpendicular to solar panels, hence tilt of the panels is an important design parameter, the panels are tilted at an angle according to the site location. This structure will be made of galvanized mild steel/ aluminum-based onsite soil and wind load parameters. The number of Array frames will be provided based on the design and site requirements. These array frames are corrosion-free

C. Inverter: The inverter is an essential component in the PV solar system. It is used to convert direct current (DC) current to alternating current (AC). This output current from the inverter will be fed to the AC distribution Board.

D. Balance of the System Components: Components such as Cables, Array Junction Box, AC Distribution Box, Earthing Kit, and Lightning Arrestors are essential to the overall safety and functionality of a solar PV system and are collectively referred to as the balance of system (BOS) components as they play a vital role in the protection of solar PV systems. An appropriate cable size should be chosen such that to minimize voltage drop.

3. Methodology

The designing of the ON-Grid solar PV system is done with the following steps: -

Step-1: Determine Daily/weekly/seasonal load, Step 2: Design of solar panel array, Step 3: Cost analysis of the system , Step-4: Calculation of Energy Payback Time

1. Site Selection: To find out the solar potential available at Aligarh, Uttar Pradesh, a reading of solar radiation for the site is required. So, these readings are taken from National Renewable Energy Laboratory (NREL), Solar Energy Centre. The geographical coordinates of our project site are: Latitude:

27.88° N, Longitude: 78.08° E

2. Design Calculations

i. System Requirements and Panel Calculation: Target System Capacity: 175 kWp, Panel Rating: 325 W per panel, Total Panels Needed =(175,000 W)/(325 W per panel) = 538.46 539 panels

ii. Energy Production Estimation: Average Daily Solar Insolation in Aligarh is approximately

5.5kWh/m^2/ day, Expected Daily Output =175 kWp x 5:5 kWh/m² ≈ 962.5 kWh/day, Annual Production = Daily output * no. days in a year = 962.5 kWh/day × 365 ≈ 351,312 kWh/year, Tilt Angle: Optimize tilt to approximately 28° to maximize exposure based on Aligarh's latitude, Space Requirement: Allow about 10m2 per kWp, totalling around 1,750m^2.

iii. Theoretical Data Calculation: No. of Modules Used (N) (Each of 325WP) = 539, Area of Single Module (A) = 1.94432 m^2 , Efficiency of the Modules (η) = 15% , Let Solar Insolation be "I". Therefore, energy generated by the plant = [N * I * η * A](KWh/day), Calculated nominal plant output (YC) = 305463.421 KWh/year. Now,

$$\text{Performance Ratio} = \frac{\text{Actual Plant Output (YA)}}{\text{(Nominal Plant Output)}} \text{ x } 100\%$$

Actual Plant Output (YA) = 200754.392 KWh,

$$Performance\ Ratio = \frac{200754.392}{305463.421} \text{x } 100\% = 65.72\%$$

Table 1 Monthly solar insolation and calculated energy generated by this plant

Months	Solar Insolation (Acc. To NREL) in KWh/m2/day	Energy Generated (Calculated) in KWh	Energy Generated (Actual) in KWh
January	4.0	19449.276	9910.298
February	4.5	19762.974	17540.531
March	5.5	26742.754	18666.899
April	6.5	30585.555	21284.164
May	6.8	33063.769	22656.687
June	6.5	30525.55	19771.438
July	5.5	26742.754	16160.125
August	5.2	25284.058	17728.625
September	5.5	25880.085	16089.312
October	5.5	26742.75	17726.125

November	4.5	21174.615	11792.25
December	4.0	19449.276	11424.938
Total		305463.421	200754.392

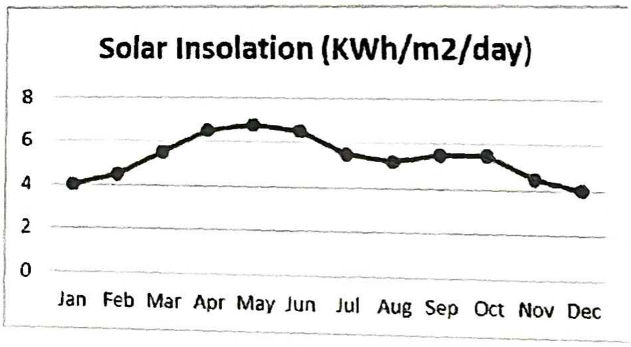

Figure 1 Graph for monthly Solar Insolation

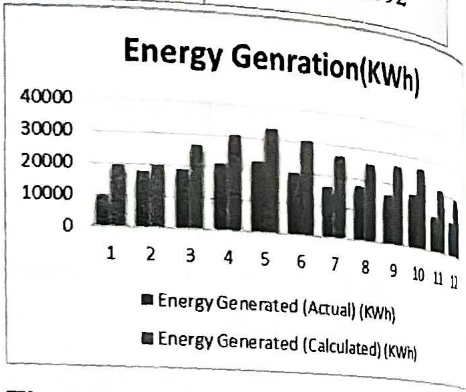

Figure 2: Graph for Energy Generation

4. Energy Payback Time

The Energy Pay-Back Time (EPBT) is a key metric in assessing the sustainability and efficiency of photovoltaic (PV) systems. It measures the time required for a PV system to generate the same amount of energy that was consumed during its production, installation, and maintenance. For Aligarh, Uttar Pradesh, a region with moderate solar irradiation, analyzing the EPBT of polycrystalline PV systems helps evaluate their economic and environmental viability. [10-11] A. Contributing Factors:

i. Technology Type: Polycrystalline silicon (poly-Si) require substantial energy for manufacturing but are capable of providing significant energy returns over their lifespan.

ii. Solar Irradiation in Aligarh: The region receives an average annual solar irradiation of approximately 1,700 kWh/m², which is categorized as medium irradiation. This directly impacts the energy output and, consequently, the EPBT of the installed PV system.

iii. Installation Type: Rooftop systems typically exhibit shorter EPBT compared to ground-mounted installations due to reduced energy requirements for support structures.

B. Polycrystalline PV Systems: Polycrystalline silicon modules are a mature and reliable technology. Their manufacturing process includes energy-intensive steps such as silicon purification, wafer production, and module assembly. Key details of their energy profile and EPBT are:

i. Energy Inputs: The manufacturing process requires approximately 4,200 MJ/m² of primary energy for frameless modules. Adding aluminium frames increases the total to around 4,600 MJ/m². Also the energy is consumed in the balance-of-system (BOS) components, such as inverters, supports, and cabling, depending on the installation type.

ii. Module Efficiency: Polycrystalline silicon modules have a typical efficiency of 12%-15% depending on the technology and design.

iii. EPBT Estimates: Solar Panel Installations: For medium irradiation levels (~1,700 kWh/m²/year), the EPBT for polycrystalline PV systems is estimated to be 3 years. High

Irradiation Regions: In areas with stronger solar resources (~2,200 kWh/m²/year), the EPBT is shorter, typically 2 years.

C. EPBT of our system: With medium solar irradiation, polycrystalline PV systems offer promising energy payback periods: This installation repays the energy investment within 3 years and continue to provide clean energy for an additional 25 years of their lifespan.

D. Environmental Impact: Installing polycrystalline PV systems not only ensures a favourable EPBT but also contributes to significant environmental benefits. Over its lifetime, a polycrystalline PV system can prevent the emission of substantial greenhouse gases compared to conventional fossil-fuel-based power generation. With an EPBT of 3 years, these systems will operate pollution-free for approximately 25 years, making them a key component of sustainable energy strategies.

E. Future Improvements in Polycrystalline PV Systems: Several advancements in polycrystalline PV technology and manufacturing processes are expected to reduce EPBT further:

i. Material Efficiency: Thinner silicon wafers and reduced wastage during production could lower energy consumption by 30%-40%. Development of solar-grade silicon feedstocks, designed specifically for PV manufacturing, could further cut energy requirements.

ii. Efficiency Gains: Expected improvements in polycrystalline module efficiency to 15%-17% by 2025 could significantly enhance energy output, reducing EPBT to 2 years or less under medium irradiation levels.

iii. Energy-Efficient Manufacturing: Scaling up production and optimizing facility operations, such as reducing overhead energy use, are projected to decrease the energy input per module area.

5. Carbon Footprint Effect on Air Pollution

Carbon footprint is the amount of greenhouse gases (GHG) emitted into the atmosphere by an individual, organization, event, or product. These gases, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), are significant contributors to climate change due to their heat-trapping capabilities, leading to global warming. However, these emissions also impact air quality, as they are often accompanied by pollutants like particulate matter (PM), sulphur dioxide (SO_2), and nitrogen oxides (NO_x), which degrade air quality and harm human health[5,8,15]. By reducing the carbon footprint through renewable energy solutions like solar power, organizations can not only offset GHG emissions but also significantly reduce air pollution, thereby contributing to cleaner air and a healthier environment.

Solar photovoltaic (PV) systems offer a sustainable approach to reducing carbon footprints by generating clean, renewable energy. Unlike fossil fuel-based power sources, solar PV systems convert sunlight directly into electricity without emitting greenhouse gases or air pollutants. By replacing or supplementing traditional energy sources with solar power, organizations can significantly reduce their Scope 2 emissions, which are tied to electricity consumption from fossil fuel-based grids. The use of solar PV systems not only cuts down on CO_2 emissions but also helps alleviate other harmful pollutants associated with fossil fuel combustion, such as nitrogen oxides (NO_x), sulphur dioxide (SO_2), and particulate matter (PM). This transition to solar energy can improve air quality, particularly in areas with high vehicular emissions, such as university campuses. In this way, solar PV systems reduce the overall carbon footprint and help mitigate local air pollution, contributing to a healthier environment.

Table 2: Air pollution of four-wheeler vehicles for 2023

Number of Vehicles	Age (Year)	Distance Travelled per Day (Km)	Number of Weekdays in a year	Emission Factor (gCo2/Km)	Carbon Emission per Year (gCO2)
732	10	10	260	80	152505600
488	8	10	260	70	88961600
732	6	10	260	60	114379200
488	4	10	260	50	6354400
				Total	379648000

Table 3: Air pollution of two-wheeler vehicles for 2023

Number of Vehicles	Age (Year)	Distance Travelled per Day (Km)	Number of Weekdays in a year	Emission Factor (gCo2/Km)	Carbon Emission per Year (gCO2)
126	10	10	260	180	5896800
84	8	10	260	160	34944000
126	6	10	260	140	45864000
84	4	10	260	120	26208000
				Total	1408056000

To calculate the carbon offset, we need to determine how much CO_2 emissions are avoided by generating that much electricity using solar power instead of conventional fossil fuel sources.

We will need the carbon emission factor, representing the amount of CO_2 emitted per unit of electricity generated using a fossil-fuel-based power source. Typically, in India, this factor is approximately 0.82 kg CO_2 per kWh.

$$Carbon\ Offset\ (\text{kg CO}_2) = \text{Annual Electricity Production (kWh)} \times \text{Emission Factor (kg CO}_2\text{/kWh)}$$

Given: Annual electricity production: 200,754.392 kWh, Emission factor: 0.82 kg CO_2/kWh

$$Carbon\ Offset\ (\text{kg CO2}) = 200{,}754.392\ \text{kWh} \times 0.82\ \text{kg CO2/kWh} = 164618.6\ kg\ CO2$$

Based on Table data, Table 2 gives the Air pollution of Cars and Table 3 gives the Air pollution of Bikes for the year 2023. Taking additional 30% for external vehicles, Total CO_2 emissions from cars is 1,830,472 kg CO_2 whereas Total CO_2 emissions from bikes is 493,542.4 kg CO_2

Combined total CO_2 emissions = 1,830,472 + 493,542.4=2,324,014.4 kg CO_2 From the above calculation, Carbon offsets approximately 164,618.6 kg CO_2 annually. To calculate percentage offset:

$$Percentage\ Offset = \frac{Offset\ by\ PV\ Systems}{Total\ Vehicle\ Emissions}\ x\ 100\% = \frac{164618.6}{2324014.4}\ x\ 100\% = 7\%$$

The solar PV system offsets approximately 7.08% of the total annual CO_2 emissions generated by vehicles on the campus.

6. Conclusion

This study demonstrates the efficacy and environmental benefits of integrating a grid-connected 175 kWp solar photovoltaic system at Aligarh Muslim University's car parking facility. The system's performance was rigorously analyzed, with key metrics such as the performance ratio (PR) and annual energy yield indicating a robust efficiency level, especially given the specific climate conditions of Aligarh. The significant carbon offset potential achieved through CO_2

emission reductions highlights the system's contribution toward institutional carbon neutrality. With an annual energy yield of 200,754 kWh, the PV plant not only helps to reduce electricity costs but also offsets 164,618 kg of CO_2 emissions per year, representing a 7% reduction in the campus's vehicular CO_2 emissions. These findings underscore the viability of PV installations in institutional settings for both economic savings and substantial reduction in air pollution. The success of this project serves as a valuable case study for similar PV installations, emphasizing the importance of site-specific design and performance assessment. It offers insights that can guide future installations, contributing to the broader adoption of sustainable energy solutions within educational institutions and other large-scale infrastructures.

REFERENCES

1. Naskar, Rakesh & Ghosh, Saswata & Mandal, Ratan. (2016). Analysis of Carbon Credit of a 5KWP Solar Photovoltaic Power Plant at JIS College of Engineering, Kalyani. Imperial Journal of Interdisciplinary Research (IJIR). Vol-2. Page 1506 - 1511.
2. Nyamathulla, Shaik, and Dhanamjayulu Chittathuru. 2023. "A Review of Multilevel Inverter Topologies for Grid-Connected Sustainable Solar Photovoltaic Systems" Sustainability 15, no. 18: 13376. https://doi.org/10.3390/su151813376
3. Zhang, Y., et al. (2021). "Economic and environmental assessment of PV systems with a focus on carbon credits and financial incentives." Renewable Energy, 179, 1142-1153
4. P. C. Babu, S. S. Dash, R. Bayındır, R. K. Behera and C. Subramani, "Analysis and experimental investigation for grid-connected 10 kW solar PV system in distribution networks," 2016 IEEE International Conference on Renewable Energy Research and Applications (ICRERA), Birmingham, UK, 2016, pp. 772-777, doi:
5. 10.1109/ICRERA.2016.7884441
6. W. Hudy, M. Piaskowska-Silarska, H. Noga, W. Kulinowski and K. Pytel, "Analysis of the possibility of reducing the amount of air pollution using photovoltaic systems," 2018 19th International Carpathian Control
7. Conference (ICCC), Szilvasvarad, Hungary, 2018, pp. 565-569, doi: 10.1109/CarpathianCC.2018.8399694 [6] N. Kularatna and B. H. Sudantha, "An Environmental Air Pollution Monitoring System Based on the IEEE 1451 Standard for Low-Cost Requirements," in IEEE Sensors Journal, vol. 8, no. 4, pp. 415-422, April 2008, doi:
8. 10.1109/JSEN.2008.917477.
9. S. A. Arefifar, F. Paz and M. Ordonez, "Improving Solar Power PV Plants Using Multivariate Design Optimization," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 5, no. 2, pp. 638-650, June 2017, doi: 10.1109/JESTPE.2017.2670500.

   A. V. Pérez Ramos, R. M. Layme Lara and R. A. Velásquez, "Topological Inverter Design Applied to Solar PV Plant: Systematic Review," 2021 IEEE Engineering International Research Conference (EIRCON), Lima, Peru, 2021, pp. 1-4, doi: 10.1109/EIRCON52903.2021.9613526.
10. Amores, B., & Fuentes, C. (2021). Comparative analysis of energy payback time in photovoltaic systems across regions with varying solar irradiance. Journal of Cleaner Production, 295, 126419.

11. Salibi, Marc, et al. "Energy Payback Time of Photovoltaic Electricity Generated by Passivated Emitter and Rear Cell (PERC) Solar Modules: A Novel Methodology Proposal." EU PVSEC 2021 Proceedings, 2022, pp. 4CO.4.5. DOI: 10.4229/EUPVSEC20212021-4CO.4.5.

12. Amores, B., & Fuentes, C. "Comparative Analysis of Energy Payback Time in Photovoltaic Systems across Regions with Varying Solar Irradiance." Journal of Cleaner Production, vol. 295, 2021, p. 126419.

13. Nyamathulla, Shaik, and Chittathuru, Dhanamjayulu. "A Review of Multilevel Inverter Topologies for GridConnected Sustainable Solar Photovoltaic Systems." Sustainability, vol. 15, no. 18, 2023, p. 13376. DOI: 10.3390/su151813376.

14. Zhang, Y., et al. "Economic and Environmental Assessment of PV Systems with a Focus on Carbon Credits and Financial Incentives." Renewable Energy, vol. 179, 2021, pp. 1142-1153.

15. Pérez Ramos, A. V., Layme Lara, R. M., and Velásquez, R. A. "Topological Inverter Design Applied to Solar PV Plant: Systematic Review." IEEE Engineering International Research Conference (EIRCON), 2021, pp. 14. DOI: 10.1109/EIRCON52903.2021.9613526.

16. Hudy, W., et al. "Analysis of the Possibility of Reducing Air Pollution Using Photovoltaic Systems."International Carpathian Control Conference (ICCC), 2018, pp. 565-569. DOI: 10.1109/CarpathianCC.2018.8399694.