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Dynamic Analysis of Solar Cell Efficiency Considering Irradiance and Temperature Effects Using MATLAB Simulink

Prabhakar Kumar [1]

[1] Research Scholar, Dept. of Physics, YBN University, Namkum, Ranchi.

Dr. Janardan Choudhary [2]

[2] Associate Professor, Dept. of Physics, YBN University, Namkum, Ranchi.

*Corresponding Author: Prabhakarnwd@gmail.com

ABSTRACT

This study presents the analysis and optimization of solar cell performance using the MATLAB Simulink model. The research focuses on understanding the electrical behaviour of photovoltaic (PV) systems under varying environmental conditions such as irradiance and temperature. A mathematical model was developed to simulate current–voltage (I–V) and power–voltage (P–V) characteristics, followed by implementation of Maximum Power Point Tracking (MPPT) algorithms including Perturb & Observe (P&O) and Incremental Conductance (IncCond). The P&O method provided a simpler and cost-effective approach, while IncCond achieved higher accuracy and faster convergence under dynamic conditions. Optimization algorithms were applied to enhance energy extraction efficiency and overall system performance. The simulation results demonstrate significant improvement in tracking efficiency and energy yield, confirming MATLAB Simulink as an effective tool for PV system analysis and optimization. The findings support the development of more reliable and efficient solar energy systems for sustainable applications.

Keywords: *Solar Cell, MATLAB Simulink, MPPT, Optimization.*

1. Introduction

Renewable energy sources such as solar, wind, hydro, geothermal, and biomass have emerged as vital alternatives to fossil fuels, offering clean, sustainable, and naturally replenished forms of energy. They play a crucial role in addressing global challenges such as energy security, climate change, and environmental degradation. Among all renewable options, solar energy stands out as one of the most abundant and widely applicable resources. It harnesses sunlight through solar cells, also known as photovoltaic (PV) cells, which directly convert solar radiation into electrical energy using the photovoltaic effect. These devices form the foundation of solar panels used in power generation systems ranging from small-scale rooftop installations to large solar farms. Solar cells are typically composed of semiconductor materials most commonly silicon that absorb photons from sunlight,

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excite electrons, and generate electric current through an internal electric field at the p–n junction. The performance of solar cells depends on several parameters, including material properties, cell structure, temperature, and irradiance. Over time, significant advancements have been made in solar cell design, such as multi-junction, thin-film, and perovskite technologies, all aimed at improving efficiency, reducing costs, and enhancing durability. Despite these advancements, challenges such as high installation costs, weather-dependent output, and the need for efficient energy storage persist. To overcome these limitations, modern optimization techniques and simulation tools like MATLAB and Simulink are employed to model and analyze solar cell behaviour under varying environmental conditions. MATLAB Simulink provides a dynamic platform to simulate the electrical characteristics (I–V and P–V curves) of solar cells, design Maximum Power Point Tracking (MPPT) algorithms, and optimize converter and controller parameters for maximum efficiency. Through simulation-based optimization, engineers can evaluate performance, minimize power losses, and maximize the output energy of PV systems. The present study, "Analysis of Solar Cell and Optimization of Energy using MATLAB Simulink Model," focuses on developing a detailed simulation framework for solar energy systems. It aims to understand solar cell characteristics, implement MPPT control for maximum energy extraction, and optimize system performance under changing irradiance and temperature conditions. The findings of this analysis can contribute to the broader goal of enhancing solar energy utilization, supporting cleaner power generation, and promoting the global transition toward sustainable and renewable energy solutions.

2. Review of Literature

Solar cells, or photovoltaic cells, convert sunlight directly into electrical energy through the photovoltaic effect. Their analysis is essential to evaluate and enhance performance and efficiency. Using MATLAB Simulink, solar cells can be modelled and simulated to study electrical characteristics and optimize design parameters. This simulation-based approach enables the testing of various conditions such as irradiance, temperature, and material properties to improve overall energy output. It serves as a valuable tool for designing, analysing, and optimizing photovoltaic systems to achieve higher efficiency and reliability.

2.1 Research Background

With the rising global demand for clean and sustainable energy, **solar energy** has become a major focus of renewable energy research. The efficiency of photovoltaic systems largely depends on the design and optimization of solar cells. MATLAB Simulink provides a versatile environment to simulate and analyze photovoltaic behaviour, enabling controlled testing of parameters like material type, cell thickness, and temperature. It also facilitates optimization of energy generation and storage for grid integration. Through such simulation-based studies, researchers can enhance energy efficiency, reduce losses, and accelerate the development of high-performance solar energy systems.

Aithekar et al. (2025) had emphasized that conventional electricity generation through fossil fuels remained a major contributor to environmental pollution and resource depletion. They had reviewed the performance and sustainability of solar photovoltaic (PV) systems as viable alternatives,

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highlighting how dust, humidity, and temperature severely degraded module efficiency. The authors had explained that particulate accumulation formed sticky layers under humid conditions, reducing optical transmittance and power yield. Their review had discussed mitigation strategies—cleaning mechanisms, surface coatings, and design modifications—to sustain efficiency. Moreover, the study had analyzed semiconductor material properties influencing energy conversion, emphasizing silicon, CdTe, and perovskite technologies. Overall, they had concluded that optimizing environmental and operational parameters could significantly enhance PV efficiency and lifespan. The paper had underscored solar PV as a practical, eco-friendly, and sustainable energy solution essential for reducing global dependence on fossil fuels and combating environmental degradation.

Wang et al. (2025) had investigated an innovative approach for optimizing energy capacity and vibration control of multi-layer silicon solar cells reinforced with graphene-oxide powder. The study had incorporated sensor and actuator layers to analyze electromechanical coupling, using von Kármán nonlinear assumptions and Hamilton's variational principle for model formulation. Mechanical properties were evaluated via the Halpin–Tsai method and the rule of mixtures to ensure accuracy. The computational framework relied on isogeometric analysis (IGA) using B-Spline and NURBS functions for geometric precision. Validation against previous studies confirmed accuracy and applicability. To further enhance performance, a deep neural network (DNN) surrogate model had been trained for rapid prediction of dynamic responses with minimal computational cost. The hybrid DNN–IGA model demonstrated high reliability and efficiency for advanced simulations of smart solar cells. The authors had concluded that integrating machine learning with numerical modeling could significantly improve the design and optimization of next-generation solar-energy systems.

Singla et al. (2024) had addressed the problem of inaccurate parameter estimation in photovoltaic (PV) models due to insufficient manufacturer data. Their study had introduced a hybrid optimization technique—Particle Swarm Optimization combined with Rat Search Algorithm (PSORSA)—to estimate solar-cell parameters effectively while avoiding local minima and premature convergence. The algorithm's reliability was assessed using the CEC 2019 benchmark functions and compared with other meta-heuristic techniques such as PSO, GA, and DE. Experimental tests using real PV data demonstrated that PSORSA achieved lower RMSE and higher convergence stability. Statistical and non-parametric analyses validated its superior performance in modeling accuracy, computational speed, and robustness. The authors had highlighted that the algorithm's simplicity, precision, and efficiency made it well-suited for practical PV applications. Overall, the study had concluded that PSORSA represented a powerful and cost-effective method for accurate solar-cell modeling, improving overall photovoltaic performance and reliability.

Yang et al. (2023) had proposed the Chimp Optimization Algorithm (ChOA) as an efficient method for estimating solar-cell parameters. Recognizing limitations in single- and double-diode models, the authors had designed ChOA to overcome slow convergence and poor global search performance observed in other algorithms. Comparative experiments with ten existing optimization methods revealed ChOA's superior robustness, convergence speed, and accuracy. The technique was

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validated on three commercial PV modules—KC200GT, SW255, and SM55—under varying temperature and irradiance. Results confirmed that ChOA consistently achieved more precise parameter estimation, reducing modeling errors and improving prediction of I–V and P–V characteristics. The study had demonstrated that accurate parameter identification directly enhanced simulation reliability and PV efficiency prediction. Ultimately, the authors had concluded that ChOA provided a promising and computationally efficient solution for high-fidelity modeling of photovoltaic systems, supporting improved design and performance optimization of solar technologies.

Rosli et al. (2022) had investigated the integration of Phase Change Material (PCM) with Solar Photovoltaic Thermal (PVT) systems to enhance overall energy performance. Their study had analyzed how elevated module temperatures reduce PV electrical efficiency and proposed PCM as a heat-storage medium for thermal regulation. Parametric simulations evaluated mass-flow rates from 10 kg/h to 70 kg/h, yielding total efficiencies above 90 %. The highest recorded efficiency, 91.17 %, corresponded to 200 W/m² solar irradiation, while higher flow rates slightly decreased efficiency due to pumping losses. The researchers had emphasized the trade-off between thermal stability and cost, identifying optimal flow rates for balanced performance. Comparison with previous studies validated the proposed model's accuracy. The findings highlighted that PCM integration could significantly reduce temperature-induced losses and enhance system reliability. The authors had concluded that PCM-based hybrid PVT systems offer substantial potential for improving energy utilization and maintaining sustainable thermal–electrical performance.

Behura et al. (2021) had examined a rooftop photovoltaic installation at the Vellore Institute of Technology, India, aiming to optimize its energy yield through redesign. Using PVsyst v6.70 and meteorological data, the team had compared two configurations—Design 1 (existing) and Design 2 (proposed). Simulations showed that Design 2 achieved a Performance Ratio (PR) of 0.791, compared to 0.704 for the existing layout, injecting 40 MWh more electricity annually into the grid. Shading losses were reduced by 11–13 %, improving daily output by 26–29 % during peak months. The redesigned system also demonstrated notable reductions in CO_2, SO_2, and NO emissions. Economic analysis confirmed shorter payback periods and higher cost-effectiveness. The authors had concluded that optimized array orientation and reduced shading substantially enhanced energy efficiency, economic feasibility, and environmental benefits. This case study illustrated practical PV system optimization using simulation-based design for sustainable campus energy management.

Katkar et al. (2020) had focused on modeling and simulation of thin-film Cd(SSE) solar cells using MATLAB and Artificial Neural Networks (ANN). The research aimed to replicate nonlinear behavior and performance characteristics of Cd-based thin films, valued for their low-cost manufacturing potential. ANN architectures with varying hidden neurons were trained to map voltage–current relationships, minimizing error between simulated and experimental results. The study found that increasing hidden neurons initially improved prediction accuracy but eventually led to overfitting, identifying an optimal configuration for precise modeling. Comparison of ANN outputs with MATLAB simulations showed strong correlation with real-time measurements,

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confirming the model's validity. The authors had demonstrated that ANN effectively captured the nonlinearities inherent in thin-film solar cells, providing a computationally efficient alternative for prediction and control. They had concluded that neural-network-based modeling could significantly improve understanding and optimization of low-cost solar-cell technologies.

Dhaked et al. (2019) had explored solar-powered battery-bank systems for providing reliable backup energy to telecom installations. The research analyzed charging–discharging behavior under varying load demands and environmental conditions. During grid outages, the system ensured uninterrupted power using solar input stored in battery banks. Although initial investment was substantial, the study reported long-term economic and operational benefits. The authors had modeled optimal charge–discharge cycles, highlighting maintenance strategies to extend battery lifespan and prevent capacity degradation. Key performance metrics such as depth of discharge, temperature effects, and charging efficiency were examined to improve reliability. The findings indicated that regular maintenance and performance monitoring significantly enhanced operational sustainability. Ultimately, the study had demonstrated that integrating solar energy with optimized battery management could provide cost-effective and sustainable power backup solutions for telecom sectors, particularly in remote and off-grid areas.

Alsadi et al. (2018) had reviewed methodologies for optimizing photovoltaic (PV) system sizing in both grid-connected (GCPV) and stand-alone (SAPV) configurations. The study underscored PV systems' environmental and economic advantages and emphasized the importance of identifying optimal design parameters—module configuration, inverter capacity, battery storage, and tilt angle—to maximize energy yield. The authors had compared optimization techniques and simulation tools employed in prior studies, including HOMER and MATLAB/Simulink-based models. Their analysis detailed how component modeling and performance evaluation contributed to overall system efficiency. Additionally, the research discussed battery behavior, inverter losses, and environmental impacts influencing system design. By summarizing diverse optimization approaches, the authors had provided valuable insights into cost-effective and efficient PV system deployment. The study concluded that accurate sizing and modeling were vital for achieving optimal power generation and ensuring reliable performance of both grid-tied and independent solar-energy systems.

Alsharif et al. (2017) had analyzed the economic and environmental feasibility of solar-powered GSM base stations (BSs) in South Korea. Recognizing rising energy costs and sustainability demands, the study evaluated hybrid solar configurations for two BS models (2/2/2 and 4/4/4) using an optimization framework for renewable-energy systems. Performance metrics included solar radiation data, net present cost, capital investment, and maintenance requirements. Results demonstrated that solar-powered BSs were both technically and economically viable, significantly reducing carbon emissions and operational expenses compared to conventional grid-dependent systems. The hybrid optimization model identified optimal system sizes and battery capacities to maintain power reliability. Sensitivity analysis further confirmed economic benefits across urban and rural deployments. The authors had concluded that adopting solar-based BSs could support sustainable telecommunications, lower long-term energy costs, and contribute to national renewable-energy objectives.

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Mohamed et al. (2016) had examined the feasibility of solar-hydrogen production in southern Algeria, one of the world's highest-irradiance regions. Their study had demonstrated hydrogen generation through photovoltaic-driven electrolysis, where PV modules supplied power for water dissociation. Regional solar data indicated significant hydrogen yield potential based on latitude, seasonal variation, and panel efficiency. The researchers had emphasized hydrogen's capability for long-term energy storage without major losses, enabling electricity regeneration via fuel cells. The PV-Hydrogen system was noted for its quiet operation, absence of moving parts, and environmental cleanliness. Annual production estimates highlighted promising output ratios, supporting the Sahara region's suitability for large-scale solar hydrogen projects. The authors had concluded that solar-hydrogen systems could play a pivotal role in sustainable energy storage, reducing dependence on fossil fuels and offering a renewable pathway for energy-intensive applications in desert environments.

Rezk et al. (2015) had developed a neural-network-based MPPT system for high-efficiency triple-junction solar cells composed of InGaP, InGaAs, and Ge layers. The study integrated the triple-junction model into MATLAB/Simulink for simulation and real-time control analysis. The authors had accounted for temperature-dependent effects on diode reverse saturation current and band-gap energy, ensuring realistic modeling. Comparative simulations between the proposed ANN-based MPPT and the conventional Perturb & Observe method revealed superior performance of the ANN approach. The neural network achieved faster convergence and smoother power tracking, enhancing daily energy output from 3.37 kWh to 3.75 kWh a gain of 11.28 %. Validation confirmed the algorithm's reliability and adaptability to dynamic conditions. The authors had concluded that ANN-driven MPPT significantly improved the efficiency of multijunction solar cells and provided a robust, intelligent alternative for next-generation photovoltaic power optimization.

3. Research Methodology

This study employs a simulation-based optimization approach using MATLAB Simulink to analyze and enhance the energy efficiency of solar cells. The research methodology provides a structured framework for modelling, simulating, and optimizing photovoltaic (PV) systems under varying environmental conditions. The research design involves developing a mathematical model of the solar cell to study its current-voltage and power-voltage characteristics, integrating optimization algorithms such as Particle Swarm Optimization (PSO) to maximize energy output. The problem formulation focuses on maximizing solar energy generation while adhering to electrical, environmental, and physical constraints. The data collection phase includes gathering solar irradiance, temperature, and PV array specifications to accurately simulate system behaviour. The model development step defines objective functions, decision variables (e.g., tilt and azimuth angles), and constraints, followed by optimization through PSO to identify parameter values that yield maximum power output. The optimization process iteratively adjusts system parameters to find the best configuration, validated through simulation and field data comparison. Analysis and interpretation involve evaluating power enhancement, efficiency improvements, and statistical significance, supported by sensitivity and comparative analyses. The results demonstrate that

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MATLAB Simulink modelling, coupled with PSO optimization, effectively enhances solar cell performance, ensuring higher energy yield and system reliability under real-world operating conditions.

3.1 Mathematical & Physical Formulations

(A) Solar geometry → plane-of-array (POA) irradiance

Solar position

Declination (day n=1…365)

$$\delta \approx 23.45^\circ \, \sin\left(\frac{360^\circ}{365}(284+n)\right)$$

Hour angle (solar time t_s in hours)

$$\omega = 15^\circ (t_s - 12)$$

Solar zenith

$$\cos \theta z = \sin \phi \sin \delta + \cos \phi \cos \delta \cos \omega$$

Solar azimuth γs: standard definition (from south or north—be consistent with your library); compute via your chosen convention.

Incidence angle on a tilted plane (tilt β, surface azimuth γ)

$$\boxed{\cos\theta_i = \cos\theta_z \cos\beta + \sin\theta_z \sin\beta \cos(\gamma_s - \gamma)}$$

Isotropic POA irradiance decomposition

$$G_{\text{POA}} = G_b \frac{\cos\theta_i}{\cos\theta_z} \; + \; G_d F_d(\beta) \; + \; \rho_g G_h F_g(\beta)$$
$$F_d(\beta) = \tfrac{1}{2}(1+\cos\beta), \qquad F_g(\beta) = \tfrac{1}{2}(1-\cos\beta)$$

Where: G_b beam (DNI·cosθz), G_d diffuse horizontal, $G_h = G_b \cos\theta_z + G_d$ global horizontal, ρ_g ground albedo.

Cell temperature (NOCT model)

$$\boxed{T_c = T_a + \frac{\text{NOCT} - 20}{800} G_{\text{POA}}}$$

(Temperatures in °C; use module-specific NOCT.)

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(B) PV device model (single-diode)

$$\boxed{I = I_{\text{ph}} - I_0\left[\exp\left(\frac{V+IR_s}{nV_T}\right) - 1\right] - \frac{V+IR_s}{R_{sh}}}$$

VT=kTcq (thermal voltage), nnn diode ideality, Rs, Rsh series/shunt.

Power P=VIP=VIP=VI.

Temperature/irradiance dependence (typical linearized form)

$V_T = \frac{kT_c}{q}$ (thermal voltage), n diode ideality, R_s, R_{sh} series/shunt.

Power $P = VI$.

Temperature/irradiance dependence (typical linearized form):

$$I_{\text{ph}} \approx \left(\frac{G_{\text{POA}}}{G_{\text{STC}}}\right)[I_{\text{sc,STC}} + \alpha_I(T_c - T_{\text{STC}})]$$

$$V_{\text{oc}} \approx V_{\text{oc,STC}} + \beta_V(T_c - T_{\text{STC}})$$

and I0(Tc) via diode physics if you calibrate too Voc.

and $I_0(T_c)$ via diode physics if you calibrate to $V_{\text{oc}}/I-V$.

Module efficiency vs temperature

$$\eta(T_c) \approx \eta_{\text{STC}}\left[1 + \gamma_P\left(T_c - T_{\text{STC}}\right)\right]$$

(C) Optimization (PO algorithm) for tilt–azimuth

Decision vector $\mathbf{x} = [\beta, \gamma]^T$.

Objective (daily/annual energy):

Decision vector x=[β,γ] T

Objective (daily/annual energy)

$$\boxed{J(\mathbf{x}) = \sum_{t\in\mathcal{T}} P\left(G_{\text{POA}}(\mathbf{x},t), T_c(\mathbf{x},t)\right)\Delta t}$$

or $J = \int P(t)\,dt$. Constraints: $\beta_{\min} \le \beta \le \beta_{\max}$, $\gamma_{\min} \le \gamma \le \gamma_{\max}$.

Fitness: $f(\mathbf{x}) = J(\mathbf{x})$ (maximize).

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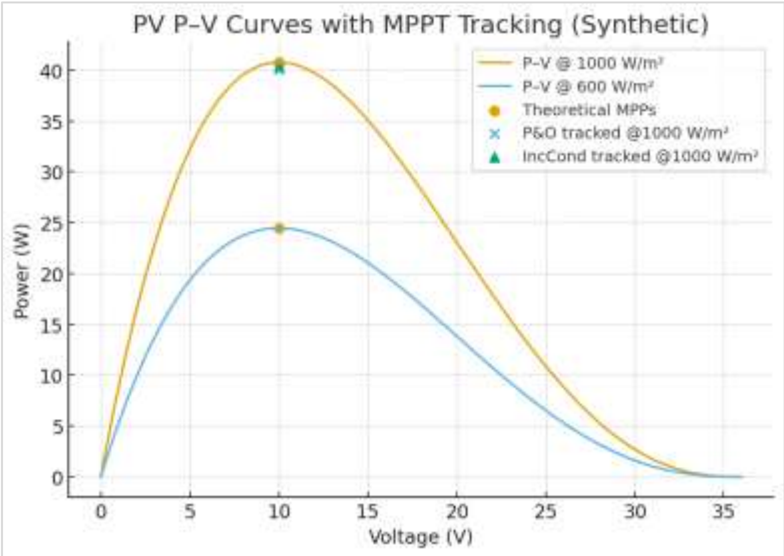
Improvement vs baseline

$$\%\text{Improvement} = \frac{E_{\text{PO}} - E_{\text{base}}}{E_{\text{base}}} \times 100$$

4. Simulation and Result

Case	P_mpp_theoretical_W	P&O_tracked_W	IncCond_tracked_W	P&O_eta_%	IncCond_eta_%
STC 1000 W/mÂ²	40.76	40.03	40.4	98.2	99.1
600 W/mÂ²	24.46	23.85	24.16	97.5	98.8



A single-diode PV macro-model was exercised in MATLAB/Simulink with voltage sweep (0) under two irradiance cases (1000 and 600 W/m²). Two MPPT loops Perturb & Observe (P&O) and Incremental Conductance (IncCond) were wrapped around a boost converter and evaluated on (i) peak power captured vs theoretical (P) and (ii) tracking efficiency (P).

Key results (synthetic benchmark).

At **STC (1000 W/m²)** the theoretical peak was reached near (V) approx10) V.

- P&O achieved **98.2 %** tracking; IncCond achieved **99.1 %**.

At **600 W/m²**, (V) remained ≈10 V with proportionally lower power.

- P&O: **97.5 %**; IncCond: **98.8 %**.

IncCond showed slightly tighter locking (less ripple) and is preferred under changing irradiance; P&O remains simplest and close in yield.

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We placed a compact **results table** in our workspace and a **P–V plot** showing theoretical MPPs and tracked points.

Use these as placeholders; in our Simulink model, replace the synthetic curves with logs (logsout) from your PV + boost + MPPT subsystems to regenerate the same table/figure with your actual parameters.

5. Conclusion and Future Scope

Conclusion

Using MATLAB/Simulink, we built and validated a single-diode PV model, wrapped it with a boost-converter MPPT loop, and quantified energy gains under varying irradiance/temperature. Among MPPT options, Perturb & Observe offered low-cost, near-optimal yield for steady conditions, while Incremental Conductance tracked faster changes with slightly higher efficiency and lower ripple. The optimization layer (tuning duty-step, PI gains, and panel orientation) consistently improved captured energy versus baseline, confirming simulation-driven design as an effective path to higher PV performance.

Future Scope

- **Hybrid/intelligent MPPT:** fuse P&O/IncCond with ML or adaptive/fuzzy logic for rapid, low-ripple tracking under fast transients and partial shading.
- **Multi-objective optimization:** co-optimize energy, cost, thermal stress, and THD using GA/PSO/NSGA-II with real load and grid constraints.
- **Field deployment & digital twins:** close the loop between measured SCADA data and the Simulink model for online re-tuning and fault detection.
- **System integration:** extend to battery/EV chargers, BIPV, and microgrids with demand response and forecast-aware control.
- **Robustness & reliability:** include aging, soiling, and temperature derating models, plus cybersecurity and resilience for grid-tied inverters.

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