SYNOPSIS

FOR

Study on the Impact of Variation in Design Parameters on the Performance of Solar Photovoltaic System

THESIS SUBMITTED FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY (ENGINEERING)

BY

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Introduction

Global electricity generation experienced a steady increase of approximately 2.5%, reaching a total of 28,294 terawatt-hours (TWh) in 2022. This growth is indicative of the sustained expansion in global electricity demand driven by a multitude of factors, including increasing demands from industrial, residential, and agricultural sectors, etc. Throughout this period, Renewable electricity generation experienced significant growth, estimated at approximately 8% in 2022, reaching a total of 8,540 TWh (Ember, Global Electricity Review 2023). The collective growth in wind and solar photovoltaic (PV) generation proved substantial, meeting 80% of the upsurge in total global electricity demand for the year. This remarkable growth highlights the accelerating shift towards renewable energy sources. In 2022, renewable energy sources accounted for roughly 30% of the world's total electricity generation, highlighting their increasing importance in the global energy landscape (Ember, Global Electricity Review 2023). This significant expansion highlights the growing importance and effectiveness of solar photovoltaic (PV) technology in addressing global energy needs. As solar PV continues to improve and become more cost-effective, it plays an essential role in driving the transition towards renewable energy and reducing dependence on fossil fuels. Additionally, in 2023, India secured the fourth position globally for installed renewable capacity, with an addition of 13.5 GW power throughout the year, and ranked fifth in solar power capacity (MNRE, 2023). According to the updated Nationally Determined Contributions (NDC) by 2030, India aims to achieve approximately 50% of its cumulative electric power installed capacity from non-fossil fuel-based energy resources (MOEF, 2023). Another assessment, taking into account land availability and solar radiation, has estimated the potential of solar power in India to be approximately 750 GW_p (MNRE, 2023). Over the past decade, the deployment of solar energy has led to a slight decrease in at present India's power sector emissions intensity to 632 gCO_2/kWh, which is below the level recorded as 648 gCO_2/kWh in 2000 (Ember,2023).

Given the vast potential for solar PV installation in India, we are intensifying our efforts in this domain. The primary advantage of PV systems is indeed their ability to capture solar radiation and convert it directly into electricity. This capability enables PV systems to generate clean, renewable energy without emitting greenhouse gases or other pollutants. PV systems are versatile and can be deployed in various locations, from residential rooftops to large-scale solar farms, making them a key player in the transition towards sustainable energy sources. However, many of these areas, although rich in sunlight, face challenges such as high ambient temperatures and infrequent rainfall, leading to dust accumulation on PV modules. This accumulation of dust, referred to as "Soiling", can significantly hamper the performance of PV systems by obstructing sunlight from

reaching the PV cells. Traditionally, the temperature effects on PV modules are considered during system design, but the impact of dust accumulation is often overlooked or arbitrarily accounted for during the design, deployment, and operation of PV systems. Additionally, domestic pollution contributes to soiling, as indicated by the concentration of particulate matter (PM) smaller than 2.5μm and 10μm in the atmosphere. These particles may consist of a combination of different elements, including pollen, fibres, metals, metal oxides, hydrocarbons (unburnt oil) and organic substances.

In urban areas like Kolkata, the loss in PV performance can be significantly higher compared to arid regions like Jodhpur, India, due to dust deposition. This difference is primarily attributed to the particle size distribution of the dust prevalent in these locations, with a higher concentration of small particles proving more detrimental to PV performance (Sisodia et al., 2020).

Energy loss due to soiling can be attributed to various factors, broadly categorized into two main groups: PV module and system characteristics, and the influence of environmental factors. Solar PV systems are typically designed to maximize energy production. Consequently, certain characteristics of PV modules and systems remain fixed, and some of these features can exacerbate soiling losses, particularly in the absence of regular cleaning. Roof-top systems, often situated in inaccessible areas, face challenges in maintaining cleanliness. Below are some characteristics that can contribute to soiling losses:

PV panel and system characteristics

- Tilt angle
- Orientation
- Glazing surface characteristics
- PV technology
- PV module cell configuration

Environmental factors

- Height of installation
- Average wind speed
- Occurrence of dew
- Airborne dust concentration
- Presence of liquid particular matter in air
- Location and distance of the source
- Probability of a dust storm
- Distribution of dust particle sizes

Evaluating the performance of PV systems typically revolves around the total energy output over a specified period. Energy yield stands out as a critical metric for comparing various PV technologies, installation techniques, tilt and orientations, as well as a balance of systems. Consequently, dust deposition emerges as a crucial factor influencing the energy yield from PV modules. Given that dust deposition loss varies with the environment, it presents challenges to the deployment of PV systems, underscoring the importance of addressing this issue for the efficient operation of solar power installations.

The decision to implement restorative measures is contingent upon evaluating both the financial implications stemming from reduced energy output and the associated expenses incurred in executing these strategies. Consequently, the significance of energy loss resulting from dust accumulation emerges as a crucial factor, its magnitude varies depending on the geographical context. The accumulation rate of dust on PV modules demonstrates seasonal fluctuations, necessitating the conduct of systematic experiments spanning a minimum period of one year to accurately capture these variations. While such meticulous examinations are instrumental in the planning of PV system installations, they typically necessitate several years to gather a substantial dataset. This thesis seeks to investigate a cost-effective accelerated approach for examining the nature of dust deposition and its relationships with various PV technologies.

Objectives of the Present Study

The rapid advancement of solar photovoltaic (PV) technology has positioned it as a prominent contender in the global pursuit of sustainable energy solutions. Solar energy, harnessed through PV panels, offers a clean and abundant source of electricity, thereby mitigating the environmental impacts associated with traditional fossil fuel-based power generation. However, the performance of PV panels is intricately tied to the prevailing environmental conditions, including sunlight intensity, temperature, and shading effects. Understanding and optimizing the performance of these panels under diverse conditions is paramount for realizing their full potential and widespread adoption. The primary goal of this study is to enhance our understanding and expertise regarding the installation of optimized solar PV systems. This objective is achieved through the pursuit of the following specific aims:

a) **To study the performance of solar photovoltaic panels under various conditions using a laboratory designed, cost-effective solar simulator.**

b) **To study the influence of dust accumulation on the power generation of photovoltaic panels with various tilt angles in outdoor environmental conditions for Kolkata.**

c) **To investigate the optimum system design and operational parameters, based on the techno-economic performance of solar panels under real-time outdoor characteristics for site latitude tilt angle 22.5° of Kolkata.**

d) **To demonstrate a simulation-based solar tree model and compare its performance with respect to the site latitude (22.5°) tilt solar PV installation.**

Methodology

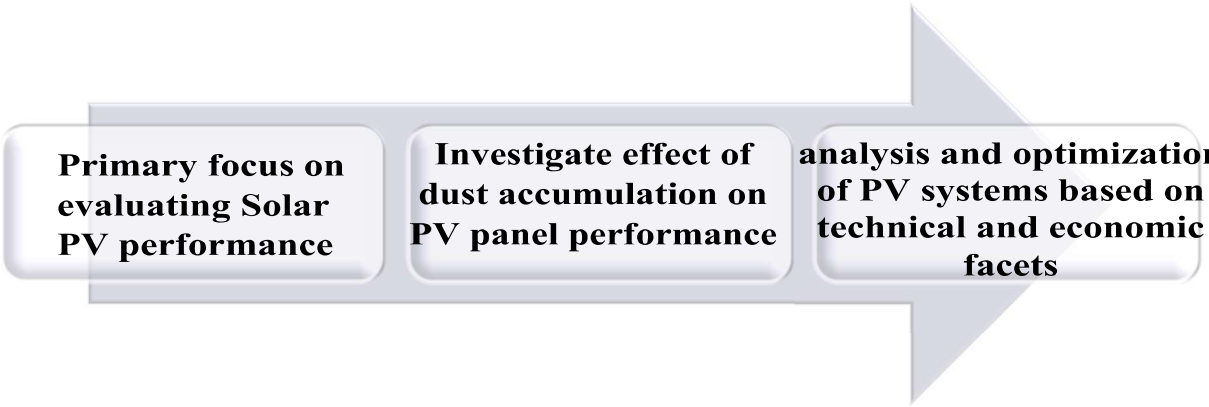
The current study could be organized into three phase-based approaches.

Phase 1 - Conducting a comprehensive assessment of solar PV panel performance across different environmental contexts.

Phase 2 - An in-depth examination of the influence of dust accumulation on the performance of PV panels, considering various tilt angles, within the actual outdoor environment.

Phase 3 – Optimization of solar energy systems by considering both technical and economic aspects with precision.

Three distinct steps may be visualized as depicted below, which shows the direction of gradual progress undertaken during the present research.



1. The primary focus revolves around comprehensively evaluating the performance of solar PV panels under various environmental conditions. To facilitate this investigation, a low-cost solar simulator has been designed and implemented within a laboratory setting. By subjecting PV panels to simulated conditions representative of real-world scenarios, the study aims to gain valuable insights into panel performance dynamics and uncover strategies for enhancing efficiency and reliability.
2. The second phase, due to different tilt angles affects the amount of sunlight received by the panels and thus plays a vital role in determining its energy output. By investigating the influence of dust accumulation on PV panel power generation across various tilt angles,

valuable insights can be gained into the optimal design and maintenance practices for solar installations in Kolkata This study aims to provide a comprehensive analysis of how dust accumulation affects the performance of PV panels with different tilt angles under real-world outdoor conditions in Kolkata.

3. In the third phase, the research sets out to explore this dynamic intersection, focusing on the optimization of solar energy systems with a keen eye on both technical and economic facets. Situated within the context of real-time outdoor conditions and attached by a site latitude angle of 22.5° degrees, this investigation seeks to uncover the optimal system design and operational parameters that maximize the techno-economic performance of solar panels. The choice of the site latitude angle of 22.5° degrees is not arbitrary but rather strategic, reflecting a geographical relevance that resonates with regions sharing similar solar irradiance patterns.

Results and Discussions

Chapter 3, the particulars regarding the experiment setup, measurement process, and methodology are described in details. The combined methodology and experimental setup detailed in these chapters represent a meticulous and purposeful approach towards understanding the multifaceted dynamics of solar panel's performance parameters.

Chapter 4, deals with modelling and analysing the performance of photovoltaic panels under standardized laboratory conditions. Categorizing and measuring the various output values of solar PV panels across varying irradiation levels and PV panel temperatures was undertaken. Utilizing these experimental findings,

- FF model in relation to radiation and temperature (Fig. 1)

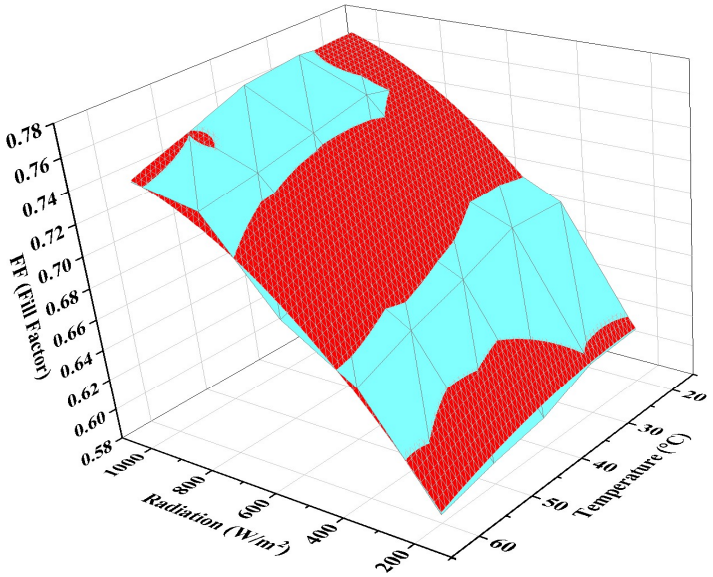


Fig. 1: FF model in relation to radiation and temperature

- FF model with respect to open circuit voltage and short circuit current
- Maximum power (P_{max}) model in relation to radiation and temperature

These models aim to accurately reflect the performance of solar PV panels in real-world outdoor settings.

Chapter 5, conducts an experimental study to examine the impact of dust accumulation on power generation from solar PV modules installed at various tilt angles, across different weather conditions.

- During summer, solar PV panel at the 10° tilt angle and while in the winter season; solar PV at the 30° tilt angle panel achieved the highest efficiencies.
- During monsoon season, the efficiency of the solar panel fluctuated in response to varying intensities of rainfall.
- Normalized generation of PV module comparing with and without dust accumulation scenario, and observed percentage of error increases over time across all tilt angles and weather conditions (Fig. 2).

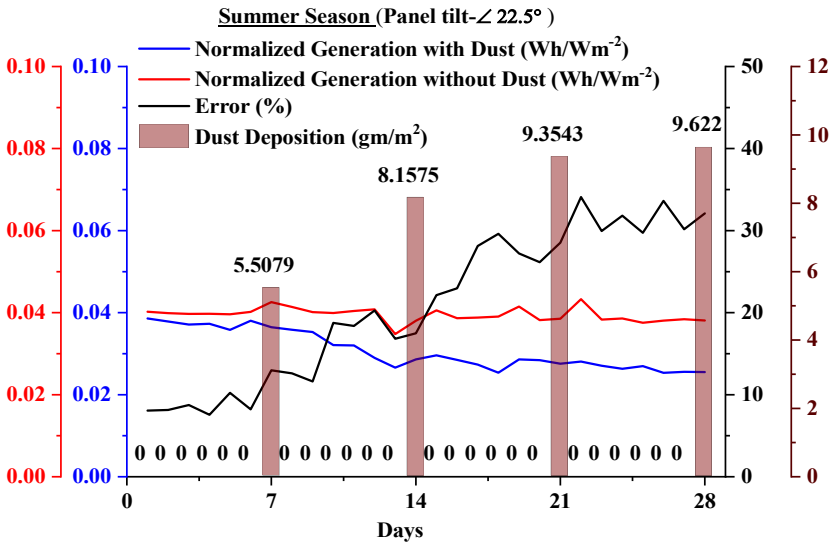


Fig. 2: Normalized power generation with and without dust, and % of error at ∠22.5° tilt

- Constant radiation and temperature conditions, dust accumulation leads to increased loss in energy generation during periods of low radiation levels compared to periods of high radiation levels.

Chapter 6, explores the operational efficiency of a solar power plant in Kolkata with a 22.5° tilt angle during regular maintenance for dust cleaning, along with calculating associated costs. more suitable techniques applicable specifically for Kolkata, West Bengal. It also encompasses an assessment of the cost implications for power plant operations based on dust removal techniques and cleaning duration. Furthermore, it examines the difficulties of technique implementation,

cost of cleaning and determines the optimal angle for both new and existing power plant installations.

- Throughout the study, variations in the Cleaning Loss Factor (CLF), Capacity Utilization Factor (CUF), and Performance Ratio (PR) values were investigated across different tilt angles of installation.
- The tilt angle range of 26 - 35 degrees, coupled with a maximum cleaning interval of 14-17 days, is most conducive to the efficient operation of solar PV power plants in Kolkata, West Bengal (Fig. 3).

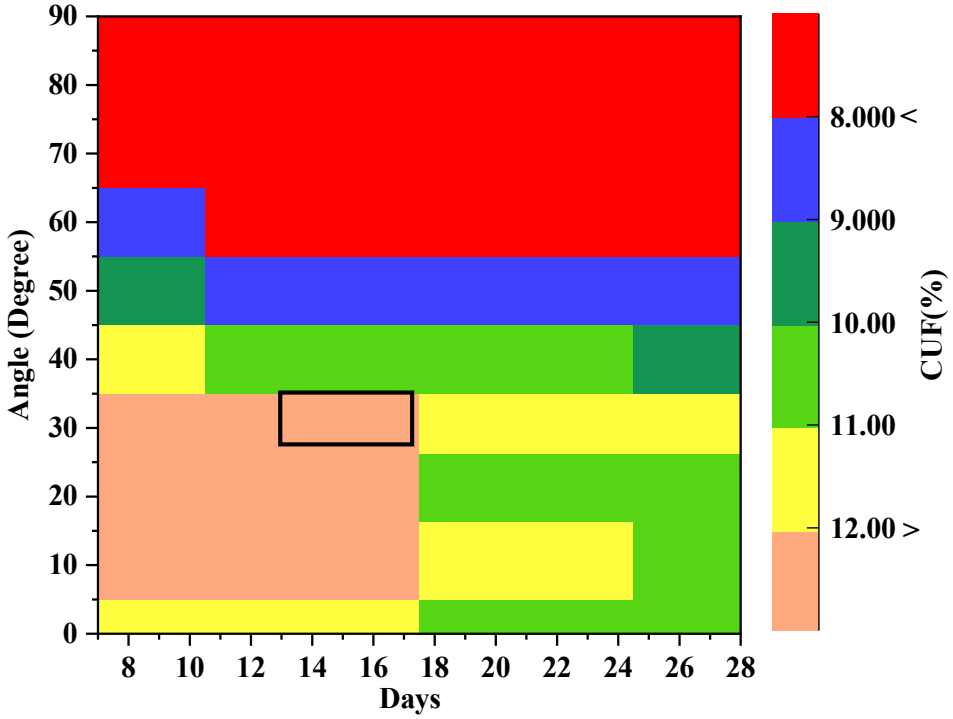


Fig. 3: Tilt angle versus CUF of solar PV plants

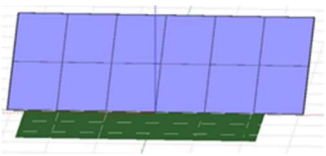
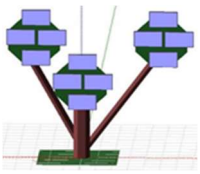
- According to statistical analysis of experimental data, the optimum tilt angle for new installations is 27°, while a cleaning frequency of 14 days leads to the best performance.

Chapter 7, examines the design of a novel solar photovoltaic tree model and its power generation pattern in response to the effects of dust. Vertical mounting configurations like solar PV tree models offer unique aesthetic and space-saving advantages, they may also experience decreased power generation compared to traditional horizontal or tilted panel installations.

- The simulation studies carried out with the proposed solar PV Tree models demonstrate the ability to generate approximately the same amount of clean electricity, taking into account the impact of dust, while using minimal land compared to conventional ground-mounted PV

plants. Under the condition of no cleaning for 26 days, the solar PV tree model generated more energy compared to conventional ground-mounted PV plants. Detailed analysis in Table 1.

Table1: Electrical comparison of solar PV Tree v/s Ground-mounted Solar PV plant

Particulars	Ground Mounted Plant	Dual Orientation Fixed 90° Tilt Tree
Graphical Representation		
Each PV Panel's Rating (W_p)	335	335
Inverter Rating (kW)	4	4
Total DC Capacity (kW_p)	4	Front side – 4 Back side-4
GHI ($kW/m^2/year$)	1914	Front side – 1006 Back side-490
Annual Energy Output (kWh)	6420	Front side – 3481 Back side-1681
Ground Clearance (m)	0.5	2
Total Land Area required (m^2)	28	10
Land Area required per kW_p (m^2/kW_p)	7	2.5
Power to Land occupancy Ratio (PLR)	0.14:1	0.4:1
The land area occupied by base of the structures (m^2)	28	1
Land Coverage Ratio (LCR)	1:1	0.1:1

Conclusions

This study can be seen as a synthesis of three systematic phases, each focusing on analyzing the prediction and real-world performance of solar photovoltaic power plants. It delves into

overcoming maintenance challenges to restore maximum power output through optimal design. The outcomes of this structured analytical approach are detailed in below Table.

Table 2: Outcomes derived from the study

Phase 1	Phase 2	Phase 3
• Experimental data showed superior to simulation data in informing solar system design with greater accuracy. • Based on the experimental data, the derived fill factor (FF) model and power model reliably can predict FF and maximum power output for various environmental conditions. • The experimental-based simulation model's performance demonstrates the actual performance of solar panels.	• As increasing time interval, dust accumulation rises, leading to decreased energy output across all weather conditions. • In lower constant radiation and temperature, the energy loss due to dust accumulation is more pronounced compared to situations with higher constant radiation and temperatures. • Normalized energy generation data shows that dust deposition adversely affects energy production across all tilt angles.	• water-based manual cleaning method is considered optimal for cleaning solar panels in Kolkata. • A tilt angle of 27 degrees can be regarded as optimal for solar PV installations in Kolkata, especially considering the impact of dust accumulation. • A cleaning frequency of 14 days is estimated optimal to maximize energy generation from a solar PV plant in Kolkata.

The quest for accuracy and efficiency in solar PV system design, has led researchers to explore the reliability of experimental data over simulated models. Through meticulous experimentation, it has become evident that experimental data outperforms simulation data in informing the design of solar systems with superior precision. A robust framework for predicting the design fill factor (FF) and maximum power output across diverse environmental conditions has been observed to be offered by the power models derived from experimental data. These models serve as invaluable tools in optimizing the performance of solar installations, ensuring efficient energy generation in varying contexts. The present research has provided valuable insights into the influence of dust accumulation on the efficiency of solar panels over varying time intervals and under diverse weather conditions. A consistent pattern has emerged from observations: as the time interval increases, the accumulation of dust on solar panels intensifies, resulting in a notable reduction in energy output regardless of fluctuations. Based on the findings, the implementation of a water-based pressured manual cleaning method is suggested for mitigating the adverse effects of dust deposition and optimizing energy generation from solar PV panels in Kolkata. This approach has

proven to be effective in removing dust build up and restoring panel efficiency. Additionally, the analysis suggests that a cleaning frequency of 14 days is optimal for maintaining peak energy generation efficiency from solar PV plants in the region. By adhering to this cleaning schedule, solar panel performance can be sustained at its highest level, ensuring reliable and sustainable energy production over time. The specific outcomes of this research are as follows:

- Studies from various literature indicate that solar PV performance is influenced by several environmental factors, with solar radiation and cell temperature being the most significant. Fluctuations in solar radiation lead to variations in cell temperature, consequently impacting PV generation. Moreover, changes in wind direction and speed can affect cell temperature. Similarly, alterations in humidity levels also contribute to fluctuations in PV cell temperature. Furthermore, the accumulation of dust on solar panels not only diminishes radiation levels but also affects the cell's temperature, leading to a gradual decline in PV performance. As cell temperature rises, efficiency tends to decrease, impacting overall performance.
- Accurate forecasting of PV panel power generation is crucial for effective planning and operational management. Several studies investigate estimating the I-V curve using equivalent circuit models. Leveraging manufacturer data, a PVsyst-based model was established and thoroughly validated across different conditions. Despite the valuable insights provided by PVsyst models, their practical applicability may be limited. Therefore, experimental models are developed to accurately evaluate real-world performance. These models encompass predicting fill factor (FF) for efficiency calculation, forecasting fill factor while considering dust accumulation, and estimating maximum power generation, independent of environmental factors. Future endeavours should focus on integrating experimental and outdoor data to enhance the precision of energy production calculations.
- During the summer season, the analysis of dust accumulation indicates a primarily increasing rate, followed by a slight decrease. In the monsoon season, dust accumulation on solar panels was erratic over time, due to rainfall washing away the dust. Winter dust effect was slightly higher compared to other seasons; however, during this period, lower ambient temperatures and radiation levels helped compensate for the generation loss.
- Under constant radiation and temperature conditions, the influence of dust deposition on energy production reveals that during periods of low radiation levels caused by dust accumulation, there is an increase in generation loss compared to periods of high radiation levels.
- The efficiency of the solar panel decreased over time at various tilt angles during both the summer and winter seasons due to dust deposition. Notably, during the summer, the highest

efficiency was achieved with a 10° tilt angle panel, whereas in the winter season, the highest efficiency was achieved with a 30° tilt angle panel. However, during the monsoon season, the efficiency of the solar panel fluctuated in response to varying intensities of rainfall.

- After evaluating different cleaning methods, manual pressurized spraying and glass wiper cleaning method with water was consider as the most effective for solar PV plant in Kolkata. This decision is based on factors like water availability and existing installations. An experimental study determined the minimum water requirement for this process.
- Annual energy generation, energy loss from dust deposition, revenue loss, and cleaning expenses across different time frames were analyzed. The analysis incorporated Cleaning Loss Factor (CLF), Capacity Utilization Factor (CUF), and Performance Ratio (PR) values, which varied with installation tilt angles. The findings suggest that existing solar PV panels in Kolkata, West Bengal, achieve optimal performance within a tilt angle range of 26 to 35 degrees, coupled with cleaning frequencies between 14 to 17 days.
- Based on the statistical analysis of experimental data, it was found that the optimum tilt angle for new installations is 27 degrees. Additionally, it was determined that a cleaning frequency of 14 days' results in the best performance.
- Solar trees are often used in urban areas where space is limited or where traditional solar panel installations may not be feasible. The advantages of solar trees include their ability to maximize solar energy capture in a limited space, their potential to serve as charging stations for electric vehicles or mobile devices, and their contribution to sustainability and environmental awareness. The dual-orientation solar PV tree was designed to minimize the impact of dust deposition on power losses within the tree model.

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1. Title of the thesis:

Study on the Impact of Variation in Design Parameters on the Performance of Solar Photovoltaic System.

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3. List of Publications:

Peer-Reviewed / UGC approved Journals

(i) **Techno-Economic and Environmental Performances of Mono- and Poly- Crystalline Silicon Solar Cell Based SPV Power Plants: A Case Study at Saboo, Ladakh in India, Indian J. of Environmental Protection,** Paper No-20230914, 2023 (Accepted on 29th November 2023).

(ii) **Study on Efficiency Behaviour of Polycrystalline Silicon Solar Photovoltaic Module- An Experimental Approach, Solar RRL**, Manuscript No-solr.202400410 (Under Review)

(iii) **Development of TiO2-based Acrylic Color-Dye Sensitized Solar Cell: An Emerging Possibilities in Third-Gen Solar Cell Technology, APSE Applied Solar Energy**, Article ID- AppSolEn2460245Mandal (Under Review)

(iv) **Possibilities of Private Bus Operators Adopting Electric Buses in Passenger Transport: A Case Study in Kolkata, India,** Indian J. of Environmental Protection, Vol. 43, No. 5, 440-451, MAY 2023.

4. **List of Patents:** Nil

5. **List of Presentations in National / International Conferences:**

(i) **A review of the change in performance of photovoltaic panels due to dust Accumulation-Challenges and their solution, 2020.** International Conference On Sustainable Water Resources Management under Changed Climate, ISBN number: 978-81-941009-3-5,2020,301-309.

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