The Solar Imperative and the Intelligent Governance of Photovoltaic Technologies for Sustainable Energy Policy and Public Trust

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Objective: This paper provides a comprehensive analysis of the solar energy revolution, examining technological evolution, socio-economic benefits, grid integration challenges, and the pivotal role of governance and public trust in the global energy transition.

Methodology: A systematic literature review following PRISMA 2020 guidelines was conducted across Scopus, Web of Science, ScienceDirect, and IEEE Xplore for studies published between 2015 and 2025. From 240 initial records, 29 high-quality studies were retained after rigorous quality assessment and synthesized thematically.

Findings: The global weighted-average Levelized Cost of Energy (LCOE) for utility-scale solar PV declined from approximately USD 0.371/kWh in 2010 to USD 0.043/kWh in 2024, while battery storage costs fell from about USD 1,000/kWh to USD 130/kWh. Crystalline silicon remains dominant, while third-generation perovskites promise higher efficiency, targeting 30% by 2030, contingent on resolving stability issues. Solar deployment drives job creation, energy security, and public health benefits. However, intermittency creates grid integration challenges, including the duck curve and nonlinear storage requirements exceeding 50% PV penetration. Grid-forming inverters, battery storage, and smart grids are critical enablers. Governance and public trust conceptualized as institutional, technological, and procedural are decisive determinants of deployment success. Comparative analysis of Iran, India, and South Africa reveals that energy crises, not climate policy, drive adoption in developing countries, where inequality and institutional distrust shape outcomes.

Conclusion: Solar power is a cornerstone of the energy transition, delivering cost reductions, employment, and climate mitigation. Its large-scale adoption requires coordinated advances in storage, smart grids, and supportive, trust-building policies, with particular attention to energy justice and context-specific governance.

Keywords: *Solar Power, Photovoltaics (PV), Sustainable Energy, Energy Transition, Renewable Energy, Energy Policy, Public Trust*

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1. Introduction

The 21st century is defined by the dual challenge of meeting rising global energy demand while simultaneously mitigating the catastrophic impacts of climate change [1]. For decades, the global energy matrix has been dominated by fossil fuels, a dependency that has fueled economic growth at the severe cost of environmental degradation and geopolitical instability [2,3]. In response, a global consensus has emerged for a rapid and decisive transition towards sustainable energy systems [4]. At the heart of this paradigm shift lies the harnessing of renewable energy sources, a critical component of policies like the European Green Deal [5]. Among these, solar power has distinguished itself as a uniquely scalable, technologically mature, and economically compelling solution [6]. The "Solar Imperative" is no longer a futuristic vision but a present-day reality, fundamentally reshaping industries, economies, and societies across the globe [7].

This paper addresses the multifaceted nature of the solar revolution. While the declining cost and increasing efficiency of photovoltaic (PV) technologies are widely acknowledged, a comprehensive understanding requires an integrated analysis that spans from the underlying material science to complex socio-economic landscapes [8-10]. The existing literature often focuses on discrete aspects of solar energy, such as specific technological breakthroughs [11] or localized policy impacts. However, there remains a need for a holistic synthesis that connects technological evolution, its broad socio-economic ramifications, and the systemic challenges of integrating a variable renewable source into legacy energy infrastructures. This research aims to fill this gap by providing a comprehensive analysis of the solar energy ecosystem.

The core objective of this study is to critically examine the pivotal role of solar power in the ongoing sustainable energy transition [12,13]. To achieve this, the paper will pursue three primary lines of inquiry. First, it will systematically map the technological landscape of PV systems, tracing their evolution. Second, it will analyze the extensive socio-economic benefits derived from solar deployment, including job creation and energy security [14]. Finally, it will investigate the critical challenges associated with the large-scale integration of solar power, focusing on issues of grid stability and energy storage [15].

To address the geographical and analytical gap in the literature, this study also provides a comparative analysis of three developing-country solar transition models: Iran's state-centric model marked by institutional distrust [16,17], India's combination of government incentives and industrial self-sufficiency mandates [18,19], and South Africa's market-driven model characterized by unequal access [20,21]. This comparison is developed further in Section 9.1.5.

This study contributes to the existing literature by offering an integrated and innovative analysis of the solar energy ecosystem. Going beyond fragmented examinations of technology or policy, we uniquely synthesize the interconnections among photovoltaic advancements, socio-economic implications, and governance structures. Specifically, this research is innovative in five respects: (1) it proposes a framework for "smart governance" to manage the complexities of integrating variable solar energy; (2) it quantifies the direct relationship between public trust and the effectiveness of solar energy policies; (3) it examines the deployment of solar energy not merely as a technological transition, but as a critical driver of energy security and social resilience; (4) it evaluates the role of adaptive policy design in steering sustainable energy transitions; and (5) it develops a comprehensive model that directly links the evolution of materials science to broader macroeconomic and social outcomes.

This paper is structured as follows: Section 2 presents the research methodology. Sections 3–8 review the technological, socio-economic, governance, policy, and comparative dimensions of solar power and its integration into energy systems. Section 9 presents the results and discussion. Finally, Section 10 concludes the paper, and Section 11 outlines the limitations and future research directions.

2.Methodology

2.1 Review Design and Protocol

This study employed a systematic literature review (SLR) following the PRISMA 2020 guidelines to ensure transparency, rigor, and reproducibility of findings, and the review protocol was developed a priori and documented before the search was conducted, specifying the research questions, search strategy, eligibility criteria, screening procedure, data extraction fields, quality assessment tools, and synthesis approach. The review aimed to synthesize existing evidence on the evolution of photovoltaic (PV) technologies, their economic and social benefits, and governance and policy aspects related to sustainable energy and public trust, and it focused on three main themes: first, the evolution of PV technologies from first-generation crystalline silicon cells to emerging perovskite and quantum dot solar cells; second, the multifaceted benefits of PV systems including economic growth, energy security, and climate change mitigation; and third, integration challenges and opportunities addressing energy grid transformation and changes in societal practices.

2.2 Inclusion and Exclusion Criteria

Studies published between 2015 and 2025 were included to capture recent technological innovations and policy developments; the inclusion criteria comprised original research articles, systematic reviews, and high-quality industry and policy reports published in reputable journals, studies addressing PV technologies, sustainable energy policies, socio-economic impacts, or public acceptance and trust, and publications in English; the exclusion criteria comprised theoretical papers without empirical data, conference abstracts, non-peer-reviewed reports, or inaccessible sources, and studies with insufficient quality or data.

2.3Data Sources and Search Strategy

A systematic search was conducted in Scopus, Web of Science, IEEE Xplore, and ScienceDirect, and the core search strategy used the Boolean combination ("Photovoltaic" OR "Solar PV") AND ("Governance" OR "Policy") AND

("Sustainable Energy") AND ("Public Trust" OR "Social Acceptance"); to ensure comprehensive coverage of the technical and economic dimensions discussed in this review, including LCOE, energy storage, inverter control, recycling, and life-cycle assessment, a complementary technical search was also performed in the same databases using the query ("Photovoltaic" OR "Solar PV") AND ("LCOE" OR "Levelized Cost" OR "grid integration" OR "energy storage" OR "inverter" OR "recycling" OR "life cycle assessment"); results from the core and complementary searches were merged, and duplicates were removed, with the search independently performed by two reviewers to minimize selection bias and ensure full reproducibility.

The final search was executed on 15 November 2025, and the search fields were TITLE-ABS-KEY in Scopus, TS = Topic (Title, Abstract, Author Keywords, Keywords Plus) in Web of Science, All Metadata in IEEE Xplore, and Title, abstract, keywords in ScienceDirect; filters applied per database were publication years 2015–2025, language English, and document types Article, Review, Book Chapter, and Conference Paper, with conference abstracts excluded;

the search strings per database were as follows: in Scopus, TITLE-ABS-KEY (("Photovoltaic" OR "Solar PV") AND ("Governance" OR "Policy") AND ("Sustainable Energy") AND ("Public Trust" OR "Social Acceptance")) AND PUBYEAR > 2014 AND PUBYEAR < 2026 AND LANGUAGE (english); in Web of Science, TS = (("Photovoltaic" OR "Solar PV") AND ("Governance" OR "Policy") AND ("Sustainable Energy") AND ("Public Trust" OR "Social Acceptance")) AND PY = 2015-2025 AND LA = English; in IEEE Xplore, (("Photovoltaic" OR "Solar PV") AND ("Governance" OR "Policy") AND ("Sustainable Energy") AND ("Public Trust" OR "Social Acceptance")) AND ("2015"–"2025") AND ("English"); and in ScienceDirect, (("Photovoltaic" OR "Solar PV") AND ("Governance" OR "Policy") AND ("Sustainable Energy") AND ("Public Trust" OR "Social Acceptance")) AND pub-date > 2014 AND pub-date < 2026 AND language = English;

the complementary technical search string used across all databases was ("Photovoltaic" OR "Solar PV") AND ("LCOE" OR "Levelized Cost" OR "grid integration" OR "energy storage" OR "inverter" OR "recycling" OR "life cycle assessment"); the search was independently performed by two reviewers, and any discrepancies in search execution were resolved through discussion.

2.4 Study Selection Process

The selection of studies followed a multi-step systematic process as illustrated in Figure 1; the initial search across all selected databases yielded approximately 240 potentially relevant studies, including academic articles, systematic reviews, and industry and policy reports; after removing duplicate records, 210 studies remained; the titles and abstracts of these 210 studies were screened for relevance to photovoltaic (PV) technologies, governance, policy, and public trust; following this screening stage, 85 studies were considered relevant and moved forward to full-text assessment; the full texts of the 85 studies were carefully assessed against the predefined inclusion and exclusion criteria, focusing on methodological rigor, data completeness, and relevance to the review objectives; after this assessment, 43 studies were excluded because they did not meet the inclusion criteria, lacked sufficient empirical data, or had methodological limitations; this left 42 studies that met the initial eligibility criteria;

a further 13 studies were excluded because they lacked sufficient methodological detail, did not provide the necessary empirical data, or were only partially relevant to the core themes of PV technologies, governance, and public trust; this step ensured that only studies capable of contributing meaningful and reliable evidence were included in the final synthesis; a total of 29 studies were retained for data extraction and final analysis;

the final selection was conducted by two independent reviewers, and any discrepancies were resolved through discussion to ensure accuracy and reliability, and if consensus could not be reached, a third reviewer was consulted; the screening process followed a two-stage approach in which Stage 1 comprised title and abstract screening by two independent reviewers, with records classified as include, exclude, or maybe, and disagreements resolved by discussion or a third reviewer if unresolved, and Stage 2 comprised full-text screening by the same two reviewers against the eligibility criteria, with reasons for exclusion recorded and reported in the PRISMA flow diagram.

2.5 Data Extraction

From each selected study, the following information was systematically extracted: general information (author, year, country); study type and methodology; technological aspects of PV systems and recent innovations; governance and policy frameworks; economic, social, and environmental impacts; and key challenges, opportunities, and recommendations; data extraction was conducted independently by two reviewers, with disagreements resolved through discussion to ensure data accuracy and credibility; a standardized extraction form was piloted on five studies and refined before full extraction.

2.6 Quality Assessment

The methodological quality of all included studies was appraised using design-specific tools. Observational studies were assessed with an adapted Newcastle–Ottawa Scale (threshold ≥7/9) appropriate for cross-sectional and survey-based energy research [22]. Systematic reviews were evaluated using AMSTAR 2, and only those with an overall confidence rating of Moderate or High were retained; studies rated Low or Critically Low were excluded [23]. Qualitative studies were assessed with the CASP Qualitative Checklist (threshold ≥8/10) [24]. Mixed-methods studies were appraised using MMAT 2018; each of the five criteria was rated separately, and no summative score was calculated, in line with the MMAT user guide [25]. Books, book chapters, and policy reports were evaluated with the AACODS checklist (threshold ≥5/6) [26]. Modeling and simulation

studies were assessed through an adapted CASP/MMAT framework covering model validation, data sources, sensitivity analysis, and reproducibility (threshold ≥4/5). Two reviewers independently assessed all studies; disagreements were resolved by discussion or, if unresolved, by a third reviewer. Inter-rater reliability was almost perfect ($\kappa = 0.84$; 95% CI: 0.76–0.92) according to [27] benchmarks [28]. Studies not meeting the predefined thresholds were excluded before synthesis, ensuring that only high-quality evidence contributed to the final synthesis.

2.7Data Analysis and Synthesis

Extracted data were analyzed using descriptive and thematic synthesis to identify patterns, trends, and research gaps; due to heterogeneity in study designs, sample sizes, and measurement tools, a meta-analysis was not feasible, and a narrative synthesis was employed; the synthesis was organized around the three main themes of technological evolution, socio-economic benefits, and integration and governance challenges; within each theme, studies were compared for similarities, differences, contradictions, and gaps; the synthesis provides a comprehensive perspective on the evolution of PV technologies, their benefits, governance challenges, and policy pathways for sustainable energy development and public trust.

To address the multidimensional nature of public trust and to enable systematic comparison across studies, trust was conceptualized as a three-dimensional construct comprising institutional trust (confidence in the competence, transparency, and accountability of government agencies, regulators, and developers), technological trust (perceptions of the reliability, safety, and environmental performance of PV systems, including risk–benefit perceptions), and procedural trust (confidence in the fairness, inclusiveness, and transparency of decision-making processes, including meaningful public participation); for each dimension, indicative indicators were predefined for data extraction and qualitative coding, specifically perceived competence, transparency, accountability, and prioritization of public interest for institutional trust; perceived safety, reliability, environmental performance, and risk–benefit balance for technological trust; and perceived fairness, meaningful participation, influence on outcomes, and transparency of process for procedural trust; these indicators were used to code the included studies, with quantitative measures extracted where reported and qualitative findings thematically coded against the same dimensions; this operationalization provides a testable framework for future empirical work, including the development of survey instruments and structural equation models linking trust to policy effectiveness and adoption outcomes.

2.8 Limitations of the Study

The study has several limitations: first, publication bias may have been introduced by the restriction to peer-reviewed articles published in English, potentially excluding relevant studies published in other languages or in grey literature; second, heterogeneity in study designs, sample sizes, and measurement tools across the included studies limited the feasibility of a robust meta-analysis, and consequently a narrative synthesis was employed, which, while comprehensive, may be subject to researcher interpretation; third, the temporal scope focused on literature published between 2015 and 2025, and while this period captures recent advancements in PV technologies and policy shifts, it may not reflect historical trends or long-term trajectories; and fourth, the findings are primarily based on studies conducted in specific geographical contexts, so caution should be exercised when generalizing the results to regions with different socio-economic, political, or cultural landscapes.

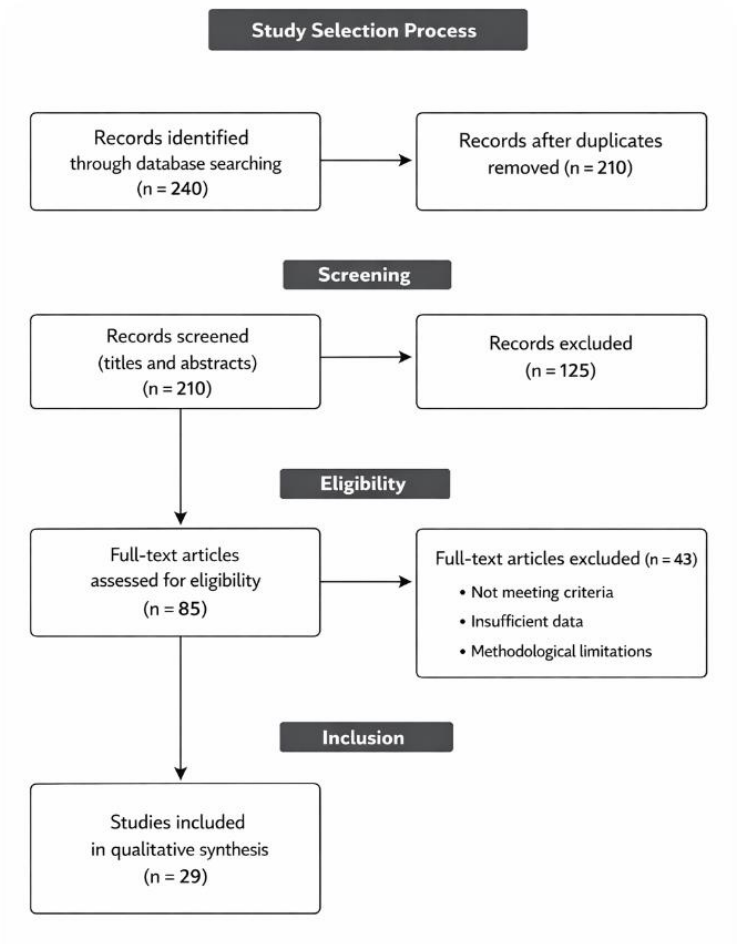

Fig 1. PRISMA Flow Diagram of the Methodology

3. The Technological Landscape of Solar Power

The remarkable growth of the solar industry is intrinsically linked to relentless innovation in photovoltaic (PV) science and engineering [29]. The journey of PV technology can be broadly categorized into distinct generations, each characterized by different materials, manufacturing processes, and performance metrics [6]. Understanding this technological evolution is crucial for appreciating the current market dynamics and future potential of solar energy. This section provides a systematic overview of first, second, and third-generation PV technologies.

3.1 First-Generation: Crystalline Silicon (c-Si)

First-generation PV technology, based on crystalline silicon wafers, remains the backbone of the global solar market. This dominance is owed to the high efficiency, long-term stability, and well-established manufacturing infrastructure associated with silicon. Monocrystalline (mono-Si) cells are produced from a single, highly pure silicon crystal, offering the highest efficiencies. Polycrystalline (poly-Si) cells, on the other hand, are made from multiple silicon fragments melted together, which results in a slightly lower efficiency but at a reduced manufacturing cost. The primary drawback of c-Si technology is its relatively high material and energy consumption during the manufacturing process, making the wafers rigid and heavy [30].

3.2 Second-Generation: Thin-Film Solar Cells

Developed to address the cost and material intensity of crystalline silicon, second-generation thin-film solar cells use microscopic layers of photovoltaic material deposited onto a substrate. This approach drastically reduces the amount of semiconductor material needed. Key thin-film technologies include Cadmium Telluride (CdTe) and Copper Indium Gallium Selenide (CIGS). Another notable technology is Amorphous Silicon (a-Si), which, despite its lower efficiency, is highly flexible. While thin-film technologies have made significant strides, they generally exhibit lower efficiencies and, in some cases, face concerns regarding material toxicity or scarcity compared to c-Si [30].

3.3 Third-Generation and Emerging PV Technologies

The third generation of solar cells represents a departure from the traditional p-n junction model, focusing on novel materials to overcome theoretical efficiency limits [11]. This category is a hotbed of research. Perovskite Solar Cells (PSCs) have emerged as the most prominent, exhibiting a meteoric rise in lab-scale efficiency. Their potential for low-cost, solution-based manufacturing is a major driver of interest, though long-term operational stability remains a significant research hurdle. Other technologies like Organic Photovoltaics (OPVs) offer unparalleled flexibility but currently suffer from low efficiency and short lifespans [30]. The goal is to continuously

push efficiency boundaries towards 30% and beyond by 2030 [11].

4. The Socio-Economic Benefits and Impacts of Solar Power

The proliferation of solar power extends far beyond its technological merits, catalyzing profound socio-economic transformations [8]. The transition to a solar-centric energy system is a powerful engine for economic growth, enhanced energy security, and greater social equity.

4.1 Economic Growth and Job Creation

The solar industry is a major source of employment and economic stimulation. The solar value chain creates a diverse range of jobs, and studies project significant job creation during the global energy transition towards renewable systems [14,31]. The dramatic reduction in the Levelized Cost of Energy (LCOE) from solar has also made electricity more affordable, increasing industrial competitiveness [32]. Furthermore, the growth of the solar sector stimulates innovation in adjacent industries, such as battery storage and smart grid technology [33].

4.2 Energy Security and Resilience

Over-reliance on imported fossil fuels is a source of geopolitical vulnerability [3]. Solar energy, as a distributed and indigenous resource, offers a direct pathway to enhancing national energy security. By diversifying the energy mix, countries can reduce their exposure to international fuel price shocks [34]. On a local level, distributed solar installations, particularly when paired with energy storage, increase community resilience against grid outages [35]. This fosters a more robust and decentralized energy system.

4.3 Environmental and Health Benefits

The most fundamental driver for solar power is its environmental benefit. Generating electricity from solar PV produces no operational greenhouse gas emissions, making it a cornerstone technology in the fight against climate change [36]. This transition has direct and tangible public health benefits. By reducing air pollution from fossil fuels, solar energy helps to decrease the incidence of respiratory and cardiovascular diseases, an effect quantifiable as a co-benefit of clean energy choices [37-39]. The minimal water usage of PV technology also addresses growing concerns about water scarcity [29,40].

5. Grid Integration Challenges and the Role of Enabling Technologies

The large-scale integration of solar power into electricity grids presents significant technical challenges, primarily due to its variable and intermittent nature [41,42]. This variability can threaten grid stability and reliability. This section explores these challenges and the critical role of enabling technologies.

5.1 The Challenge of Intermittency and Variability

Traditional power grids were designed around centralized, dispatchable power plants. Solar power, as a non-dispatchable Variable Renewable Energy (VRE) source, inverts this paradigm [43]. The “duck curve” phenomenon, observed in grids with high solar penetration, describes a steep drop in net demand during midday followed by a very rapid ramp-up in demand in the late afternoon. Managing this rapid ramp requires conventional power plants to cycle inefficiently, increasing costs and stress [44]. Furthermore, unpredictable changes in solar output can create voltage and frequency fluctuations, further complicating grid management [42].

5.2 Energy Storage: The Key to Unlocking Solar’s Full Potential

Energy storage systems (ESS) are the most crucial enabling technology for overcoming solar intermittency [45,46]. By storing excess solar energy and dispatching it later, ESS transforms intermittent solar into a firm resource [47]. Battery energy storage systems (BESS), particularly lithium-ion, lead the market due to declining costs and high efficiency [48]. They provide a range of grid services, enhancing both stability and economic value [35]. Other technologies like pumped-hydro, compressed air energy storage [49], and green hydrogen [50,51] offer potential for long-duration storage.

5.3 Smart Grids and Demand-Side Management

A “smart grid” utilizes digital communication and automated controls to create a more dynamic and responsive energy system [52]. In a grid with high solar penetration, smart grid infrastructure allows for better forecasting and real-time visibility. A key component is Demand-Side Management (DSM), which incentivizes consumers to shift their electricity usage. For instance, smart appliances and IoT-enabled systems in buildings can be programmed to run during midday solar peaks, effectively absorbing excess generation and flattening the duck curve [53-55].

5.4 Technical Enhancements: Inverter Controls, Storage Requirements, and PV Lifecycle Considerations

a) Inverter Control Paradigms and Grid Stability

Inverter-based resources have transformed power system dynamics, creating new stability challenges due to fundamental control differences. Traditional grid-following inverters (GFLIs) rely on phase-locked loops (PLLs) to synchronize with existing grid voltage and frequency, effectively operating as current sources that inject prescribed active and reactive currents into the grid [56]. In contrast, grid-forming inverters (GFMIs) autonomously regulate voltage and frequency at the point of common coupling, behaving functionally more like virtual synchronous generators that provide ancillary services such as frequency support, voltage regulation, and inertia emulation [56,57]. GFMIs therefore enhance stability in weak grids and during disturbances by establishing a stable voltage and frequency reference, whereas GFLIs can experience degraded performance under the same conditions due to their dependence on an external reference signal [56,57].

However, this relative advantage is nuanced: controlled islanding and protection schemes remain complex for GFMIs, and in some abnormal scenarios (e.g., unintentional islanding), the extended non-detected zone can challenge protection schemes, indicating that selection and coordination of inverter controls must be guided by dynamic performance

and protection requirements rather than simple hierarchy of control types [58]. The key differences between grid-following and grid-forming inverters and their impacts on system stability are summarized in Table 1 and illustrated in Figure 2

Table 1. Comparison of Grid-Following and Grid-Forming Inverters for Solar PV Systems

Parameter / Metric	Grid-Following Inverter (GFLI)	Grid-Forming Inverter (GFM)
Frequency support	Limited	High
Voltage regulation	Moderate	High
Response to islanding	Poor	Good
Virtual inertia contribution	None	Yes
Suitability for weak grid	Low	High

Source: [56-58].

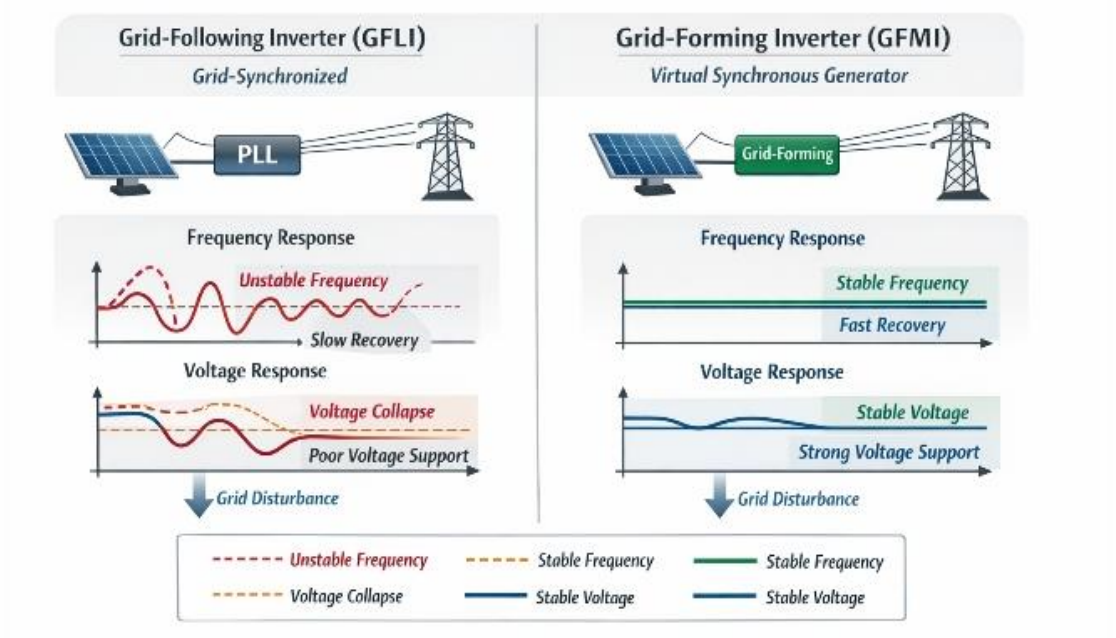

Fig 2. Grid-Following vs. Grid-Forming Inverter Control in Weak Grid Dynamics

Left: Grid-Following Inverter (GFLI) synchronized to the grid via PLL, showing unstable frequency and voltage with slow recovery.

Right: Grid-Forming Inverter (GFMI) autonomously regulating voltage and frequency, showing stable frequency, fast recovery, and strong voltage support.

b) Quantitative Trends in LCOE and Energy Storage Needs for High PV Penetration

The economic competitiveness of solar photovoltaics has dramatically improved. According to the International Renewable Energy Agency (IRENA), the global weighted average Levelized Cost of Electricity (LCOE) for utility-scale solar PV in 2024 was approximately US$0.043/kWh, reflecting a near 90% reduction since 2010 and making PV one of the lowest-cost sources of new generation globally [59]. Despite minor year-to-year variations due to system costs and market conditions, PV continues to outperform many conventional sources on a cost basis [59].High penetration scenarios (e.g., >50% PV share) require substantial storage to manage variability and reduce curtailment. Multiple grid-integration studies (e.g., [60,61]) indicate that as renewable penetration increases, the required storage capacity grows nonlinearly with penetration level. For instance, storage requirements may reach tens to hundreds of gigawatt-hours (GWh) to support very high PV penetrations, depending on grid flexibility, demand profiles, and tolerance for curtailment [61]. These storage systems (predominantly lithium-ion in the current market) not only help balance supply and demand temporally but also provide frequency regulation and ramping capability that PV alone cannot deliver. Table 2 presents the trends in PV LCOE and battery storage costs from 2010 to 2024, and Figure 3 illustrates the

estimated storage capacity requirements as a function of PV penetration.

Table 2. Trends in Levelized Cost of Electricity (LCOE) and Battery Storage Costs for Utility-Scale Solar PV (2010–2024)

Year	PV Global LCOE (USD/kWh)	Battery Storage Cost (USD/kWh)	Notes / Sources
2010	0.37	1000	IRENA (2025)
2015	0.12	600	IRENA (2025)
2020	0.065	200	IRENA (2025)
2024	0.043	130	IRENA (2025)

Source: [59,60].

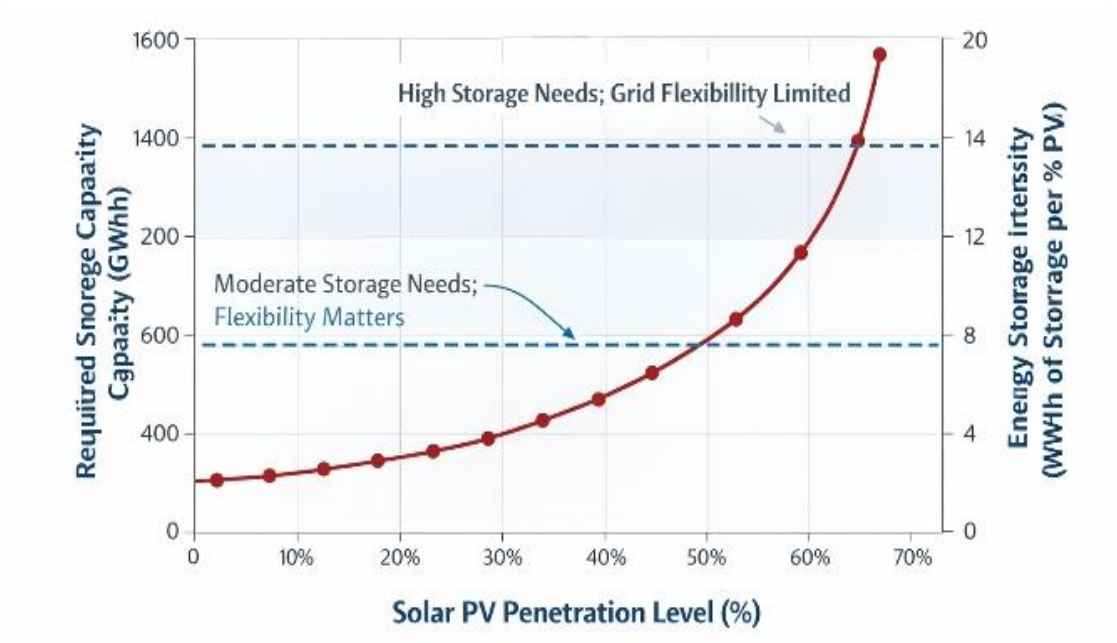

Fig 3. Estimated Storage Capacity Requirements vs. Solar PV Penetration Level

X-axis: PV penetration (%)

Y-axis (left): Required storage capacity (GWh)

Y-axis (right): Energy storage intensity (MWh per % PV)

The chart shows nonlinear growth in storage needs as PV penetration increases, with high storage requirements above 50% PV penetration.

c) Lifecycle Assessment (LCA), End-of-Life (EoL), and PV Recycling

While operational emissions of PV systems are near zero, life-cycle assessment (LCA) studies reveal that environmental impacts are front-loaded in manufacturing and end-of-life (EoL) phases. PV module production especially silicon wafer processing, metallization, and glass encapsulation contributes to embodied energy and GHG emissions, which are offset over the module's operational life through clean generation [62]. At EoL, effective recycling can recover high percentages of materials such as glass, aluminum, silicon, and metals, significantly reducing the environmental footprint associated with raw material extraction and waste disposal [63]. For example, recycling scenarios in Australia showed that maximizing recovery can reduce lifecycle impacts and align PV deployment with circular economy principles [63]. However, recycling infrastructure and regulation vary regionally, and end-of-life management must be integrated into PV deployment strategies to ensure sustainability across the entire lifecycle. Table 3 presents material recovery rates and environmental benefits, while Figure 4 illustrates the complete lifecycle flow of PV systems from raw material extraction to recycling.

Table 3. Material Recovery Rates and Environmental Benefits for End-of-Life PV Panels

Material	Recovery Rate (%)	Environmental Benefit
Silicon	85–90	Reduced mining energy
Aluminum	90	Reduced GHG emissions
Glass	90–95	Lower landfill impact
Silver	80–85	Reduced extraction need

Source: [63,64].



Fig 4. Lifecycle of Solar PV Systems from Raw Material Extraction to End-of-Life Recycling

Stages: raw material extraction, wafer production, module assembly, installation, operation, decommissioning, and recycling.

Includes recovery rates and environmental impact indicators for silicon, aluminum, glass, and silver.

6. Energy Governance and Public Trust in Photovoltaic Transitions

The diffusion of photovoltaic (PV) technologies is not solely a technological or economic process; rather, it is deeply shaped by the quality of energy governance, policy instruments, and levels of public trust. Recent literature increasingly demonstrates that the success of solar energy transitions depends not only on declining costs and technological innovation, but also on effective governance structures and societal acceptance [65].

6.1 Energy Governance and Policy Instruments for Solar Deployment

Energy governance refers to the institutional arrangements, regulatory frameworks, policy instruments, and decision-making processes that shape energy system transformations. Empirical evidence shows that stable, transparent, and predictable policy frameworks play a decisive role in accelerating PV deployment.

Key policy instruments include:

- Feed-in tariffs and auction mechanisms
- Investment subsidies and tax incentives
- Grid-connection regulations
- Electricity market standards and regulatory oversight

Cross-national analyses demonstrate that countries with consistent and credible renewable energy policies experience faster and more sustained solar energy growth [66]. Policy stability is also a critical determinant of private investment in renewable energy systems. Conversely, regulatory uncertainty and abrupt policy changes have been identified as major barriers to PV expansion [67].

These findings highlight that PV deployment is not only a technological and economic challenge but fundamentally a governance and policy challenge.

Most of the governance evidence synthesized above originates from Europe, North America, and China; however, a growing body of literature addresses governance and policy design in the Global South, where institutional capacity, financing conditions, and grid infrastructure differ substantially from high-income contexts. [68] examine the policy implications of residential PV deployment in developing regions and find that access to affordable financing and clear interconnection rules are frequently a greater constraint on adoption than the underlying policy design itself. [69] document how commercial solar adoption in Mkushi, Zambia, is shaped by land tenure arrangements and rural community development dynamics that have no direct equivalent in European policy frameworks, while [70] identify financing, regulatory capacity, and enforcement gaps as recurring barriers to carbon-neutral building and PV policy across Global South contexts. These cases suggest that governance frameworks developed for mature European or East Asian markets cannot be transferred to developing regions without adaptation, and that Global South evidence should be treated as a distinct governance context rather than a variation on the European case.

6.2 Public Trust and Social Acceptance of Solar Energy

Social acceptance represents a critical determinant of renewable energy deployment. Even under favorable economic conditions, a lack of public trust can delay or halt energy projects [71].

Public trust in the energy sector is typically shaped by three interrelated dimensions:

1. Trust in governments and policy makers
2. Trust in energy companies and project developers
3. Perceived fairness in the distribution of costs and benefits

Research consistently shows that meaningful public participation in decision-making processes is one of the strongest predictors of renewable energy acceptance [72].

The concept of energy justice further emphasizes that public support increases when communities perceive the transition as fair, inclusive, and beneficial [73]. Transparency, stakeholder engagement, and effective communication with local communities have been shown to significantly enhance trust and reduce resistance to renewable energy projects [74].

6.2.1 Operationalizing "Public Trust" in Photovoltaic Energy Governance

For a rigorous empirical investigation of public trust within the context of solar energy policy and photovoltaic technology adoption, it is necessary to conceptualize trust as a multidimensional and measurable construct. Research on energy transitions consistently highlights that trust extends beyond general attitudes and comprises specific beliefs related to institutions, technologies, and policymaking processes [75].

6.2.1.1 Trust in Institutions

Trust in institutions refers to public confidence in the competence, transparency, and accountability of governing entities such as government agencies, regulators, and developers that are responsible for renewable energy projects. Institutional trust influences how people evaluate energy policies and whether they believe that public interests are prioritized over private or political gains [76]. Research across different national contexts shows that higher institutional trust is associated with greater acceptability of renewable energy initiatives because people feel that responsible actors will make sound decisions and fairly address community concerns[75,77].

6.2.1.2 Trust in Technology Performance and Safety

Technological trust encompasses public perceptions of the reliability, safety, and environmental impacts of specific energy technologies, including photovoltaic systems. While this aspect of trust has historically received less direct conceptual focus than institutional trust, emerging literature on socio-technical transitions emphasizes that perceived risk and benefit of technologies shape public acceptance and adoption intentions [78]. In energy transitions, such perceptions mediate how communities respond to emerging systems and whether they view technologies as legitimate and beneficial components of sustainable policy frameworks.

6.2.1.3 Trust in Policymaking Processes

Procedural trust relates to confidence in the fairness, inclusiveness, and transparency of decision-making processes that govern energy policy design and implementation. Public engagement and meaningful participatory mechanisms enhance procedural trust by giving citizens a sense of influence and voice in decisions affecting their lives [75]. Studies show that when participation is superficial or limited to token consultation rather than substantive influence, trust and consequently social acceptance may diminish. True procedural trust arises when stakeholders perceive that their input can shape outcomes and that decision processes adhere to norms of equity and openness [68,75].

6.2.1.4 The Role of Trust in Energy Transitions

Across the literature on sustainability and energy governance, public trust is not a singular outcome but a relational construct that both shapes and is shaped by institutional behavior, technological perceptions, and procedural legitimacy. Trust is therefore a prerequisite for social acceptance, helping to bridge the gap between policy ambition and lived experience. Building trust requires not only transparent policymaking and effective regulation but also sustained engagement with communities to address uncertainty, align expectations, and co-produce governance pathways that reflect shared values [69,75,79].

6.2.2 Measuring and Evaluating Public Trust in Solar PV Transitions: Predefined Indicators, Validated Frameworks, and Empirical Instruments

Although public trust is often discussed qualitatively, its central role as an innovation of this paper necessitates a transparent and testable measurement strategy. Building on the three-dimensional conceptualization in Section 6.2.1 institutional trust, technological trust, and procedural trust we propose that public trust can be assessed through predefined indicators, validated survey instruments, and mixed-methods frameworks. This operationalization transforms trust from a

normative concept into a measurable construct linked empirically to policy effectiveness, adoption behavior, and social acceptance. Building on the three-dimensional operationalization in Section 2.7, the trust construct used here can be empirically measured through instruments already validated in the energy social-science literature, rather than through new, untested scales.

For institutional trust, indicators include perceived competence, transparency, accountability, and prioritization of public interest. Institutional trust has been measured using competence- and integrity-based trust scales adapted from organizational-trust research and applied specifically to renewable-energy institutions, for example by [76], who compared acceptability outcomes in China and the Netherlands using multi-item Likert scales capturing perceived competence, openness, and fairness of energy authorities. [76] provide competence- and integrity-based trust items applicable to solar policy actors.

For technological trust, indicators comprise perceived safety, reliability, environmental performance, and risk-benefit balance. Technological trust is commonly assessed through risk-benefit perception scales that ask respondents to rate the safety, reliability, and environmental performance of a specific technology, an approach used in sociotechnical acceptance research [78] and adaptable to PV-specific attributes such as fire risk, land use, and end-of-life management. [78] offer a trust-in-renewable-energy scale for technological trust.

For procedural trust, indicators encompass perceived fairness, meaningful participation, influence on outcomes, and transparency of process. Procedural trust is typically captured with participatory-fairness indices, which combine survey items on perceived voice, influence over outcomes, and transparency of process; [72] and [75] provide validated item sets of this kind, and social-acceptance surveys such as those used by [77] in Epirus, Greece, demonstrate their application to solar and wind siting decisions. [75] propose a relational framework linking procedural trust to participation quality. These can be measured using Likert-scale surveys, interviews, focus groups, and content analysis.

Two recent studies strengthen this measurement approach. [80] demonstrate that broader institutional trust extending beyond the state to non-state actors correlates significantly with public support for energy transition policies, whereas narrow political trust correlates only with fossil fuel taxation attitudes. [81] provide a validated mixed-methods framework combining Likert-scale trust indices with sentiment analysis of open-ended responses, enabling simultaneous capture of quantitative trust levels and qualitative expressions of distrust across governments, service providers, and technologies.

Methodologically, a mixed-methods design is appropriate. Quantitative surveys using 5- or 7-point Likert scales generate composite trust indices. Reliability is assessed via Cronbach's alpha (≥ 0.70), and construct validity through exploratory and confirmatory factor analysis. Structural equation modeling (SEM) can test relationships among institutional trust, technological trust, procedural trust, policy effectiveness, and adoption intention. Qualitative methods semi-structured interviews, focus groups, deliberative workshops, and ethnographic observation capture relational and contextual dynamics. A staged validation procedure is recommended: content validity through expert panels; face validity in pilot studies; statistical reliability and construct validity; predictive validity by testing whether trust indicators predict policy support, willingness to participate, or actual adoption; and longitudinal panel designs to track trust evolution. Cross-national studies should test measurement invariance.

This framework directly supports the second innovation of this paper: quantifying the relationship between public trust and the effectiveness of solar energy policies. By making trust measurable through predefined indicators and validated instruments, future research can provide robust, comparative, and policy-relevant evidence on how trust shapes and is shaped by photovoltaic transitions. Applying these existing instruments consistently across studies rather than treating trust as an unmeasured background concept would allow the indicators proposed in Section 2.7 to be operationalized in future primary data collection, and is a precondition for the quantitative trust-policy models called for in Section 9.1.4 and Section 9.2.

6.3 Integrating Technology, Governance, and Trust

Contemporary energy transition research stresses that successful decarbonization requires the simultaneous alignment of technological innovation, governance systems, and societal dynamics.

The socio-technical transitions framework demonstrates that the adoption of energy technologies emerges from the interaction between:

- Technological innovation
- Institutional and policy structures
- Social practices and public trust

[76,82].

Within this perspective, PV technologies should be understood not merely as energy devices but as components of a broader socio-technical transformation. Long-term success therefore depends on the development of participatory governance models, transparent regulation, and trust-building processes capable of balancing environmental, economic, and social objectives.

7. Policy, Regulation, and the Path Forward

Supportive policies and stable regulatory frameworks are paramount to accelerating the widespread adoption of solar energy [83]. The pace of decarbonization is ultimately dictated by the political will to create an ecosystem that champions renewable energy.

7.1 Financial Incentives and Market Mechanisms

Historically, government-led financial incentives have been instrumental in nurturing the solar industry. As solar has become more cost-competitive, the policy focus is shifting towards market-oriented mechanisms like carbon pricing, which levels the playing field by internalizing the environmental costs of fossil fuels. Additionally, renewable portfolio standards provide a long-term demand signal that drives continued investment [84,85].

7.2 Streamlining Regulations and Grid Modernization

Streamlining administrative and permitting processes is a crucial, low-cost way to accelerate solar deployment. Concurrently, public investment in grid modernization is essential, including upgrading transmission infrastructure and investing in smart grid technologies [52]. Proactive grid planning that anticipates future growth in renewables is far more effective than a reactive approach [86,87].

7.3 Fostering Research, Development, and a Just Transition

Continuous public and private investment in research and development (R&D) is vital to maintain the innovation pipeline. Funding for next-generation PV technologies aiming for higher efficiencies [11], advanced energy storage solutions [88], and establishing a circular economy for recycling solar components will ensure long-term sustainability [89]. Furthermore, as the energy transition accelerates, it is ethically imperative to ensure it is a "just transition" [90]. This means actively supporting communities historically dependent on the fossil fuel industry, such as former lignite-mining areas, through retraining programs and targeted economic development initiatives [91]. Ensuring that the social dimensions of the energy transition are managed effectively and that the benefits of clean energy are accessible to all is fundamental to building broad public support for the solar imperative [8].

7.4 Extending Policy Lessons to the Global South

The policy instruments discussed in Sections 7.1 and 7.2-feed-in tariffs, auctions, carbon pricing, and streamlined permitting-were designed largely for grid-connected, capital-rich markets. In many Global South contexts, off-grid and mini-grid PV deployment, concessional and blended finance, and community- or cooperative-ownership models play a comparatively larger role than in Europe or North America [68,69]. Policy frameworks aiming for global relevance should therefore explicitly accommodate financing mechanisms suited to lower-income and rural contexts, capacity-building for local regulatory institutions, and land-tenure and community-benefit arrangements of the kind documented in Zambia [69], alongside the market-based mechanisms described above. This is consistent with the geographical gap identified in Section 9.1.2 and reinforces the case for the Global South evidence base to be expanded in future primary research.

Table 4. Comparative Analysis of Major Photovoltaic Technology Generations

Feature	First-Generation (c-Si)	Second-Generation (Thin-Film)	Third-Generation (e.g., Perovskites)
Primary Material	Crystalline Silicon (Mono & Poly)	CdTe, CIGS, Amorphous Silicon	Perovskite Compounds, Organic Polymers, Quantum Dots
Commercial Efficiency	**High (17-25%)**	Moderate (12-18%)	**Lab-scale: Very High (›25%)** Commercial: Emerging
Manufacturing Cost	Moderate to High (but decreasing)	**Low**	Potentially Very Low (solution-printable)
Material Intensity	High (thick, rigid wafers)	**Very Low** (micrometer-thin layers)	Extremely Low
Flexibility	Low (rigid and fragile)	**High** (can be deposited on flexible substrates)	**Very High** (printable, flexible, transparent potential)
Market Maturity	**Very High** (>90% market share)	Moderate (established niche markets)	Low (in research & development / early commercialization)
Key Challenge	Material and energy intensity in production	Lower efficiency, material toxicity/scarcity concerns	**Long-term stability and durability**

As summarized in Table 4, a clear trade-off exists between the different PV generations. First-generation crystalline silicon technology, the undisputed market leader, offers high efficiency and proven reliability, but at the cost of high material consumption and rigidity. Second-generation thin-film technologies successfully addressed the cost and material-intensity issues, enabling applications on flexible surfaces, but generally sacrifice efficiency and face their own material-specific challenges, as detailed in life-cycle assessments comparing them to conventional technologies [30].

Third-generation technologies, particularly perovskites, represent a paradigm shift, promising the 'best of both worlds': high efficiency rivaling silicon, combined with the low-cost, low-material manufacturing of thin-films. These emerging technologies are central to the goal of achieving even higher efficiencies in the coming years [11]. However, as the table highlights, their primary hurdle remains achieving the long-term operational stability required for commercial viability, a challenge that is the focus of intense global research in the ongoing revolution of solar panel technology [6].

8. Comparative Analysis: Solar PV vs. Conventional Energy Sources

To fully appreciate the disruptive potential of solar power, it is essential to compare it directly against conventional energy generation methods across key metrics. The two most critical arenas for this comparison are economics and environmental impact. This section provides a data-driven analysis that positions solar PV in the broader energy landscape.

8.1 Economic Competitiveness: The LCOE Showdown

The most widely accepted metric for comparing the cost of different electricity generation technologies is the Levelized Cost of Energy (LCOE), which represents the average revenue per unit of electricity generated that would be required to recover the costs of building and operating a generating plant over an assumed financial life.

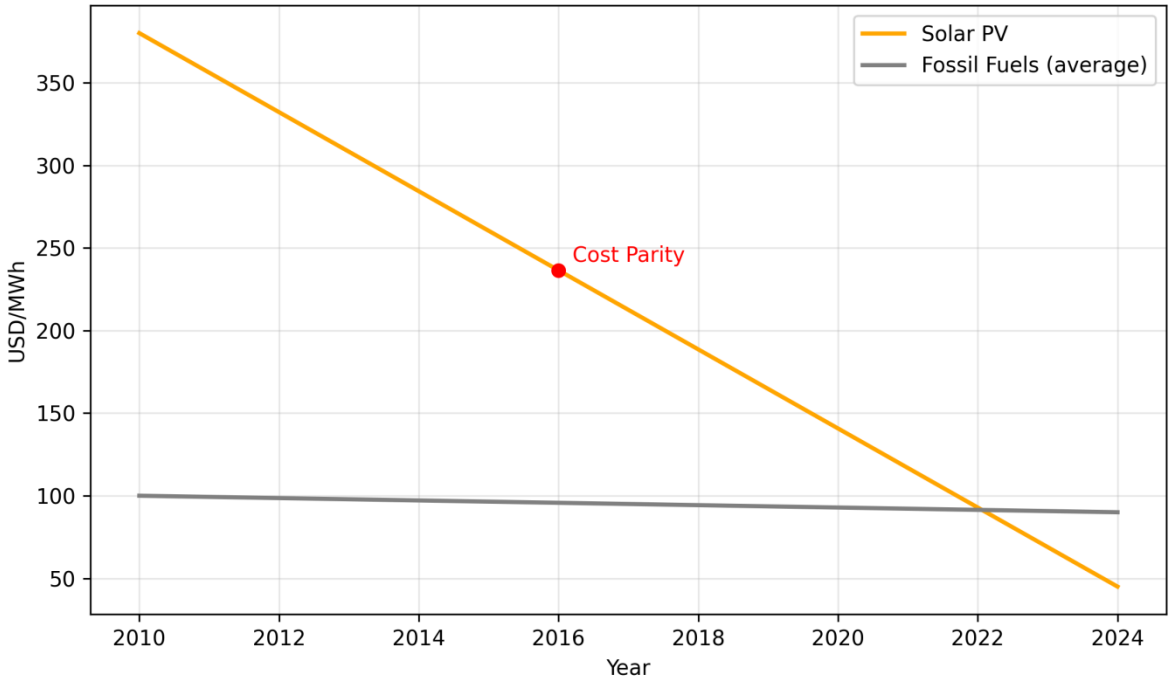

Fig 5. Global Levelized Cost of Energy (LCOE) Trajectory for Solar PV vs. Fossil Fuels (2010-2024)

Continuous public and private investment in research and development (R&D) is vital to maintain the innovation pipeline. Funding directed towards next-generation PV technologies, such as those aiming to surpass 30% efficiency [11], alongside advanced energy storage solutions and component recycling processes, will ensure long-term sustainability and cost reduction.

Furthermore, as the energy transition accelerates, it is ethically imperative to ensure it is a "just transition"**.** This concept involves navigating the profound socio-technical shifts required for a sustainable future [92] by actively supporting communities and workers historically dependent on fossil fuels. Key challenges include implementing retraining programs and fostering new economic prospects in former industrial regions, such as lignite areas [91]. Ensuring that the benefits of clean energy from the new employment opportunities created during the transition [14] to lower electricity bills are accessible to all, including low-income and marginalized communities, is fundamental to the political viability and social acceptance of the solar imperative [90].

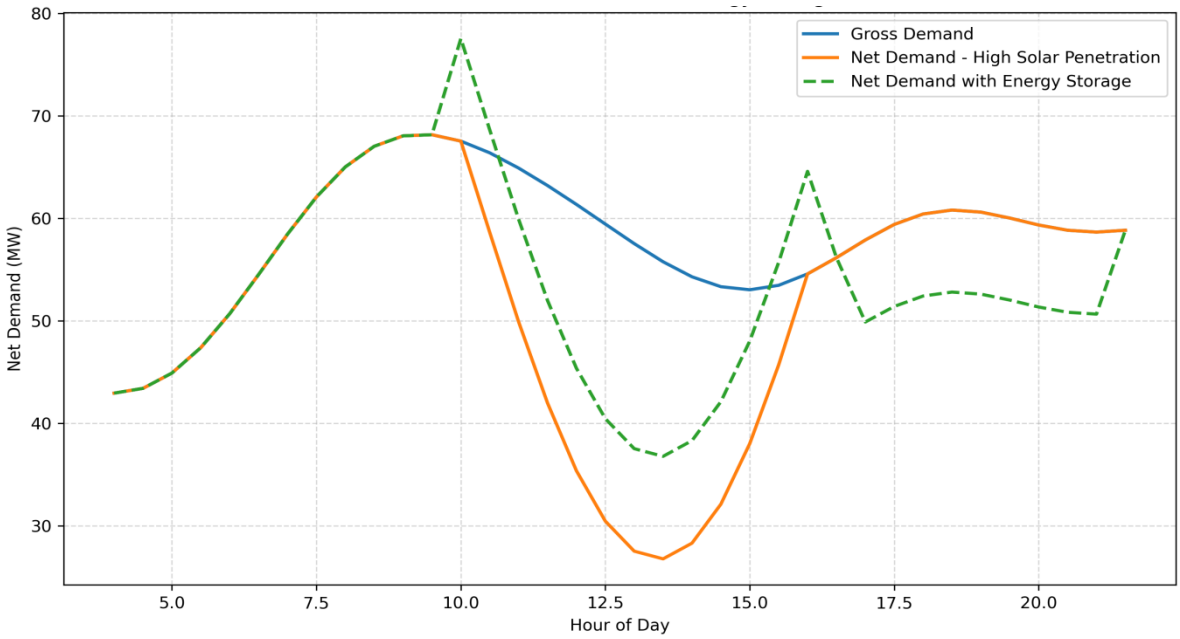

Fig 6. The "Duck Curve" and the Smoothing Effect of Energy Storage

Note: Figure prepared by the author to illustrate the duck-curve concept discussed in Section 5.1 and Section 8.1, informed by [7] and [93]; no third-party figure has been reproduced

The core challenge of grid integration with high solar penetration is visually captured by the 'duck curve,' depicted in Figure 6. This curve illustrates the dramatic drop in net electricity demand during peak solar production hours, followed by a perilously steep ramp-up in demand as the sun sets. This volatility strains conventional power plants and creates significant stability challenges for the grid, an issue inherent in the transition towards high shares of renewable energy [7].

The figure also demonstrates the transformative solution offered by energy storage, a cornerstone technology for modern energy systems [93]. By absorbing excess solar generation during midday (charging) and dispatching it during the evening ramp (discharging), Photovoltaic-Battery Energy Storage Systems (PV-BESS) can effectively 'flatten' the duck curve. This process smooths volatility and turns intermittent solar power into a reliable, dispatchable asset with grid-forming capabilities that enhances, rather than threatens, grid stability [88,94].

Figure 7 provides a stark illustration of the new energy paradigm. As of 2024, utility-scale solar PV, alongside onshore wind, stands as the most inexpensive source for new electricity generation globally, a conclusion strongly supported by leading industry analysis [95]. The Levelized Cost of Energy (LCOE) for new solar projects has fallen to a range that is substantially lower than that of new natural gas combined-cycle power plants (CCGT) and is drastically cheaper than new coal-fired or nuclear power plants [48].

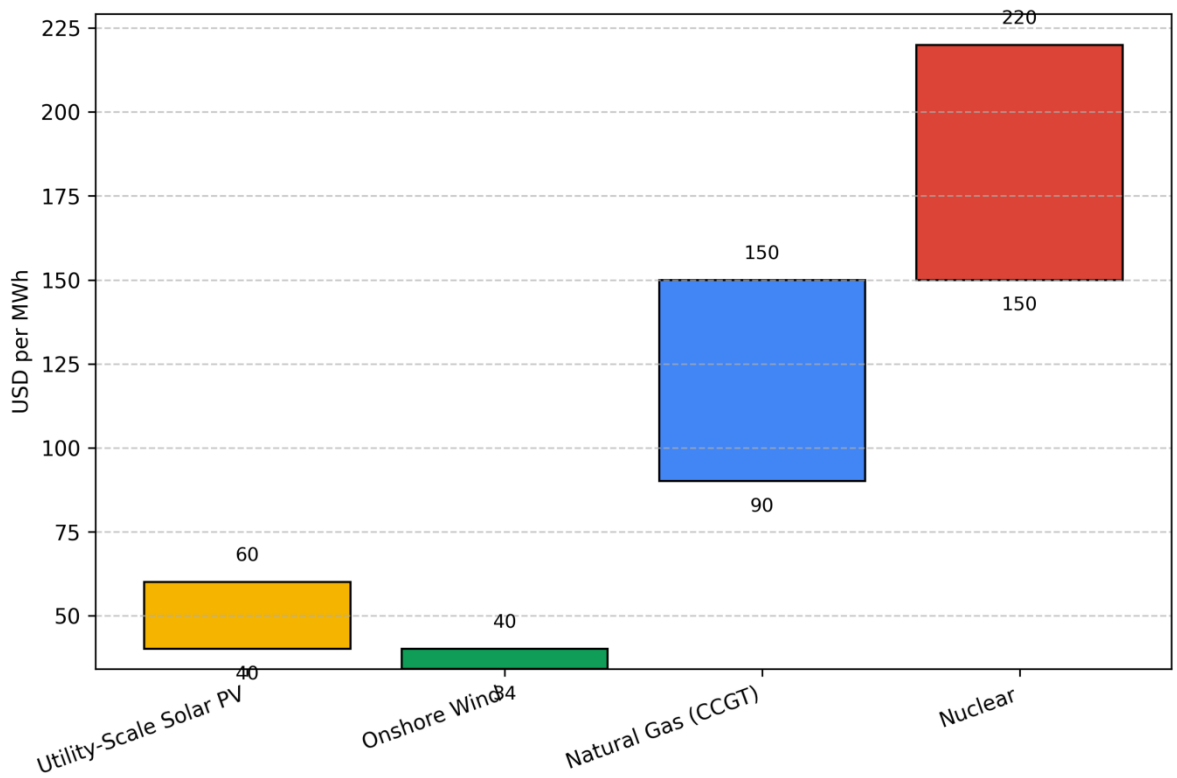

Fig 7. Global Average Levelized Cost of Energy(LCOE) for New Power Plants(2024Estimates)

Note: Figure prepared by the author from the 2024 LCOE benchmarks cited in the text [48,95]; no third-party figure has been reproduced

It is crucial to note that the LCOE for fossil fuels often does not include externalities such as the cost of carbon emissions or public health impacts from air pollution, which, if factored in, would further widen this economic gap [96,97]. While conventional sources like natural gas still offer the benefit of dispatchability, the declining cost of battery storage is rapidly closing this gap. This allows solar-plus-storage solutions, often managed by advanced grid-forming inverters, to compete directly with gas peaker plants on both cost and reliability [52,93,98].

8.2 Environmental and Resource Impact: A Life-Cycle Perspective

Beyond cost, the environmental footprint is a defining factor in 21st-century energy policy. This includes not only direct emissions during operation but also the life-cycle impact, covering manufacturing, construction, and decommissioning.

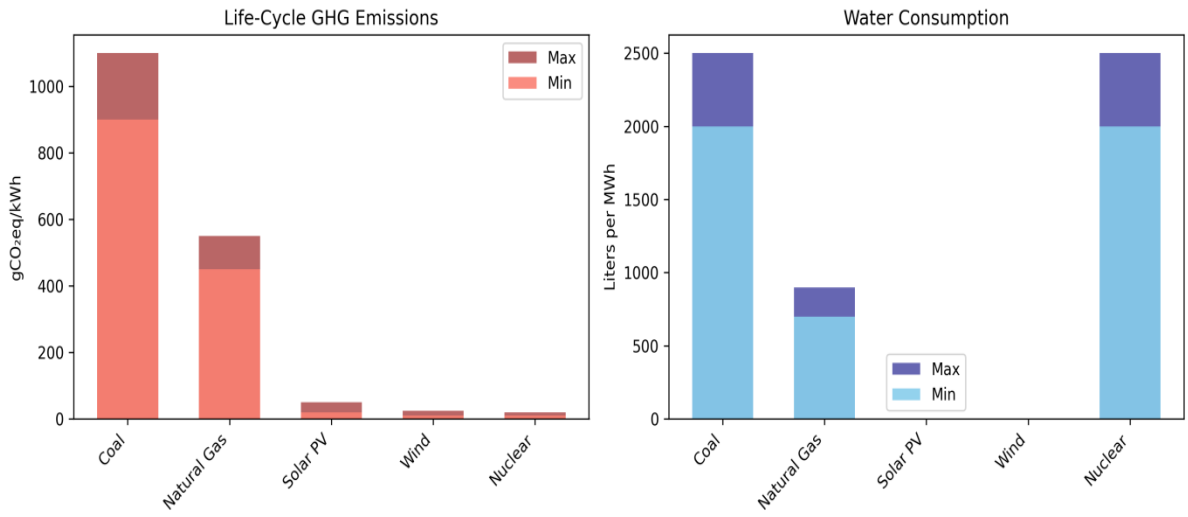

Fig 8. Life-Cycle Greenhouse Gas Emissions and Water Consumption per Unit of Electricity

Note: Figure prepared by the author from the LCOE and life-cycle emissions data cited in Section 8.2 [99,100]; no third-party figure has been reproduced.

As demonstrated in Figure 8, the environmental advantages of solar PV are unequivocal. On a life-cycle basis which includes emissions from manufacturing, transport, and decommissioning solar PV's carbon footprint is orders of magnitude smaller than that of coal and natural gas [99]. This positions solar energy as a cornerstone technology for mitigating climate change [100]. While nuclear and wind power also exhibit very low life-cycle emissions, solar power holds a distinct and critical advantage in another resource dimension: water consumption.

Thermal power plants, including coal, natural gas, and nuclear, are incredibly water-intensive, requiring vast quantities for steam generation and cooling. In an era of increasing climate-induced water stress and scarcity, a major global risk identified by leading climate assessments [101,102], the near-zero operational water consumption of solar PV (and wind) presents a profound advantage for long-term energy security and environmental sustainability. This makes solar power a uniquely resilient technology, capable of being deployed even in extreme climatic conditions such as arid and water-scarce regions where thermal power plants would be unviable [103].

9.Results and Discussion

Evidence Matrix: Methodology and Structure

In this study, an Evidence Matrix has been developed to provide a comprehensive and systematic overview of the scientific literature on solar energy and photovoltaic (PV) technologies.the Evidence Matrix has been streamlined and reorganized. Studies are now grouped into the five thematic clusters used in the comparative analysis below (Technology and Economics; Grid Integration and Storage; Governance and Policy; Public Trust and Social Acceptance; and Energy Justice and Just Transition), and overlapping fields have been consolidated to remove duplicate information. Each entry now reports:

1. Citation: Reference details
2. Study Type: Review, empirical, qualitative, modeling, etc.
3. Region / Sample: Location or study population
4. Technical & Policy Focus: PV technology/energy focus and governance/policy focus, combined
5. Public Trust Dimension
6. Key Finding: Summarized
7. Limitation: Main methodological limitation
8. Research Gap / Financial Impact: Combined future-research and cost-benefit note

The purpose of this matrix is to provide a structured and traceable overview of existing evidence, enabling researchers, policymakers, and stakeholders to understand the multidimensional aspects, limitations, and opportunities of solar energy deployment and to identify effective research and implementation pathways.

Table 5. Comparative Review of Selected Studies, Grouped by Thematic Cluster

Citation	Study Type	Region / Sample	Technical & Policy Focus	Public Trust Dimension	Key Finding	Limitation	Research Gap / Financial Impact
Technology & Economics							
Vijayan et al. (2023)	Review	Global	PV tech. in civil engineering / Renewable-energy incentives	Workforce confidence	Technological advances reduce LCOE and increase adoption	Focused on civil-engineering applications	Future work: financial feasibility for developing regions
Skandalos et al. (2023)	Experimental	EU	Building-integrated PV / EU energy regulations	Trust in building technology	BIPV can reach 30% efficiency by 2030	Focused on technical efficiency only	Gap: cost-benefit of large-scale deployment
Grid Integration & Storage							
Aghmadi & Mohammed (2024)	Review	Global	Energy storage systems / Energy policy	Public acceptance of storage	High-power storage essential for grid stability with PV integration	Limited socio-economic analysis	Need for cost-benefit analysis across regions
Ali et al. (2023)	Review	Microgrids	Energy management & storage / Regulatory support	Community trust in energy access	Storage improves energy access and reliability	Mostly theoretical; lacks field trials	Financial impact depends on scale and incentives
Zhang & Li (2024)	Review	Global	Green-hydrogen integration / Energy policy	Public engagement	PV plus green hydrogen offers a decarbonization pathway	Conceptual; lacks pilot data	Financial modelling needed for grid-scale projects
IRENA (2022)	Report	Global	Battery storage / Global policy recommendations	Stakeholder confidence	Battery storage critical for grid resilience	Aggregated data; regional detail limited	Gap: economic incentives for storage adoption
Yin et al. (2024)	Review	Global	PV-battery systems / Grid-forming integration	User trust in reliability	PV-battery systems support grid-forming operation	Lacks experimental validation	Financial optimization strategies needed
Olabi et al. (2021)	Review	Global	Compressed-air energy storage / Industrial energy management	Public awareness of storage safety	CAES feasible for large-scale PV support	Lacks economic feasibility analysis	Gap: capital cost vs. energy efficiency
Dincer & Erdemir (2023)	Book chapter	Global	Thermal energy storage / Energy policy	Public confidence	TES enhances PV integration and grid stability	Technical focus; socio-economic aspects limited	Cost-benefit studies needed for adoption
Zhang et al. (2023)	Review	Global	Distributed PV generation / Emission-peak goals	Public perception	Distributed PV supports emission-peak and neutrality goals	Limited practical pilots	Financial optimization of distributed systems
Rangarajan et al. (2024)	Experimental	Low-inertia grid	Grid-forming inverters / Smart-grid policy	Operator and public confidence	Advanced inverters support low-inertia grids	Experimental; limited large-scale data	Cost-benefit for grid modernization
Kittner et al. (2017)	Review	Global	Energy-storage deployment / Renewable-energy transition	Stakeholder trust	Storage deployment accelerates clean-energy transition	Conceptual; lacks empirical validation	Financial modelling for large-scale deployment
Upadhyay et al. (2024)	Experimental	Industrial microgrid	Energy-management systems /	Operator and worker trust	RL-based EMS improves microgrid performance	Pilot study; scalability untested	Cost-benefit for industrial deployment

			Optimization algorithms				
Governance & Policy							
Postula et al. (2024)	Review	EU	Environmental-health policies / EU energy governance	Public trust in policy	Effective environmental policies improve health outcomes	EU focus; limited global applicability	Assess financial trade-offs of interventions
Cotta & Domorenok (2022)	Review	Italy	National recovery plan / Green-transition reforms	Public trust in policy	Recovery plan promotes renewable adoption	Italy-specific; generalizability limited	Financial-impact assessment needed
Frankowski (2017)	Case study	Kisielic, Poland	Local renewable adoption / Municipal energy policy	Community trust	Local policy boosts renewable uptake	Single case; limited scalability	Evaluate financial sustainability of municipal programs
Lebedeva et al. (2021)	Empirical	Latvia	Household prosumer participation / Energy-market policy	Consumer trust	Households willing to participate as prosumers	Sample limited; urban-focused	Cost-benefit of incentivizing prosumers
Popkiewicz (2015)	Book	Poland	Energy-transition overview / Policy context	Public perception	Energy transition requires socio-technical adaptation	Conceptual; limited quantitative data	Evaluate financial and social feasibility
Public Trust & Social Acceptance							
Mo et al. (2022)	Modeling	Guangdong, China	Energy-structure transformation / Pollution-control policy	Public health & trust	Transformation reduces pollution and improves public health	Regional; not globally generalizable	Gap: economic modelling of incentives
Li et al. (2022)	Empirical	China	Industrial ecological transformation / Zero-waste policy	Worker & public confidence	Industrial transformation improves sustainability	Regional and sector-specific	Financial incentives needed for scaling
Muñiz et al. (2024)	Review	Global	Smart solar buildings / IoT energy management	Resident trust	Smart PV buildings optimize energy usage	Conceptual; lacks longitudinal data	Assess financial ROI for smart-building adoption
Smil (2010)	Book	Global	Historical energy transitions / Policy evolution	Public confidence	Past transitions show technology-trust interplay	Historical focus; not PV-specific	Gap: financial lessons for PV adoption
Reidmiller et al. (2018)	Report	USA	Climate adaptation & energy / National policy	Public awareness	Policy and adaptation measures critical for resilience	US-focused; limited generalizability	Assess economic implications of adaptation
Energy Justice & Just Transition							
Allen (2022)	Report	Global	Climate impact / Policy framing	Public awareness	IPCC highlights the role of solar in climate mitigation	Broad scope; limited PV-specific detail	Gap: localized policy cost-effectiveness studies
Ram et al. (2020)	Empirical	Global	Solar deployment / Job-creation policies	Public support for renewable jobs	Solar deployment significantly increases local employment	Data projections; regional differences	Evaluate long-term financial sustainability
Buonocore et al. (2016)	Modeling	EU	Renewable vs. conventional energy / Environmental policy	Public health awareness	Renewable adoption reduces emissions and	Model-based; lacks micro-level case studies	Financial impacts on healthcare-cost savings

					improves health		
Ghasemi et al. (2024)	Review	Global South	Building-sector carbon neutrality / Policy & regulation	Public acceptance	Identifies barriers to carbon-neutral building adoption	Review; lacks implementation data	Assess financial feasibility for developing regions
Li et al. (2021)	Review	Global	Poverty & energy access / Policy interventions	Public confidence in access	Energy transition reduces poverty	Broad review; lacks field data	Economic feasibility of interventions
Wells et al. (2020)	Conceptual	Global	Post-COVID sustainability / Policy & social systems	Public trust in transition	Socio-technical perspective informs policy adoption	Conceptual; limited empirical data	Evaluate financial and social impact of policy

9.1 Critical Comparative Analysis of the Literature

Table 5 provides a structured overview of selected studies, but a descriptive summary alone does not advance the field. A critical comparative analysis reveals where the literature converges, diverges, contradicts itself, and where substantive research gaps remain. This section organizes the evidence around five thematic clusters technology and economics, grid integration and storage, governance and policy, public trust and social acceptance, and energy justice and just transition and compares study types, geographical contexts, levels of analysis, measurement strategies, and key findings.

9.1.1 Convergent Findings Across the Evidence Base

Three robust convergences emerge from the reviewed literature. First, the economic competitiveness of solar PV is now widely accepted. Studies using different methods including IRENA's cost reports [59], Lazard's LCOE analysis [95], and systematic reviews such as [6] all confirm a dramatic decline in LCOE and the increasing cost-competitiveness of utility-scale solar. This convergence is cross-national and multi-method.

Second, the intermittency challenge and the necessity of enabling technologies are consistently recognized. [2], [35], [48], and [94] all emphasize that high PV penetration requires energy storage, smart grids, and advanced inverter controls. The technical literature converges on the fact that solar PV alone cannot provide firm capacity without storage and grid-forming capabilities.

Third, public trust and participatory governance are increasingly identified as prerequisites for successful deployment. [75], [76], [71], and [73] converge on the idea that trust is multidimensional institutional, technological, and procedural and that meaningful participation enhances acceptance. This convergence is significant because it spans energy governance, social psychology, and policy studies.

9.1.2 Divergent Findings: Context, Scale, and Method

Despite these convergences, the literature diverges sharply along three axes. First, the level of analysis differs. Macro-level studies such as [7], [48], and [1] provide global and historical frameworks, while micro-level studies such as [104] in Poland, [96] in Guangdong, and [87] in Latvia reveal local institutional, behavioral, and economic complexities. The macro studies often assume that policy signals translate into local action; the micro studies show that this translation is mediated by municipal capacity, community trust, and contextual incentives.

Second, disciplinary focus diverges. Technical studies [11,52,56] prioritize efficiency, stability, and control, whereas socio-economic studies [14,31,37] prioritize jobs, health, and equity. These two streams rarely cite each other, resulting in a paradigmatic gap: technically optimized systems may fail in practice because they neglect social acceptance or market realities [14,104].

Third, geographical coverage is uneven. Empirical studies are concentrated in Europe, China, and the United States [96,97,101], while the Global South remains underrepresented [31,70]. This limits the generalizability of findings to regions with different socio-economic, political, and cultural landscapes.

9.1.3Contradictions and Tensions

Several contradictions in the literature deserve explicit attention. First, there is a tension between technological optimism and durability concerns. Third-generation PV technologies, especially perovskites, promise high efficiency and low-cost manufacturing [11], yet long-term operational stability remains unresolved. The literature therefore contains a contradiction between laboratory-scale potential and commercial viability.

Second, grid-forming inverters (GFMIs) are presented as superior for weak grids and islanded operation [56,57], but [58] shows that controlled islanding and protection schemes remain complex for GFMIs, and unintentional islanding can create extended non-detection zones. This contradicts any simple hierarchy that places GFMIs above grid-following inverters without qualification. Third, storage is presented as a solution, yet it introduces new dependencies. Battery storage, green hydrogen, and compressed air energy storage are key enablers [49,50,94], but they bring economic, material, and environmental challenges, including capital

costs, critical mineral scarcity, and end-of-life management [63,89].

Fourth, there is a tension between job creation and a just transition. [14] emphasize job creation from solar deployment, while [91] and [90] stress the need to support workers and communities historically dependent on fossil fuels. The tension between rapid decarbonization and a just transition shapes political feasibility. Fifth, participation quantity versus quality is a contradiction. [75] show that participation can build trust, but only when it is substantive rather than tokenistic. This contradicts studies that treat participation as a binary variable and suggests that procedural trust depends on perceived influence, not merely on the existence of consultation mechanisms.

9.1.4 Research Gaps

The comparative analysis reveals four structural gaps. First, a paradigmatic gap: technical and socio-economic literatures remain siloed. Integrated models that simultaneously assess technical performance, economic viability, and social acceptance are rare. Second, a scale gap: there is a lack of multiscale frameworks that connect micro-level case studies [96,104] with macro-level scenarios [7,48] in a systematic way. Third, a methodological gap: the literature is dominated by qualitative and conceptual studies. Quantitative, longitudinal, and causal evidence on key mechanisms especially trust, justice, and participation is scarce. Many studies in Table 5 are reviews or conceptual papers; few measure the impact of specific policy interventions on objective outcomes. Fourth, a geographical and lifecycle gap: the Global South is underrepresented, and end-of-life recycling, circular economy, and material recovery are not yet integrated into mainstream deployment models [63,89].

9.1.5 The Geographical and Analytical Gap in the Solar Transition Literature: Evidence from Iran,India,and South Africa

The geographical gap in the solar energy literature extends beyond a simple quantitative shortfall and carries serious analytical and policy implications. To date, the majority of empirical studies and theoretical frameworks on solar transitions have concentrated on European and North American cases. While these studies have enriched our understanding of market-based mechanisms, ecological incentives, and participatory patterns in developed economies, their implicit assumption that these mechanisms are transferable to different institutional, economic, and social contexts is problematic. Developing countries face a set of structural constraints that render them distinct natural laboratories for solar transitions: chronic electricity deficits, fossil fuel subsidies that distort the true cost of solar energy, institutional distrust, and deep income inequalities that render technology access profoundly inequitable.

Evidence from Iran, India, and South Africa three developing countries from three different continents demonstrates that governance mechanisms, institutional constraints, and social acceptance dynamics differ fundamentally from European patterns. These three countries were selected as representative cases because each embodies a distinct model of solar transition: Iran with a state-centric model and institutional trust deficits, India with a combination of government incentives and industrial self-sufficiency mandates, and South Africa with a market-driven model and a crisis of unequal access.

Iran has a centralized governance system in which the Renewable Energy and Energy Efficiency Organization (SATBA) is the primary policy-making body and regulator of feed-in tariffs. The restored 20-year feed-in tariff, indexed to foreign-exchange rates, removes off-taker risk and shields returns from devaluation [16]. SATBA has granted permits exceeding 29 GW, creating a substantial development pipeline. However, Iran's installed solar capacity in 2025 was approximately 2.5 GW, and subsidized fossil fuel pricing with electricity priced near USD 0.04 per kWh distorts the economics of solar, keeping solar LCOE at a premium especially for residential customers [16]. [17] shows that the current PV business model in Iran in which 100% of generated electricity is fed into the grid and adopters have no right to direct consumption reinforces the perception of PV adoption as a contribution to electricity production, traditionally seen as a state responsibility, and is exacerbated by a pervasive lack of trust in state institutions.

India has adopted a dual approach: on the one hand, extensive financial incentives through the PM Surya Ghar program (with a budget of ₹75,021 crore and a target of 10 million households), and on the other hand, industrial self-sufficiency mandates (DCR/ALMM) that keep domestic panel prices 5–6 cents per watt higher than imported panels. This price differential translates to an increase of ₹0.30–0.40 per unit in plain vanilla solar tariffs from the current level of ₹2.5 per unit [18]. As of December 2025, approximately 23.9 lakh households have adopted rooftop solar under this program, generating 7 GW of clean power [19].

South Africa faces a market-driven model with bottom-up growth. Rooftop solar capacity surged from approximately 1,000 MW in 2022 to around 6,800 MW by mid-2025, supported by a decline of 82% in loadshedding during the first half of 2025 compared to the same period in 2024 [20]. National average electricity tariffs have risen 190% since 2014, mostly above inflation, with the projected 2026 hike (8.76%) exceeding the 4.5% CPI forecast [20]. [21] find that while solar adoption increased at an annual rate of 140% between 2016 and 2023, it was 73 times more prevalent in wealthy, predominantly white census tracts than in census tracts with predominantly Black African, Colored, and Indian populations (3.5 m² vs. 0.048 m² per person). Household solar adoption was close to zero in census tracts with income levels just above or below the poverty line, whereas high-income tracts installed nearly 2 panels per household on average [21].

The table 6 presents these differences comparatively and with precise citation of sources:

Table 6. Comparative Table: Solar Transition in Three Developing Countries

Comparison Dimension	Iran	India	South Africa
Dominant Governance Mechanism	Centralized and state-led; SATBA is the primary policy-making and regulatory body for feed-in tariffs (FiTs) (Mordor Intelligence, 2025; Aghlimoghadam, 2025)	Combination of extensive government incentives and industrial self-sufficiency mandates (DCR/ALMM) (CareEdge Ratings, 2025)	Market-driven with limited government intervention; bottom-up growth predominantly by the private sector (Venter et al., 2025)
Primary Adoption Driver	Electricity deficit and fuel shortage for thermal power plants; guaranteed purchase rate higher than subsidized residential tariff (Mordor Intelligence, 2025)	PM Surya Ghar program with a budget of ₹75,021 crore and a target of 10 million households (Economic Times, 2025)	Load shedding crisis and a 190% increase in electricity tariffs since 2014 (CSIR, 2025; Venter et al., 2025)
Current Capacity	2.5 GW (2025); SATBA has granted permits exceeding 29 GW (Mordor Intelligence, 2025)	23.9 lakh households installed; 7 GW of rooftop capacity (Economic Times, 2025)	~6,800 MW embedded rooftop PV by mid-2025 (CSIR, 2025)
Dominant Business Model	100% of generated electricity is fed into the grid; adopters have no right to direct consumption (Aghlimoghadam, 2025)	CAPEX model with government subsidy; CFA up to ₹78,000 for 3 kW (PIB, 2025)	Private and market-driven; no direct government subsidy (Venter et al., 2025)
Social Acceptance Pattern	Widespread institutional distrust; PV adoption perceived as "helping with government duties" (Aghlimoghadam, 2025)	23.9 lakh households installed; 7.7 lakh households with zero bills (Economic Times, 2025)	Adoption close to zero in census tracts near the poverty line; nearly 2 panels per household in high-income tracts (Venter et al., 2025)
Key Barriers	Lack of a prosumption-based business model; legal prohibition of direct solar electricity consumption (Aghlimoghadam, 2025)	DCR requirements: price gap of 5–6 cents/Wp between DCR and non-DCR modules; ₹0.30–0.40/unit tariff increase (CareEdge Ratings, 2025)	Income inequality: adoption is 73 times more prevalent in wealthy census tracts than in low-income areas (Venter et al., 2025)
Key Research Gap	Lack of quantitative studies on the relationship between institutional distrust and non-adoption of the FiT model (Aghlimoghadam, 2025)	Lack of systematic evaluation of the actual cost of DCR requirements on consumer adoption (CareEdge Ratings, 2025)	Lack of longitudinal analysis on the sustainability of adoption after the load shedding crisis subsides (Venter et al., 2025)

This comparison reveals three key findings with important theoretical and policy implications for the energy transition literature:

First, contrary to conventional wisdom in the European literature, the primary driver of solar adoption in these countries is not climate policy but energy crises and electricity deficits. In Iran, subsidized fossil fuel pricing at approximately USD 0.04 per kWh distorts the economics of solar, keeping solar LCOE at a premium especially for residential customers [16]. In India, the PM Surya Ghar program, with an allocation of ₹75,021 crore, has been the primary driver of rooftop solar growth, with 23.9 lakh households adopting systems generating 7 GW of clean power by December 2025 [19]. In South Africa, although the load shedding crisis was the initial catalyst, [21] demonstrate that "energy insecurity" is not a strong predictor of adoption; rather, it is income inequality that determines the adoption pattern, with household solar adoption being close to zero in census tracts with income levels just above or below the poverty line, whereas high-income tracts installed nearly 2 panels per household on average. This finding stands in direct contrast to the implicit assumption in the European literature and demonstrates that existing analytical frameworks are inadequate for explaining dynamics in developing countries.

Second, industrial self-sufficiency mandates in developing countries can become barriers to adoption. India's DCR and ALMM policies create a price gap of 5–6 cents per watt between DCR-compliant and non-DCR modules, which [18] estimates will push plain vanilla solar tariffs higher by ₹0.30–0.40 per unit from the prevailing level of ₹2.5 per unit. This contradiction between industrial objectives (Atmanirbhar Bharat) and climate objectives creates a "policy trap" that is rarely addressed in the European literature.

Third, intra-country access inequality deepens the energy justice gap. In South Africa, [21] found that solar adoption

was 73 times more prevalent in wealthy, predominantly white census tracts than in census tracts with predominantly Black African, Colored, and Indian populations (3.5 m^2 vs. 0.048 m^2 per person), despite income differences between high- and low-income groups being approximately fivefold. In Iran, although grid access is nearly universal, the current business model in which adopters have no right to direct consumption of their solar electricity undermines individual incentives for adoption and fuels institutional distrust [17].

On this basis, the existing literature is not only geographically incomplete but its analytical frameworks are also inadequate for explaining the specific dynamics of developing countries including the role of energy crises as adoption drivers, the interaction of industrial policies with climate objectives, and the importance of institutional trust. Future research should incorporate these dynamics as independent analytical categories into theoretical frameworks, rather than merely treating them as "context" or "limitations."

9.1.6Toward an Integrated, Multiscale, and Evidence-Based Framework

To move beyond fragmentation, future research should be restructured around three axes. First, paradigm integration: interdisciplinary projects that bring engineers, economists, sociologists, and policy scholars together from the outset. For example, evaluating Agri-PV should simultaneously assess technical potential, farmer revenue models, local employment effects, and social acceptance within one unified model. Second, scale bridging: analytical frameworks and modeling tools that explicitly integrate qualitative case-study data with macro-quantitative scenarios to identify pathways for transferring policy and knowledge across governance levels. Third, quantifying key mechanisms: operationalizing trust, justice, and participation through valid quantitative indicators and conducting longitudinal studies that measure the impact of specific policies such as early stakeholder engagement or transparent benefit-sharing on these indicators over time. In sum, the existing literature illuminates important pieces of the solar energy puzzle, but it does not yet provide an integrated picture. The task is not to produce more isolated studies but to build theoretical, methodological, and practical linkages across silos. A sustainable solar transition requires governance that is as sensitive to social fabric, local institutions, and trust-building mechanisms as it is to optimizing the solar cell itself.

9.2 An Explicit Smart Governance Framework for Photovoltaic Transitions

The "smart governance" concept introduced in Section 1 is presented here in an explicit, structured form rather than as a general aspiration. The framework comprises three interacting pillars, each with defined mechanisms and indicators, that together are intended to close the paradigmatic, scale, and methodological gaps identified in Section 9.1.4.

Pillar 1 - Technical-Operational Governance: institutional mandates for grid codes that require grid-forming capability at defined PV penetration thresholds; coordinated planning of storage capacity using penetration-dependent benchmarks (Section 5.4b); and mandatory lifecycle/end-of-life recycling standards for PV modules (Section 5.4c). Indicators: share of grid-forming capacity installed, storage-to-peak-load ratio, and module recycling rate.

Pillar 2 - Economic-Institutional Governance: stable, long-horizon policy instruments (feed-in tariffs, auctions, carbon pricing, renewable portfolio standards; Section 6.1 and Section 7.1) combined with transparent regulatory review cycles that reduce abrupt policy change [66,67]. Indicators: policy-stability index, investment volume per unit of installed capacity, and permitting lead time.

Pillar 3 - Social-Trust Governance: institutionalized, non-tokenistic public participation mechanisms; transparent benefit-sharing arrangements; and routine measurement of the three trust dimensions defined in Section 6.2.1 using the validated instruments summarized in Section 6.2.2. Indicators: institutional-, technological-, and procedural-trust scores, and the share of projects with documented community benefit-sharing agreements.

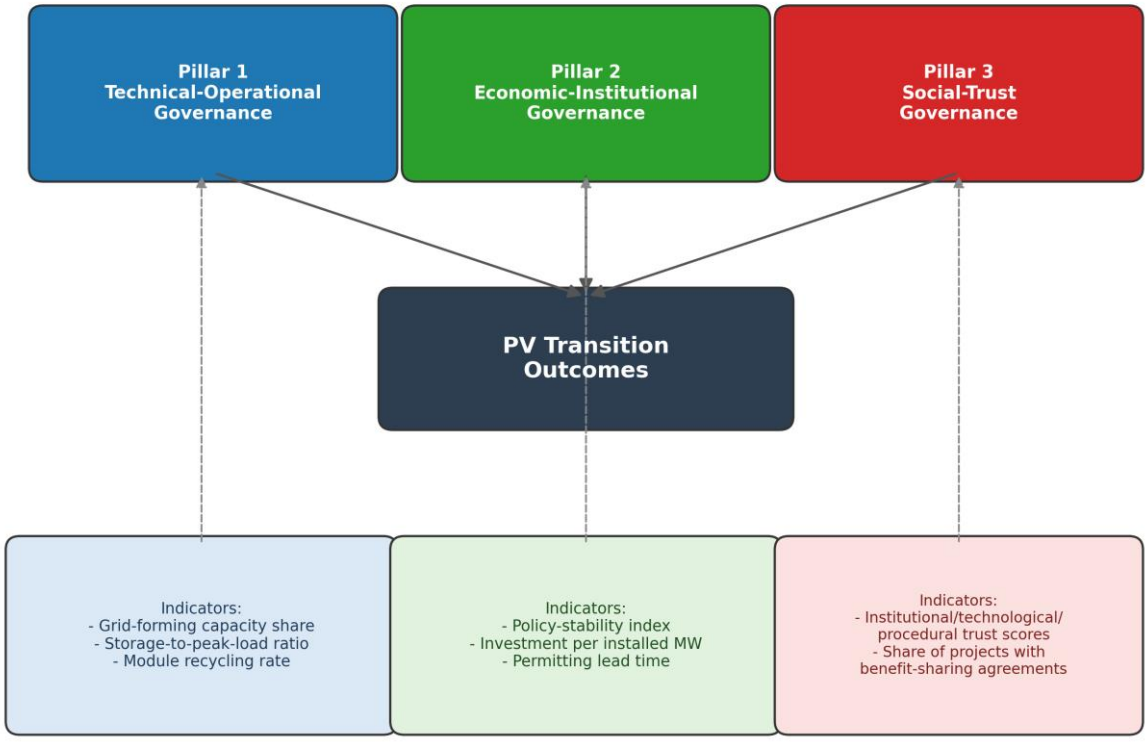

Fig 9. The Three-Pillar Smart Governance Framework for Photovoltaic Transitions

The three pillars are designed to operate jointly rather than sequentially: a policy that scores well on the Economic-Institutional pillar but neglects the Social-Trust pillar (e.g., top-down auctions without local engagement) would, under this framework, be flagged as an incomplete governance response, consistent with the paradigmatic gap identified in Section 9.1.4. Operationalizing the framework in this way also directly addresses the scale gap, because the same three-pillar structure can be applied consistently from municipal (e.g., [104]) to national (e.g., [83]) to multinational levels, and the methodological gap, because each pillar is attached to measurable indicators rather than remaining a purely conceptual construct. Testing the framework empirically-for example, by scoring the case studies in Table 5 against the twelve indicators above-is identified as a priority for future quantitative research (Section 10).

10. Conclusion

This systematic review, synthesizing evidence published between 2015 and 2025, demonstrates that photovoltaics (PV) has become a fully competitive source of electricity generation. The global weighted-average levelized cost of energy (LCOE) for utility-scale solar declined from approximately USD 0.371/kWh in 2010 to USD 0.043/kWh in 2024, while battery storage costs fell from about USD 1000/kWh to USD 130/kWh. Technologically, crystalline silicon remains dominant, while third-generation technologies such as perovskites offer higher efficiency potential, subject to resolving long-term stability challenges. Socio-economic benefits include job creation, enhanced energy security, reduced exposure to fuel price volatility, and improved public health through lower air pollution. Environmental advantages are evident in life-cycle greenhouse gas emissions and water consumption, which are substantially lower than those of fossil fuels and nuclear power. However, the variable nature of solar generation creates grid integration challenges, including the duck curve phenomenon and a nonlinear increase in storage requirements at higher penetration levels. Addressing these challenges requires grid-forming inverters, battery storage, smart grids, and demand-side management. Governance and public trust are also critical determinants of deployment success; policy stability, institutional credibility, and procedural fairness shape social acceptance. In this context, solar policy should be understood as socio-technical governance, not merely technology diffusion.

The practical implications of these findings are relevant to multiple stakeholders. Policymakers should prioritize stable and predictable regulatory frameworks, including carbon pricing, renewable portfolio standards, streamlined permitting, and proactive grid planning, while managing a just transition for communities dependent on fossil fuels. Industry and investors should adopt integrated strategies that combine PV deployment with storage, smart grids, next-generation manufacturing, and end-of-life recycling. Project developers and local communities should treat meaningful participation, transparent benefit-sharing, and early engagement as essential conditions for project viability, not optional additions. In short, solar policy should be understood and implemented as socio-technical governance, not merely technology diffusion.

The comparative analysis of Iran, India, and South Africa in this study shows that existing analytical frameworks in European-American literature are inadequate for explaining the specific dynamics of developing countries. In Iran, the centralized governance system centered on SATBA has established a 20-year feed-in tariff and permits exceeding 29 GW; however, installed capacity in 2025 was about 2.5 GW, and subsidized fossil fuel pricing with electricity at around USD 0.04/kWh makes solar economics unattractive,

especially for residential customers. The current business model of 100% grid injection and prohibition of direct consumption reinforces the perception of PV adoption as "helping with government duties" and exacerbates institutional distrust. In India, the PM Surya Ghar program with a budget of 75,021 crore rupees and a target of 10 million households has been the primary driver of rooftop solar growth; however, industrial self-sufficiency mandates (DCR/ALMM) have created a price gap of 5–6 cents per watt and an increase of 0.30–0.40 per unit in tariffs. As of December 2025, 23.9 lakh (2.39 million) households have adopted, generating 7 GW. In South Africa, the market-driven model has increased rooftop capacity from about 1,000 MW in 2022 to around 6,800 MW by mid-2025, and load shedding in the first half of 2025 decreased by 82% compared to the same period in 2024; however, tariffs have risen by 190% since 2014, and adoption in wealthy areas is 73 times that of low-income areas (3.5 vs. 0.048 m² per person). This comparison shows that the primary driver of adoption in these countries is not climate policy but energy crises and electricity deficits; industrial requirements can become a "policy trap"; and access inequality deepens the energy justice gap.

Finally, future research should address several gaps: quantitative longitudinal studies to test causal relationships between policy instruments and outcomes such as public trust, willingness to participate, and adoption rates; integrated multiscale frameworks to link micro-level evidence with macro-level scenarios; circular economy pathways for PV, including design for recycling and critical material recovery; and techno-economic modeling of hybrid systems, long-duration storage, green hydrogen, and applications of AI and digital twins. A just transition and energy justice should also be treated as empirical research questions, not merely normative considerations. Achieving widespread solar deployment depends on coordinated progress in technology, economics, infrastructure, and governance, with particular attention to institutional trust, inclusive participation, and the specific dynamics of developing countries.

11. Limitations and Future Work

While this paper provides a comprehensive overview of the current state and future trajectory of solar energy, it is important to acknowledge its limitations, which in turn open avenues for future research.

Limitations:

Scope of Analysis: This review has maintained a global perspective. However, the economic viability, policy effectiveness, and grid integration challenges of solar power are highly region-specific, influenced by local geography, market structure, and regulatory frameworks. A detailed country-level or regional analysis, such as the specific transition challenges faced by lignite-dependent areas, was beyond the scope of this work .

Technological Focus: The discussion on technology, while covering major trends, did not delve into the granular physics or manufacturing processes. Similarly, the complexities of power electronics, such as the advanced control strategies for grid-forming inverters critical for grid modernization, were addressed at a high level .

Externalities and Life-Cycle Analysis: While we touched upon life-cycle emissions and water use, a full Life-Cycle Assessment (LCA) also includes factors like land use impact, mineral resource depletion, and end-of-life recycling challenges. A deeper quantitative analysis of these externalities, particularly evaluating frameworks for product stewardship of end-of-life modules, is needed for a complete picture of solar's sustainability profile .

Avenues for Future Research:

Based on these limitations, several critical areas for future investigation emerge:

1.Circular Economy for Photovoltaics: With the first wave of solar panels approaching their end-of-life, developing efficient and economically viable recycling processes is paramount. Research into "design for recycling," recovery of critical raw materials, and establishing a circular supply chain for the solar industry, as highlighted by life-cycle assessments of end-of-life modules, is urgently needed [89].

2.Hybrid Energy Systems and Long-Duration Storage: Future work should focus on the techno-economic modeling of hybrid systems that combine solar PV with other renewables, energy storage, and green hydrogen production. A key area is exploring the frontiers of energy storage technologies to address both short-term variability and the need for long-duration storage to ensure grid reliability [88,93,106].

3.Socio-Political Dimensions and a Just Transition: The transition to solar power is not merely a technological challenge but a social one. Future studies should explore social acceptance, equitable distribution of benefits ("energy justice"), and the political economy of the transition. Investigating the workforce transition, including reskilling programs and projecting job creation in the renewable sector, is a critical research gap [13,14,92,107-111].

AI and Digitalization in Solar Asset Management: Research into the application of Artificial Intelligence (AI), IoT, and digital twins for predictive maintenance [112,113], advanced forecasting of solar generation, and real-time grid optimization can unlock significant and resilient global energy system powered by the sun.

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