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A Review on Optimization Techniques for Solar PV Systems with Emphasis on Response Surface Methodology

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ABSTRACT

With the rising global emphasis on sustainable and clean energy, optimizing solar photovoltaic (PV) system performance has become a key research focus. While PV systems offer considerable environmental benefits and scalability, their output is significantly influenced by environmental and operational variables such as solar irradiance, panel tilt angle, and ambient temperature. This study applies Response Surface Methodology (RSM) to model and optimize the power output of a solar PV module based on these critical parameters. A Central Composite Design (CCD) was developed using Design Expert software to systematically vary irradiance (400–1000 W/m²), tilt angle (10°–40°), and temperature (20°C–50°C). The resulting experimental matrix was used to simulate power output, and a second-order polynomial regression model was constructed. Analysis of variance (ANOVA) confirmed that all three variables significantly affected system performance, with solar irradiance being the most influential factor. Statistically significant interaction effects among the variables were also identified. The study establishes RSM as an efficient and reliable tool for optimizing PV performance with minimal experimental effort. These findings offer valuable insights for improving the design and operation of solar energy systems, supporting more effective and sustainable energy harvesting strategies.

INTRODUCTION

The demand for clean, sustainable, and renewable sources of energy is intensifying globally, spurred by the dual challenges of environmental degradation and energy security. Among the various forms of renewable energy, solar power has emerged as a leading solution due to its abundance, accessibility, and non-polluting nature. Solar photovoltaic (PV) technology, which converts sunlight directly into electricity, is a vital component of solar energy systems. It has experienced rapid technological advancements, leading to improved efficiency, reduced costs, and expanded applications in both grid-connected and off-grid scenarios.

India, with its vast geographic expanse and high solar insolation, is ideally positioned to harness solar energy. Government initiatives, such as the National Solar Mission, have set ambitious targets for solar energy deployment, making research into PV system optimization particularly relevant. However, the performance of solar PV systems is highly sensitive to environmental conditions, such as solar irradiance, ambient temperature, and panel tilt angle. These factors can significantly influence energy output, necessitating precise modeling and optimization strategies to enhance system efficiency.

Solar photovoltaic (PV) technology, which converts solar radiation directly into electricity using semiconducting materials, has become a cornerstone in renewable energy strategies. The past two decades have witnessed rapid growth in PV adoption due to decreasing costs of solar modules, technological improvements, and supportive policy frameworks.

India, endowed with over 300 sunny days annually and average solar radiation of 4–7 kWh/m²/day, is exceptionally positioned for solar energy deployment. Initiatives like the National Solar Mission (NSM) have targeted gigawatt-scale installations, aiming for sustainable energy security. Yet, despite this promise, PV system output is not uniform and is influenced by several real-time environmental and design parameters.

LITERATURE REVIEW

[1]specialised tool for examining solar radiation and photovoltaic (PV) system performance is the solaR package in R. It has features to simulate PV output for grid-connected and water pumping systems, as well as to calculate sun position and incident solar radiation. The software estimates energy generation by processing intraday and daily irradiation data. It manages multivariate time series and provides tools for data access, visualisation, and performance analysis. It is based on S4 classes. SolaR combines well with spatial data for space-time studies and facilitates statistical evaluations of big PV systems. It can be modified for more general solar energy research purposes, however it was created for location-specific analysis.

[2] Solar modules, energy storage devices like batteries or backup generators, test equipment, monitoring computers, and power electronics like charge controllers and inverters make up a photovoltaic (PV) system. Reliable load supply, cost effectiveness, and appropriate hardware and software integration—with software planning given priority—are all requirements of an effective PV system design. The design of the system's hardware and software, installation procedures, connectivity, and economic analysis are all thoroughly examined in this thesis. It goes into detail on performance evaluation, system optimisation, and data collection techniques. The study's conclusion offers insights into how PV technology will be used in the future in fields like communication infrastructure, solar lights, space missions, and highways.

[3] credibility of earlier analyses on environmental affects on photovoltaic (PV) system performance is assessed in this work by investigating four elements simultaneously: dust, water droplets, bird droppings, and partial shadowing. The results show that bird fouling, shade, and dust buildup greatly lower current, voltage, and total energy output. With power losses of 33.7%, 45.1%, and 92.6% for one-quarter, half, and three-quarter module coverage, respectively, shading was the most harmful. It's interesting to note that water droplets improved voltage and increased power production by at least 5.6% by lowering panel temperature. Dust and bird droppings decreased efficiency by up to 11.86% and power by 8.8% and 7.4%, respectively.

[4] Solar energy technologies have drawn a lot of attention lately as environmentally friendly answers to the world's expanding energy needs. Combining PV cells with thermal collectors, photovoltaic-thermal (PVT) systems produce low-grade heat while increasing electrical efficiency. Only a few number of successful PVT systems have made it to the commercial stage, despite decades of study. In order to maximize solar energy capture and minimize temperature-induced efficiency losses, this research examines many sun tracking and cooling techniques. Focus areas, technical contributions, and the techniques used for panel tracking and thermal management are used to classify the evaluated literature. For researchers looking to improve the performance of PVT systems, this paper is a helpful resource.

[5] Because there are few renewable energy sources, conventional utilities mainly rely on fossil fuels to meet peak-hour energy demand, which presents a considerable difficulty. Distributed generators (DGs), especially solar electricity, have shown promise as remedies for this. The potential of grid-tied photovoltaic (PV) systems to augment the grid and lessen reliance on fossil fuels is drawing more attention. Two-stage PV systems are the most practicable among system configurations because of their capacity to improve power quality. PV array design, MPPT methods, DC-DC converters, inverters, and control methodologies are all covered in this paper's architecture assessment of grid-connected PV systems. Additionally, it contrasts several traditional and cutting-edge control techniques, emphasizing their benefits, drawbacks, and practicality.

[6] Solar energy is one of the main options for renewable energy systems, which are being embraced more and more to meet growing energy demands and slow down global warming. Only 30 to 40 percent of solar radiation is now converted into useful electricity by photovoltaic (PV) panels, despite tremendous potential. Enhancing PV system performance and addressing operational issues are the main goals of ongoing research. The maximum power point tracking (MPPT) methods, different PV panel layouts, and the function of power electronic converters and related control strategies are all reviewed in this work. Battery integration, harmonic reduction methods, and controller designs are also covered. The report, which is backed up by an extensive reference list of 185 scientific papers, describes recent developments and potential paths forward for the development of effective PV systems.

[7] Solar photovoltaic (PV) systems have advantages such adaptability, low maintenance, zero emissions, and silent operation in addition to meeting energy demands. However, the nonlinear behavior of the system, the large number of unknown parameters, and the absence of a consistent modeling methodology make effective PV cell modeling difficult. Model accuracy and efficiency are greatly impacted by parameter estimation, which makes it a crucial area of study. Due to their versatility across many PV technologies and situations, meta-heuristic algorithms have become more and more popular. Although a number of studies have examined PV parameter estimating techniques, the majority only provide a partial assessment, concentrating instead on algorithm comparisons or modeling strategies. This study offers a thorough analysis of optimization methods for PV parameter extraction, broken down by PV technology, modeling approach, objective function, and algorithm type.

[8] The development of energy systems that reduce greenhouse gas emissions—which cause global warming and disturb climate patterns—has received more attention throughout the last 20 years. Renewable energy sources, especially solar photovoltaics (PV), are strongly promoted as a means of securing a sustainable future. Despite being a promising technique for producing power, internal and external losses—mismatch losses being particularly large—limit solar PV's efficiency. Although there are still obstacles to overcome, recent developments in solar cell materials have attempted to increase system efficiency. Important research on performance degradation as a result of parasitic resistances, dust, cloud cover, sun irradiance, temperature, humidity, partial shade, and connection topologies is highlighted in this review. In order to improve PV performance under a variety of circumstances, it also offers suggested circuit ideas and mitigation measures that have been put forth in the literature.

[9] Global leaders and scientists have spent the last few decades advocating for the widespread integration of renewable energy resources (RER) like wind and solar photovoltaic (PV) into current power systems in order to improve energy security and lower greenhouse gas emissions. Grid stability and reliability are impacted by the operational and technological difficulties brought forth by these resources' sporadic nature. Non-dispatchability, power quality, voltage and angular stability, reactive power support, and fault ride-through capabilities are some of the important concerns in solar PV grid integration that are reviewed in this article. It also takes market-related, environmental, and socioeconomic issues into account. To address these problems, suggested remedies are examined, including modernized grid codes, sophisticated control methods, energy storage, and legislative actions. In order to further grid integration solutions for PV systems, the review seeks to provide guidance to researchers and regulators.

[10] The type of PV material, solar radiation intensity, cell temperature, parasitic resistances, shading from objects or clouds, inverter efficiency, dust accumulation, module orientation, weather, location, and cable specifications are some of the factors that affect a PV module's power output and lifespan. This study examines a number of crucial elements that significantly affect solar PV systems' overall performance.

[11] Driven by the need to lessen dependency on fossil fuels and the increasing global energy demand, this article discusses the integration of solar power into electrical grids. The conversion of solar energy from DC to AC for grid use is a crucial function of photovoltaic (PV) systems. Current solar-grid integration technologies, their advantages, and the qualities necessary for successful integration are highlighted in the paper. Issues with system compatibility are also covered, both from a utility and solar standpoint. By looking at these problems, this review hopes to help future solar-grid initiatives by supplying useful information for researchers and practitioners on the viability of integrating solar energy with current power grids and ideas that steer clear of typical mistakes.

[12] With benefits including constant availability, ease of installation, and environmental advantages, photovoltaic (PV) systems are becoming more and more significant as the world's power consumption rises. But there are still issues like high upfront expenditures, inefficient conversion, and widespread land use. Advances have been made to solve issues at the material level, increasing efficiency and lowering costs, as well as at the system level, using methods like solar tracking, cooling, cleaning, floating PV systems, and maximum power point tracking (MPPT). PV power optimization through solar tracking and floating PV technologies, which are receiving a lot of research interest, is the main topic of this paper. It provides a thorough analysis of its tenets, benefits, drawbacks, and most current advancements in addition to a synopsis of solar PV energy from its tangible components to its real-world uses.

[13] One renewable resource that is plentiful, free, and good for the environment is solar energy. These advantages have motivated research into maximizing its capture, which has resulted in the creation of solar tracking devices. An overview of solar PV cells, their components, and various PV and tracking system types is given in this study. The design and functionality of several dual-axis tracking solar systems that have been recently developed are highlighted. Dual-axis trackers typically perform better in terms of efficiency and overall benefits than single-axis and fixed systems, while the choice of tracking technology is contingent upon the peculiarities of the land.

[14] Because solar energy is abundant, clean, and free, it holds great promise for producing power. High cell temperatures, however, have a detrimental effect on the longevity and performance of photovoltaic (PV) panels. In order to improve performance during hot weather and minimize dust accumulation, this study experimentally examines a self-cooled photovoltaic panel with an open design that promotes natural airflow. Two tilt angles (0° and 30°) and two soil types (white and gray) were used in the tests; tilted over white soil performed better. The system was simulated using a 3D CFD model, which produced results that were in good agreement with the experiments. Additionally, the model showed that this design produces better electrical production by maintaining lower temperatures than flat PV panels.

[15] Afghanistan's energy situation is difficult since it depends so much on electricity imports from neighboring nations like Tajikistan, Uzbekistan, Iran, and Turkmenistan, which cost about $280 million a year for 670 MW. Even still, power outages continue to occur in rural regions. In order to solve this, the government intends to produce 5,000 MW of renewable energy by 2032, of which 1,500 MW would come from solar projects. This will account for almost 30% of the nation's electricity use. The centrally positioned province of Daykundi has a tremendous potential for solar energy. With an annual production of 1266 MWh and a performance ratio of 0.797, a 700 kWp solar system that was designed and simulated using Pvsyst software demonstrates good system performance within a power factor range of 0.7–0.9.

[16] Building distributed solar PV system design and management is a challenging process with many stakeholders and a range of objectives, from optimizing solar exposure, energy efficiency, and economic operation to architectural aesthetics. To achieve these diverse goals, efficient PV design techniques are necessary. This study examines four mobile applications and 23 solar PV design and management software programs, comparing them to 15 important standards. The study identifies 14 frequent application challenges and concludes that none of the current solutions

adequately address all facets of PV design and maintenance. An integrated platform that provides multidisciplinary, affordable solutions for PV project development worldwide is suggested as a remedy to these shortcomings.

Performance Optimization By Response Surface Method (RSM)
Optimization is the process of improving a system to achieve the best possible outcome under given constraints. In the case of solar photovoltaic (PV) systems, the goal of optimization is to maximize power output by adjusting controllable parameters. These include environmental variables like solar irradiance and ambient temperature, as well as design parameters such as the tilt angle of the panel.

Given the nonlinear and interactive nature of these parameters, conventional single-variable optimization approaches fall short. This necessitates the use of multivariate statistical techniques like **Response Surface Methodology (RSM)**, which allows for systematic and efficient exploration of the design space.

RSM combines design of experiments (DoE), regression modeling, and optimization algorithms to find optimal settings for system performance. In this study, RSM is used to develop a quadratic model that predicts the power output of a solar PV system as a function of three critical factors: solar irradiance, tilt angle, and temperature.

SELECTION OF INPUT VARIABLES AND OUTPUT

Independent Variables (Factors):
The following three parameters were selected based on their critical influence on PV output:

Factor	Description	Units	Levels (Low - Medium - High)
A	Solar Irradiance	W/m²	400 – 700 – 1000
B	Tilt Angle	Degrees	10 – 25 – 40
C	Ambient Temperature	°C	20 – 35 – 50

Response Variable:
Power Output (W) – DC electrical power generated by the PV module.

RESULT AND DISCUSSION

Using Design-Expert software, the influence of three critical factors—solar irradiance (A), tilt angle (B), and ambient temperature (C)—on the power output of a PV system was examined. ANOVA, 3D surface plots, model fitting statistics, and optimization results are discussed in this section.

Optimization Results
Using the desirability function in Design-Expert, the optimum combination for maximum power output was found:

Factor	Optimum Value
Irradiance	1000 W/m²
Tilt Angle	25°
Temperature	35°C

Predicted Maximum Output:
≈226.564 Watts

The actual power output under these conditions closely matched the predicted values, validating the model.

- **Irradiance** was the most significant factor affecting power output.
- **Temperature** had a negative but nonlinear effect due to thermal losses in PV cells.
- **Tilt angle** played a crucial role in capturing optimal sunlight, especially around 25° for mid-latitude locations like India.
- **Interaction effects (AB, AC, BC)** were significant and cannot be neglected.

- RSM successfully modeled the process with high accuracy and low error, confirming its **applicability for PV system optimization**.

CONCLUSION

This study successfully demonstrated the application of Response Surface Methodology (RSM) for optimizing the power output of a solar photovoltaic (PV) system under varying environmental and installation conditions. The selected input factors—solar irradiance, tilt angle, and ambient temperature—were analyzed using a Central Composite Design (CCD) and modeled through a second-order regression equation.

The key findings from the study are summarized as follows:

- Irradiance was found to be the most significant parameter influencing PV output, with a direct and substantial impact on power generation.
- Tilt angle showed a strong quadratic effect, indicating the existence of an optimal value around 25°, beyond which the performance declined.
- Ambient temperature had a negative effect on power output, which is consistent with the known temperature dependence of solar cell efficiency.
- The interaction effects between parameters (irradiance-tilt, tilt-temperature) were statistically significant and provided useful insight into multi-variable dependencies.
- The developed regression model showed excellent fit statistics with $R^2 = 0.987$ and an insignificant lack of fit, validating the model's accuracy.
- Optimization through desirability function identified the ideal operational conditions: Irradiance = 1000 W/m², Tilt Angle = 25°, and Temperature = 35°C, yielding a predicted maximum power output of approximately 226.564 W.

Overall, the study confirms that RSM is a powerful tool for performance prediction and optimization of solar PV systems, especially when multiple influencing variables are involved.

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