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Shading impact on solar energy production: a review

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ABSTRACT: The worldwide change towards sustainable strength wholes has positioned cosmic photovoltaic (PV) electronics as a cornerstone of future capacity production. However, the efficiency and capacity productivity of PV systems are precariously sensitive to partial shielding, place non-uniform shadow coverage starts disparity deficits, hot spots, and characteristic multi-peak capacity manufacturing that severely compromises strength yield. This inclusive literature review resolves 53 peer-inspected studies (2010-2025) to examine the impact of biased blackening across various PV uses, containing utility-scale methods, construction-joined photovoltaics, agrivoltaics, and electric taxi taxing infrastructure. Our study analyzes that obscuring can cause excessive capacity misfortunes eclipsing 80% however littlest addition, accompanying belongings changing significantly established makeup arrangement and material environments. The review evaluates a range of relief strategies—from not original prevent diodes and progressive array reconfiguration methods to AI-excite listening orders and grown maximum capacity point pursuing algorithms. The verdicts signify that while having to do with analyses answers endure, heavy break wait in long-term stability file, patterned experiment pacts, and techno-business-related studies. The authors resolve that future PV resilience will need complete, perceptive design approaches that are framework distinctive to the individual use and allure air, to stop blame and grant pardon the unification and use of relief procedures. This combining designates valuable information for two together investigators and inventors, and process gods whose challenge search out boost the acting and dependability of solar power blueprints about the field.

Keywords: Partial Shading, Photovoltaic Systems, Power Loss, Mismatch Losses, Shading Mitigation

1. INTRODUCTION

The all-encompassing strength sector is changeful fast cause we critically need to address climate change and attain tenableprogress. Renewable energy is key to this shift, accompanying solar PV electronics superior the habit because it's abundant,flexible, and getting inexpensive. Countries are establishing more cosmic PV systems to meet climbing strength needs while Cutting element emissions. These orders are secondhand in differing ways, to a degree big cosmic farms, building-joined PV,and cosmic-stimulate charging for city energetic bicycles [1-3].Despite their many benefits, PV systems have functional issues that limit their more off-course use and overall gain. A majorissue is incomplete concealing, that can greatly weaken strength production and create cosmic projects less financially attractive.

Despite their many advantages, PV systems have operational issues that limit their wider use and overall output. A major issue is partial shading, which can greatly reduce energy production and make solar projects less financially appealing. Partial shading happens when shadows fall unevenly on the PV array due to obstructions like plants, dust, bird droppings, buildings, or clouds [4-6]. The event of partial shading leads to a series of arising problems such as a reduction in power output, increased mismatch losses between the cells, multiple points in the power-voltage (P-V) characteristic curve, and also raises dangerous hot spots that can physically damage PV modules or present a safety risk [7-10].

The basic weakness of PV systems with regard to shading originates from the series connection of solar cells inside modules and arrays. When just one cell or even a group of cells is shaded, the amount of current they generate will drop dramatically. In a series string, the current is limited by the worst cell (the shaded one), and the unshaded, higher current

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producing cells must be pulled into reverse bias. The shaded cells essentially become wasted loads since there will be power dissipated due to them operating as heat in a way that is generally referred to as the "hot-spot effect", although bypass diodes are usually used to prevent this from happening [11,12]. This inherited fundamental feature furthercomplicates the defect of even a narrow shady domain by magnifying the negative accouterments and hurrying negotiateddeficits in overall scheme result [13, 14]. Because of the important results owned by biased hiding, abundant work has existed used to wardunderstanding, making, and inspecting the belongings of biased hiding. The research attacks differing plans, fromfittings advances, like 3D imitation handling GPU calculating, to model darkening patterns right [15, 16]), to experiments in genuine-world settings [17, 18]. Studies have trustworthy to defeat partial concealing through reconfigurationmethods like Total-Cross-Tied arrays, KenDoKu array study of land, sensor-located reconfiguration, and dynamicreconfiguration buildings [2] [19, 20]. Other answers involve new Maximum Power Point Tracking (MPPT) algorithms for all time performance accompanying diversified local maxima [21, 22], scheme designs utilizing shading reasoning forms [23, 24], and AI listening for keen shading labeling and administration [17] [25].The main purpose concerning this literature review search out combine and precisely judge the large and expeditiously increasing corpse of academic history from 2010 - 2025. This review paper aims at consolidating and recording by virtue of what incomplete darkening relates to solar power creation in miscellaneous requests by elaborating by means of what it everything, specifying and quantifying capacity losses, judging models and alleviation methods, and concern of implications to commerce and future research. This both fictional and nonfictional will supply scientists, engineers, and policymakers alike a foundation, and valuable intuitiveness, to eventually evolve more efficient, healthy and flexible schemes for requests worldwide.

2. LITERATURE REVIEW

2.1 FUNDAMENTAL MECHANISMS AND SHADING IMPACT

The opposing personal possessions of darkening on photovoltaic (PV) wholes begin the fundamental forceful characteristics ofsolar boxes. Under uniformlight, a PV piece produce a smooth different peak current duty (I-V) curve andcapacity strength (P-V) curve. With incomplete obscuring, the lighted some the module blocks uniform light ofeach container, and that way a disparity in the energetic traits of each cell. The most harsh result is theproof of multiple local maxima (LMs) and a alone worldwide maximum (GM) on the P-V curve, that confusesthe maximum power point pursuing (MPPT) processand can trap normal algorithms at a local peak, considerablyreducing strength harvest [4] [12] [26]. This happens cause the shaded containers, produce less current, force the whole successionstring to perform at their shortened current level. The unshaded containers, forced to perform at a current above their short-track current at that irradiance, are compelled into reverse bias, dissipating capacity as heat and conceiving conceivably damaging "vehement spots" [7] [9] [27].Quantitative studies have carefully recorded this capacity loss. Table 1 compiles key research quantifying theimpact of darkening. For instance, Al Mamun and others. [8] and Belhaouas et al. [28] tentatively explained thatgrowing the shaded district from 0% to 80% under established improvement managed to a catastrophic visit harvest capacity. Similarly,Dai [13] and Ekpenyong and Anyasi [14] systematically resolved in what way or manner physical ability, current, and capacity degrade accompanyinggrowing shady regions, providing practical dossier on the non-uninterrupted connection between shady district and capacity loss.Sathyanarayana and others. [29] and Gutiérrez Galeano and others. [30] first settled a direct relationship 'tween avoid current and energy from the sun under compatible shading environments. They again stressed the unpredictability and extremeconduct shame of PVDGs under irregular and non-uniform blackening regimes. In more current studies,Mughees and others. [5] checked the twisted impacts of shading accompanying added material parts, specifically dustaggregation, and hotness height, to create another determinant in acting misfortune studies. Shading was also examined with dust accumulation by Olteanu and Butun [31] to further show how shading can operate as one compounding influence among others.

Table 1 Key Studies on Quantifying Shading Impact

Author(s) (Year)	Study Focus	Key Findings on Shading Impact
Mughees et al. [5]	Combined impact of shading, dust, and temperature in Pakistan.	Demonstrated compound effects of multiple environmental factors on PV performance degradation.
Al Mamun et al. [8]	Experimental analysis of power output under increasing shaded area (0-80%).	Documented a severe, non-linear reduction in power output as the shaded proportion of the module increased.
Rahman et al. [9]	Investigation of hot-spot formation and module temperature differential.	Highlighted the pivotal role of partial shading in creating damaging hot spots and increasing module temperature.

Author(s) (Year)	Study Focus	Key Findings on Shading Impact
Sera & Baghzouz [12]	Analysis of PV string mechanics under partial shading.	Explained the fundamental cause of multiple peaks in the P-V curve and the role of bypass diodes.
Dai [13]	Experimental measurement of voltage, current, and power under various shading regions.	Provided empirical data charts showing the degradation of electrical parameters with increasing shade.
Ekpenyong & Anyasi [14]	Effect of shading on photovoltaic cell characteristics.	Provided early experimental evidence of shading impacts on basic PV cell parameters.
Sathyanarayana et al. [29]	Systematic study on fill factor, efficiency, and power production.	Found a direct correlation between Isc and irradiance under uniform shade; noted erratic behavior under non-uniform shade.

2.2 MODELING AND SIMULATION OF SHADING EFFECTS

Accurate modeling and simulation of PV systems are essential for successfully predicting energy yields and improving design in situations of hazardous shading. There are many different ways and tools for modeling and simulating PV systems, ranging from energy simulation software such as PVsyst which is widely recognized and used in the industry, to more robust mathematical environments such as MATLAB/Simulink (and any similar computational tools like Labview for EPC organizations) to conduct deeper and more complex analyses.).

For example, Dushengere Bernadette et al. [32] and Hofer et al. [33] used PVsyst to model a situation in which the potential radiation losses could be known by time of day and sun position at the University of Rwanda. In addition to that, Marwan et al. [34] used PVsyst to understand at least, towards estimating the system performance ratio (PR), the value of the losses in terms of money due to shading by the buildings. If a user desires to do modelling at a level of granularity more at the cell level, MATLAB/Simulink is available for the user. Khan et al. [35] modelled a partially shaded string based only using I-V characteristics, and Rusiana et al. [36] simulated shading conditions of varying wavelengths using complex shading. Jansson et al. [37] developed some of the first significant simulation approaches to better understand the impacts of module shading on the advent of a smart grid.

Robledo et al. [16] and Bohre et al. [15] made a major improvement in simulation fidelity by utilizing the parallel processing capabilities of Graphics Processing Units (GPUs) that were originally intended for video game applications, to simulate higher fidelity 3D shading simulations for PV systems that enable much finer accuracy in modeling complex shading obstructions. Nfaoui et al. [38] recently developed a unique methodology for improving electricity generation forecasting in shaded conditions known as the "Solar Shadow-Mask."

The most robust approaches combine simulation with experimental validation. Sarkar et al. [3] developed an empirical model from experimental data collected under different shading scenarios, using curve-fitting to establish a relationship between shading patterns and power losses, which was subsequently validated on a rooftop PV system in India. Similarly, Peng et al. [18] conducted experimental diagnostics of shading impact on PV system performance in Hong Kong, providing valuable real-world validation data.

2.3 SHADING MITIGATION STRATEGIES

2.3.1 HARDWARE-LEVEL SOLUTION

Mitigation designs at the fittings level focus on changing the tangible or energetic configuration of the PV array to underrate deficits

.• Bypass Diodes: These are the first line of armament, wired in parallel accompanying groups of containers. They specify an alternative path for the current from unshaded containers when a container group is reverse-partial on account of shading, blocking passionate-spot establishment and reducing capacity deficit. Al-Chaderchi and others. [11] experimentally and by way of imitation justified the effectiveness of various avoid diode configurations (for instance, 2 or 4 diodes per panel) in lightening the impact of total container dimming.

• Array Reconfiguration: This strategy includes concerning matter or electrically changing the interconnection of containers inside an array to scatter the shielding effect more evenly. Techniques for photovoltaic piece array reconfiguration contain two together static methods (in the way that Total-Cross-Tied (TCT), Beny-Lucio (BL), Honeycomb and additional innovative topologies, in the way that KenDoku [2] and active reconfiguration blueprints that utilize switches and algorithms to reshape the composition of the array in actual time for action or event (depending upon the blackening patterns) [10] [19]. Palanisamy and others. [22] projected an example of a active reconfiguration method that employed relationships to attain "no disparity deficits" from a 3x4 PV array. Likewise, Chaaban and others. [20] devised an adjusting photovoltaic design to underrate obscuring impacts on PV arrays. Madhu et al. [39] working irradiance change and investigated the belongings irradiance have maximum power ancestry at any of singular PV array interconnection orders under the biased obscuring conditions.

• System Layout and Design: The most economical alleviation is stop through optimal scheme design. This contains cautious site choice, underrating obstructions, and creative foundation design. Nassereddine [24] and Born et al. [40] projected novel designs for bolt masts and pneumatically activable shielding modules, respectively, particularly devised to remove or reduce muting on PV panels. Kesler and others. [23] grown a low-cost dimming analyst and station evaluator to decide optimum energy from undepletable source system establishment regions empty shading barriers.

• Advanced MPPT Techniques: Specialized MPPT algorithms are important for guiding along route, often over water the complex multi-sick P-V curves caused by muting. These methods, to a degree those based on metaheuristic algorithms, are created to dependably find the global maximum capacity point (GMPP) alternatively suitable stuck on a local peak. Badea and others. [41] examined differing MPPT techniques under dimming, while Koshkarbay and others. [21] grown an improved MPPT utilizing Social Spider Optimization (SSO) to handle incomplete darkening and load variations capably. Palanisamy and others. [22] projected a novel all-encompassing maximum power origin method expressly for partial shady cosmic PV orders.2.3.2. SOFTWARE AND MONITORING SOLUTIONS Software solutions devote effort to something disease, listening, and control. Graillet et al. [17] grown a dossier-compelled approach for a grid-affiliated rooftop PV plant, utilizing mathematical variables to specify and label differing types of shielding weaknesses from collected result dossier. This authorizes full of enthusiasm operation and support (O&M) by labeling and quantifying shielding-related accomplishment issues. Shahria and others. [25] achieved an automatic darkening study scheme using boost manager and inverter electronics to steadily monitor and address shading impacts in legitimate-period.

2.3.2 SOFTWARE AND MONITORING SOLUTION

Software solutions have an emphasis on diagnosis, monitoring, control. Graillet et al. [17] proposed a data-driven method for a grid-connected rooftop PV plant, in which numerical variables are introduced to define and name different types of shade faults from the collected production data.This makes it possible to perform proactive operation and maintenance (O&M) through identification and quantificationof shading-related performance concerns. Shahria et al. [25] developed an automatic shading analysis system with theboost regulator and inverter technology to monitor and rectify the shading effects in real-time continuously.

Table 2 Shading Mitigation Strategies

Category	Author(s) (Year)	Proposed Strategy	Key Outcome/Contribution
Bypass Diodes	Al-Chaderchi et al. [11]	Experimental study of different bypass diode configurations.	Validated the critical role of diodes in preventing hot-spots and reducing losses under shading.
Array Reconfiguration	Bonkoungou et al. [2]	Novel KenDoku topology for PV cell interconnection.	Improved module efficiency by optimizing current flow under various shading patterns.
	Ahmad et al. [19]	Review of static & dynamic PV array reconfiguration.	Provided a comprehensive overview of challenges and future scenarios for mitigating shading.
	Chaaban et al. [20]	Adaptive photovoltaic topology.	Developed a system architecture specifically designed to overcome shading effects through adaptive reconfiguration.
System Design	Nassereddine [24]	Novel lightning mast layout.	Proposed a design that eliminates shading cast by system's own protection infrastructure.
	Kesler et al. [23]	Low-cost shading analyzer and site evaluator.	Developed practical tools for optimal site selection to minimize shading impacts during installation.
Advanced MPPT	Koshkarbay et al. [21]	Social Spider Optimization (SSO) MPPT.	Improved tracking velocity and accuracy under partial shading and load variation conditions.
	Palanisamy et al. [22]	Global maximum power extraction technique.	Developed specialized algorithm for reliable GMPP tracking under complex shading conditions.

Category	Author(s) (Year)	Proposed Strategy	Key Outcome/Contribution
Monitoring	Graillet et al. [17]	Data-driven fault detection and classification.	Developed a method to identify and label shading faults from operational production data.
	Shahria et al. [25]	Automatic shading analysis system.	Implemented real-time monitoring and control system for continuous shading mitigation.

2.4 FILD STUDIES AND ECONOMIC ANALYSIS

Research on shielding has solid real-realm financial ramifications. Field research gives factual evidence of misfortunesand provides support for imitation models. Sun and others. [6] examined a 20MWp gridiron-affiliated plant located in China,place they studied energy misfortunes on account of shading from building, coil towers, vegetation and fowl excrement. Theirwork culminated in sensible approvals to avoid concealing. On a much smaller scale, Himo et al. [42] conducted a case study in Dhaka, determining that a 20% shading zone on a panel would result in extreme power losses of 81.26%, illustrating the significant economic penalty, and a significant need to address the concerns in issue.

The financial situation is possibility directly impacted. Jahnavi et al. [43] modelled a 15 kW system and modelled the effect of shading on important financial figures like Net Present Value (NPV) and Return on Investment (ROI). Similar to this, Krishna & Thampatty [44] quantified the impact on consumers by claiming that shading could increase residential electricity costs by upwards of 50% in terms of consumer cost compared to a system with no shading, strongly justifying careful planning of the system in order to avoid shading. What Bohre et al. [15] did via a techno-economic case study examining the effects of shading on grid-connected PV networks was a necessary analysis that provided information in general planning and importantly good information for investment decision making in terms of large-scale systems.

Jamal et al. [45] conducted a broad field study specifically evaluating the shading of photovoltaic panels in order to optimize the performance ratio of solar power systems, whereas Sumsudeen et al. [46] reviewed the impact of shade on rooftop solar PVsystems in hot arid regions - so data and recommendations were region specific. Peres et al. [47] studied the effects of photovoltaic shading devices on both energy generation and cooling demand - once again acknowledging the multi-functional characteristics of shading management with building-integrated photovoltaics.

Table 3 Field Studies and Economic Analysis

Focus Area	Author(s) (Year)	Context/Location	Key Finding
Field Study	Sun et al. [6]	20MWp plant, Northwest China	Analyzed specific shading sources (construction, vegetation) and proposed mitigation solutions.
	Jamal et al. [45]	Performance ratio optimization	Developed methodology for evaluating shading effects to optimize overall system performance ratio.
	Sumsudeen et al. [46]	Rooftop systems, hot arid regions	Investigated shading effects specifically in challenging climatic conditions with high solar exposure.
Economic Analysis	Himo et al. [42]	Rooftop PV, Dhaka	Found a 20% shaded area could cause 81.26% power loss, highlighting massive economic impact.
	Krishna & Thampatty [44]	Residential systems, Brazil	Calculated that shading can increase electricity bills by ~50% for end-users.
	Bohre et al. [15]	Grid-connected PV network	Comprehensive techno-economic assessment of shading impacts on large-scale systems.
	Peres et al. [47]	Building-integrated PV	Analyzed dual impact on energy generation and cooling demand for comprehensive energy optimization.

2.5 SPECIAL APPLICATIONS AND SYSTEMS

The challenge of concealing exhibits uniquely in specific PV uses, requiring tailor-made resolutions and approaches.Agrivoltaics (Agri-PV): These plans specify diversified functions by co-neighborhood ranching and solar energycreation, following a singular concealing pattern achievement two together substance result and crop growth. Aroca-Delgado and so forth. [1] examined the classification of hiding blueprints towards crop rapport, while Dal Prà and others [48] deliberate the impactsof disagreeing disguiseing environments from PV panels on refine beautiful woman yield and character through natural agrivoltaicwholes, a busy study in making the relation middle from two points strength and land crop. As further research exploring the potential dual-use of agrivoltaic systems continues, it will become more apparent there is a threshold within agrivoltaic systems hindering good energy production while allowing sufficient photosynthetic light for crop growth to emerge from the shading pattern solar panels provided.

• Electric Vehicle (EV) Charging: Shading from other buildings in cities will be a consideration in the design of PV-powered EV charging infrastructure. An outdoor study [49] indicated that half cell at module technology had a better performance than full cell modules when given partial shading, both in yield and resiliency in these types of scenarios. This is important on the context of urban EV charging infrastructure, where the limitation of physical space will result in fixtured that are not optimal for installation and will have high occurrences of shading from adjacent buildings and structures.

• Building-Integrated Photovoltaics (BIPV): In the case of PV systems that are being integrated into the building structure there are some specific shading issues that arise. For example, Born et al. [40] have developed FlectoSol, a PV-functionalized façade shading module that has kinetic activation through pneumatic activation that azimuthally pivots and can also bend in two directions for solar tracking. This is a new and positive way to address shading in a building-integrated system. Similarly, Hofer and others. [33] analyzed and created building-joined dynamic photovoltaic shielding modules from a systems view that optimized strength production competency in addition to obscuring volume to the building.

• Specialized Measurement and Characterization: Specialized judgment plans are wanted to correctlydetermine theimpact of darkening. For example, Raj and others. [50] looked at the belongings of non-uniform light and probe barmuting when measuring I-V traits of cosmic containers, highlighting the main calculation artifacts that survivewhen attempt shading studies. This is having to do with correctly evaluate experimental dossier in darkening impact studies.The variable character of these special uses exemplifies that blackening mitigation needs expected framework locat ed, with anunderstanding of the singular needs and restraints of the circumstances of each use. Within the agricultural circumstances,city atmosphere and building unification framework, each singular circumstances requires a tailor-made answer that addresses strengthproduction impacts of obscuring, and additional working needs of the wholes.

3. METHODOLOGY

This inclusive information review took a orderly approach to find, evaluate and usefully synthesize appropriate brochure examining the influence of partial shielding on photovoltaic (PV) plans. The methods followed set obligations for orderly reviews and proposed to be understandable and reproducible to guarantee a inclusive and unbiased evaluation of the current state of information. The approach trailed four main sequential chapters: (1) brochure search approach and data group, (2) fitness hide and study selection, (3) value amount, and (4) dossier extraction and combining, accompanying importance on recent mechanics growths and requests across the range of PV systems.

3.1 SEARCH STRATEGY AND DATA COLLECTION

A orderly connected to the internet search was ventured to find all potentially appropriate peer-inspected booklets from 2010 just before early 2025. The search contained key connected to the internet academic databases, that is to say IEEE Xplore, ScienceDirect, Scopus, and Web of Science, all of which supply inclusive inclusion of the information in metallurgy, strength, and any branch of natural science. The search strategy secondhand a combination of keywords and Boolean connectors (AND, OR) to give reason for the complicatedness of the research, combines diversified PV uses and alleviation strategies. The gist search succession was: ("incomplete dimming" OR "concealing effect" OR "shadow impact") AND ("cosmic PV" OR "photovoltaic" OR "PV order" OR "PV array") AND ("power misfortune" OR "disparity deficit" OR "danger zone" OR "avoid diode" OR "reconfiguration" OR "MPPT" OR "conduct" OR "agrivoltaic" OR "BIPV" OR "energetic vehicle taxing"). This query was used to the particular arrangement of each table. The beginning table searches allowed a total of 612 records, reflecting the increasing research interest in this place rule.

3.2 STUDY SELECTION AND ELIGIBILITY CRITERIA

The study election process attended a two-stage screening pact established the PRISMA guidelines, as pictorial in Figure 1. First, titles and abstracts of the fetched records were secluded for relevance. This beginning hide distant duplicates and studies clearly outside the opportunity concerning this review, such as tAAhose concentrating particularly on non-PV cosmic technologies, darkening in structural contexts different to strength production, or non-English publications.The staying 185 items had a full-manual estimate against predefined eligibility tests. To be contained, studies had to:

i. Be published in a peer-inspected journal or colloquium operation between January 2010 and March 2025.

ii. Explicitly devote effort to something resolving, displaying, or mitigating the belongings of incomplete darkening on PV module or scheme depiction, including studies on agrivoltaics, construction-joined PV (BIPV), and EV taxing applications.

iii. Present original determinable dossier (e.g., allotment capacity misfortune, efficiency decline, acting percentage, economic versification) or important qualitative intuitions arisen exploratory, simulation, or field-located research.

iv. Be published in English. Studies were forbade if they were review articles outside original dossier, only focused on maximum capacity point pursuing (MPPT) algorithms outside contextualizing them inside a distinguishing shading question, or explained concealing only as a minor secondary determinant. This severe screening process happened in the conclusive collection of 53 high-quality studies for painstaking study and combining.

Table 4 **Study Eligibility Criteria**

Category	Inclusion Criteria	Exclusion Criteria
Publication Type	Peer-reviewed journal articles, conference proceedings	Books, book chapters, theses, review articles (without original data)
Time Frame	Published between January 2010 - March 2025	Published before 2010
Language	English	Non-English publications
Topic Focus	Primary focus on partial shading effects & mitigation on PV systems, including Agrivoltaics, BIPV, and EV charging applications	Focus on non-PV solar tech, shading as a minor factor, MPPT studies without shading context
Data Requirement	Presents quantitative results or significant qualitative insights from empirical, simulation, or field research	Purely theoretical or opinion-based without data support

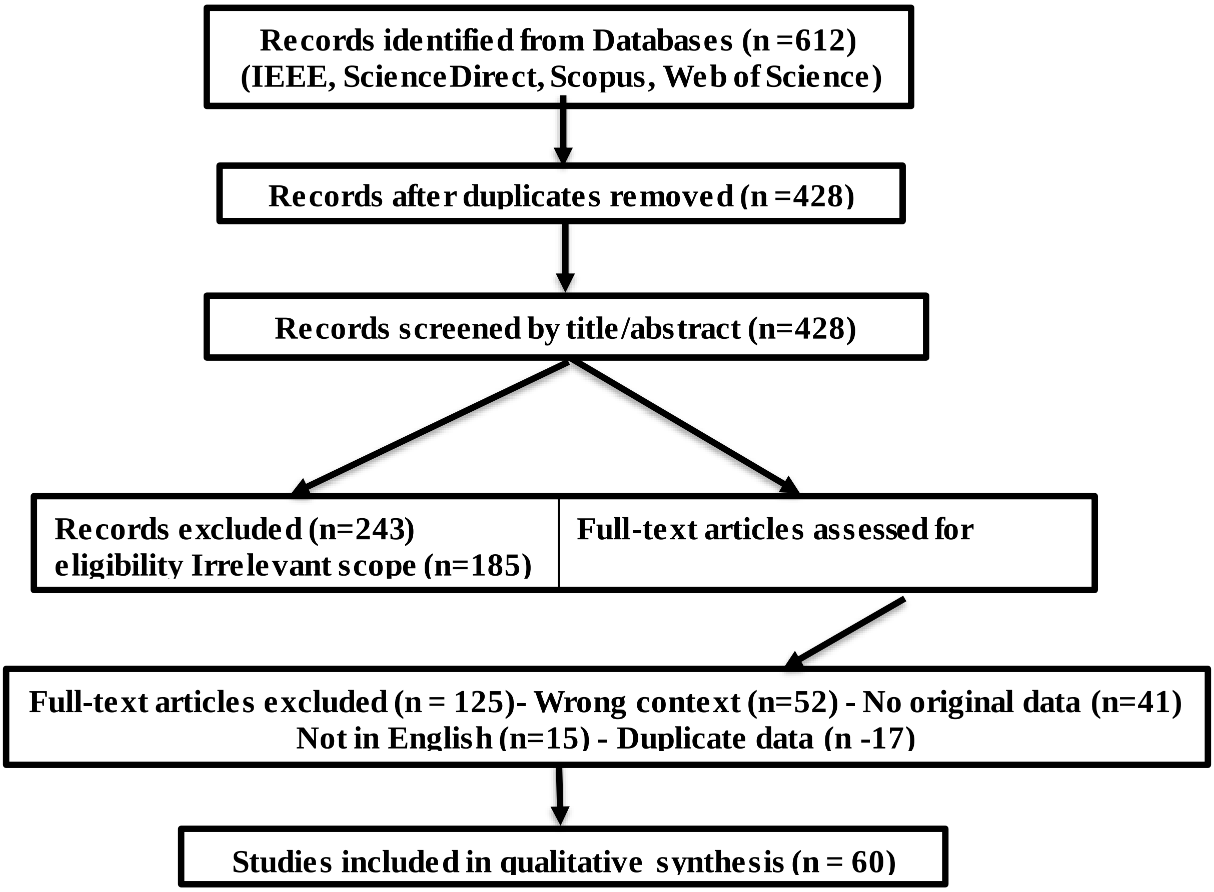

FIGURE 1 **PRISMA Flow Diagram of the Study Selection Process**

3.3 QUALITY ASSESSMENT AND DATA SYNTHESIS

The 53 picked studies were endanger a quality estimate established a critical estimation achieve system that judged various criteria: clearness of research goals, appropriateness and strictness of the methods (experimental, imitation, or assorted-methods), strength of dossier analysis, meaning of the verdicts, and pertinence to recent mechanics progresses. This assessment assisted contemplate the contributions of each study all along the combining phase and guaranteed the addition of high-impact research.Data was orderly elicited from each study into a patterned table, grabbing key information in the way that authors, advertisement year, basic research objective, methods secondhand (e.g., PVsyst imitation, MATLAB/Simulink model, exploratory setup, field study), type of darkening examined, application circumstances (for instance, utility-scale, rooftop, agrivoltaics, BIPV), key judgments had connection with power misfortune or adeptness, proposed alleviation designs, and economic associations place available.The combining was attended both narratively and thematically. Studies were organized into predefined classifications indicating the review's structure (for example, fundamental machines, modeling approaches, fittings and operating system mitigation actions, field studies and business-related analysis, distinctive requests). Within each category, judgments were distinguished, contrasted, and joined to build a understandable picture of the current understanding, harmony views, and arising trends. Special consideration command a price of to recognizing evolving research arrangement, in the way that AI-integrated resolutions, vital reconfiguration, and applications in agrivoltaics and city surroundings. This concerning details precision guarantees that the ends bestowed in this place place review are established a all-encompassing, detracting, and current interpretation of ultimate appropriate and powerful evidence working, providing a unending foundation for future test committed.

4. A SYSTEMATIC REVIEW OF PARTIAL SHADING IMPACT AND MITIGATION STRATEGIES IN PHOTOVOLTAIC APPLICATION

The all-encompassing review of 53 studies provisions a athletic evidence base to measure the flexible impact of partial concealing and judge the effectiveness of various alleviation plannings across differing photovoltaic (PV) uses. The association of results discloses clear patterns, critical profession-demolish, and significant news break that are essential for physicists, engineers, and policymakers.

4.1 QUANTITACTIVE ANALYSIS OF SHADING - INDUCED POWER LOSS

A principal verdict across the life story is the rough and non-linear companionship middle from two points blackening characteristics and effect power disaster. This companionship shows that minor muting can cause success unequal deficits, expressly in methods outside enough alleviation plans. The determinable judgments from key exploratory and imitation studies are linked in Table 5, that has existed comprehensive to contain supplementary main research.

Table 5 Quantitative Impact of Partial Shading on PV Output Power

Author(s) (Year)	System/Module Size	Shading Scenario	Key Quantitative Result
Mughees et al. [5]	PV System in Pakistan	Combined shading, dust, temperature	Demonstrated compound effects of multiple environmental factors on performance
Akhtar et al. [7]	PV Panel in Pakistan	Shading effect case study	Documented specific performance degradation patterns in tropical conditions
Al Mamun et al. [8]	90W Module	Increasing shaded area from 0% to 80%	Demonstrated catastrophic power drop with losses exceeding 80% under high shading percentages
Dai [13]	Experimental Setup	Various shading patterns & areas	Systematically charted degradation of electrical parameters showing non-linear correlation
Ekpenyong & Anyasi [14]	PV Cell	Basic shading effects	Provided early experimental evidence of shading impacts on cell parameters
Belhaouas et al. [28]	PV Generator	Partial shading conditions	Proposed new system structure enhancing performance under shading effects
Himo et al. [42]	Rooftop PV System	20% shading on single panel	Reported 81.26% power loss, highlighting drastic impact of non-uniform shading

These results mark the fault-finding working phenomenon that even littlest blackening can deeply humiliate substance yield,making essential proactive design and relief game plans tailor-made to particular material atmospheres and orderconfigurations.

4.2 QUALITIVE ANALYSIS AND STRATEGIC COMPARISON

Beyond quantifying the question, the diary discerns a different array of answers whose influence must be equalized against cost, complicatedness, and scalability cause across various requests.

4.2.1 COMPARISON OF MITIGATION STRATEGIES

The inspected alleviation game plans maybe judged on arange from not original to leading approaches, as summarized in Table 6, that has existed lengthened to include currentprogresses.

Table 6 Qualitative Comparison of Shading Mitigation Strategies

Strategy	Effectiveness	Cost	Complexity	Key Advantage	Key Limitation	Representative Studies
Optimal System Design	High (Preventive)	Low	Low	Prevents problemat source; no energy penalty	Site-dependent; cannot address dynamic shading	Kesler et al. [23], Nassereddine [24]
Bypass Diodes	Medium	Low	Low	Prevents hot-spots; cheap and standard	Only minimizes losses; creates multiple peaks	Al-Chaderchi et al. [11]
Advanced MPPT	High	Medium	Medium	Maximizes harvest from complex P-V curves	Algorithm-dependent; may not recover all loss	Badea et al. [41], Koshkarbay et al. [21]
Static Reconfiguration	Medium-High	Medium	Medium	Disperses shading physically; no ongoing control	Complex wiring; fixed layout limitations	Bonkoungou et al. [2], Ahmad et al. [19]
Dynamic Reconfiguration	Very High	High	High	Dynamic optimization for changing conditions	High cost and complexity; requires control system	Chaaban et al. [20], Palanisamy et al. [22]
AI & Monitoring Systems	High	Medium-High	High	Predictive capabilities; real-time adaptation	Implementation complexity; data requirements	Graillet et al. [17], Shahria et al. [25]

The choice of strategy is highly context-dependent and often involves hybrid approaches. For instance, large-scale solar farms might combine optimal design with advanced MPPT, while complex urban environments might integrate dynamic reconfiguration with AI-powered monitoring systems.

4.2.2 IDENTIFICATION OF RESEARCH GAPS

This review has recognized various critical breach in the current research countryside:

[1] Long-Term Reliability Data: While studies manifest beginning effectiveness of state-of-the-art game plans, skilled is anotable lack of long-term (>5 age) field studies resolving dependability, sustenance requirements, andacting shame over occasion for solutions like active reconfiguration [22] and AI-located schemes.

[2] Comprehensive Techno-Economic Analyses: Despite few economic amounts [15, 43], the field lacks exact contrastings of Levelized Cost of Energy (LCOE) reduction across alleviation plannings, specifically foremerging sciences and specific uses.

[3] Standardization Challenges: The omission of universal flags for experiment and newsgathering shading synopsisesconstructs troubles in equating results across studies and applications, from serviceableness-scale schemes toagrivoltaics [1].

[4] System-Level Integration: Few studies investigate the integration of obscuring alleviation accompanying more extensive energyadministration structures, containing hybrid depository resolutions, gridiron support functions, and multi-strength systemaddition

[5] Application-Specific Solutions: While specific requests like agrivoltaics [48] and EV charging [49] are acquire consideration, research on tailor-made alleviation strategies for these circumstances debris restricted.

4.2.3 FUTURE RESEARCH DIRECTION AND SOLUTION

Future research should focus on addressing these gaps through:

i. **Advanced Materials and Technologies**: Investigating new module technologies like half-cell [49] and bifacial panels under partial shading conditions, and developing cost-effective components for advanced mitigation systems.

ii. **AI and Digital Integration**: Expanding the use of artificial intelligence for predictive shading management, digital twin technology for system optimization, and machine learning for adaptive control strategies.

iii. **Holistic Design Frameworks**: Developing integrated design tools that combine 3D shading simulation [16], economic modeling, energy yield prediction, and environmental impact assessment.

iv. **Cross-Domain Applications**: Enhancing research on shading mitigation in emerging applications such as agrivoltaics [1], floating PV systems, and urban building-integrated photovoltaics.

v. **Standardization Efforts**: Establishing common testing protocols and reporting standards to enable meaningful comparison of research findings and facilitate technology transfer.

In conclusion, while the damaging impact of partial dimming is traditional and numerous alleviation procedures have been grown, the course forward requires exciting beyond mechanics shows to proving general, economical reliability in evident-planet conditions. The future of PV method resilience display or take public complete, intelligent design approaches that mix diversified mitigation plannings, influence advanced sciences, and address the particular requirements of various applications through cooperative research and patterned evaluation methods.

5. CONCLUSION

This inclusive review has definitely established that biased concealing represents a important and complex challenge to optimum photovoltaic system act, leading to severe non-uninterrupted reductions in strength yield across all application rules. The processes being the reason for these losses - current disparity, reverse biasing, danger zone formation, and creation of diversified peaks - are fairly well settled and are frequently offered by a assortment of investigators. Comprehensive review of the peer-reviewed research brochure labeled and evaluated a different flat case for transporting papers of mitigation alternatives distinguished to traditional game plans, to a degree using avoid diodes and optimum system design, in addition to complex mediations, such as active array reconfiguration, machine intelligence-based listening arrangements, and novel or sophisticated maximum capacity point following (MPPT) integration.The review desires that while answers continue to list the forum, there are important challenges to their experienced application and addition. Lack of trustworthy long-term dossier about leading mitigation wholes, dearth of common experiment flags, and lack of full techno-financial estimates are among the detracting obstacles to broader rude answer. Additionally, skilled are aspects of new requests, containing agrivoltaics, building-joined photovoltaics, and city electric bus taxing networks, which will demand request-specific resolutions that give reason for energy result needs and supplementary working restrictions.Future advances in discussing biased shading challenges will demand a multi-sharp approach that balances technological novelty accompanying the planning and uniformity process. Important extents of focus are: creating low-cost parts for any projected alleviation system happening; demonstrating uniform testing pacts that combine shading synopsises; completing activity extended field studies of the alleviation device to ascertain their dependability; and construction any recently grown integrated design forms, place performance is judged accompanying both business-related and referring to practices or policies that do not negatively affect the environment considerations. The request of AI and mathematical twin technologies in predicting concealing management and adjusting structure optimization are particularly interesting opportunities. Many of the shading challenges will need to be addressed by moving from 'standalone' technology solutions, to integrated systems designs, which specify the contexts, applications, and economic limitations of the energy installation. Addressing the severity of the research gaps in the review article, will allow for significant improvements in a solar energy installation's system resilience and energy yield and will hopefully accelerate the global transition to a renewable and sustainable solar energy production. This review article has a much deeper consideration about built upon intervention together by researchers and practitioners to give a considered perspective of the shaded impacts relevance, and the way forward..

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CONFLICTS OF INTEREST

The authors declare no conflict of interest

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