CHAPTER 2

REVIEW OF LITERATURE

2.1 Introduction

This chapter presents a comprehensive literature review on key aspects relevant to the research, focusing on multiple dimensions of solar photovoltaic (PV) energy systems. The review covers: (i) Solar photovoltaic (PV) energy systems, including applications such as rooftop solar installations, ground-mounted projects, solar irrigation, and EV charging integration; (ii) GHG emissions and lifecycle assessment (LCA), evaluating the environmental sustainability of solar PV systems; (iii) Mathematical modeling techniques, investigating quantitative approaches for solar energy estimation, energy yield prediction, and system optimization; (iv) Tools for solar energy assessment, exploring geographic information system (GIS) methodologies and the Python PVLib library for precise performance modeling; (v) Barriers and enablers for large-scale deployment, identifying policy, financial, and technological challenges, along with strategies to drive widespread adoption; and (vi) Economic analysis and business models, covering techno-economic assessment methods such as net present value (NPV), levelized cost of electricity (LCOE), and payback period (PBP), as well as business models integrating government policies and financial incentives. This literature review aims to synthesize existing research, identify knowledge gaps, and establish a strong foundation for the proposed study, contributing to the optimization of solar energy deployment in rural Assam while ensuring environmental and economic sustainability.

2.2 Solar photovoltaic energy systems

2.2.1 Overview of solar PV technology

Solar photovoltaic (PV) technology has evolved significantly over the years, contributing to the shift toward renewable energy. PV technology converts sunlight directly into electricity using semiconductor materials, primarily silicon-based solar cells. The efficiency and performance of PV systems have improved due to innovations in materials, cell structures, and manufacturing techniques, such as advancements in monocrystalline and polycrystalline silicon solar cells, thin-film solar cells, and emerging perovskite solar cells [1]. Advancements in module design, maximum power point tracking (MPPT) technology, and bifacial solar panels have enhanced the overall efficiency and reliability of solar PV systems. These improvements contribute to greater energy yields, reduced costs, and increased adoption across residential, commercial, and utility-scale applications [2].

Early PV systems relied on crystalline silicon cells, but innovations have led to the development of thin-film technologies and perovskite solar cells, which offer higher efficiencies and lower production costs. Now, advancements in bifacial modules, passivated emitter and rear cell (PERC) technology, and tandem solar cells have contributed to enhanced energy yields [3]. These developments, coupled with improvements in manufacturing processes and energy storage integration, have expanded the applicability of solar PV across various sectors, making it a vital component in the transition to a sustainable energy future [4].

2.2.2 Applications of solar PV in energy systems

Rooftop solar PV for residential, commercial, and industrial applications

Rooftop solar PV systems have seen widespread adoption globally, driven by their ability to enhance energy self-sufficiency and reduce grid dependence across residential, commercial, and industrial sectors [5]. These systems cater to residential, commercial, and industrial sectors by reducing grid dependency and ensuring energy cost savings. Residential rooftop PV installations typically range between 1 kW and 10 kW, while commercial and industrial setups often exceed 100 kW, depending on energy demand. Countries such as China, the United States, and India lead in rooftop PV deployment, with India aiming for 40 GW of rooftop solar under the National Solar Mission [6]. Economic incentives, such as net metering, subsidies, and feed-in tariffs, have significantly contributed to the adoption of these systems. Studies indicate that rooftop solar PV can achieve capacity utilization factors (CUF) between 15-20%, with performance ratios often exceeding 75%, ensuring reliable power generation in suitable climatic conditions [7]. In certain regions, high initial investment costs remain a barrier, particularly in residential applications, though innovative models such as centralized community-based installations have demonstrated potential in improving affordability and achieving cost competitiveness with grid electricity [8].

Ground-mounted solar PV systems for utility-scale deployment

Ground-mounted solar PV systems serve as a key component of utility-scale renewable energy generation, providing large-scale power output for grid integration. These installations are designed for high-capacity energy production, ranging from multi-megawatt to gigawatt-scale projects, and necessitate extensive land availability for optimal deployment [9]. Ground-mounted PV installations benefit from advanced tracking technologies that enhance energy generation by optimizing solar irradiance capture. Single-axis and dual-axis tracking systems improve panel orientation throughout the day, increasing overall efficiency and power output [10]. Countries such as China, the United States, and India dominate in utility-scale solar deployment, with large-scale projects exceeding 1 GW, such as the Bhadla Solar Park in India (2.25 GW) and the Tengger Desert Solar Park in China (1.5 GW) [11]. These installations contribute significantly to decarbonization efforts by replacing fossil fuel-based power generation, with potential reductions of over 800,000 metric tons of CO_2 emissions per gigawatt per year [12].

Solar photovoltaic water pumping systems for irrigation

Solar photovoltaic water pumping systems provide a sustainable alternative for agricultural irrigation, particularly in areas with limited grid reliability [13]. These systems are designed with varying power capacities and discharge rates, depending on solar availability, pump efficiency, and irrigation requirements [14]. Advanced technologies, such as maximum power point tracking (MPPT) controllers, enhance operational efficiency by optimizing energy utilization, making them more effective than conventional diesel-powered pumps [15]. The adoption of solar water pumping has also led to significant cost savings in irrigation while contributing to the reduction of carbon emissions, supporting both economic and environmental sustainability [16].

Integration of solar PV with EV charging infrastructure

The integration of solar photovoltaic systems with EV charging infrastructure offers a sustainable approach to reducing reliance on conventional energy sources while enhancing the efficiency of transportation electrification [17]. Solar-powered EV charging stations are being deployed in several countries, including the United States, China, and India, with major projects integrating solar canopies and battery storage to enable round-the-clock charging [18].

Solar-powered EV charging stations integrate on-site photovoltaic systems with capacities ranging from distributed generation setups to utility-scale installations. Fast-charging infrastructure demands high power input, often operating in the megawatt range to support rapid energy transfer [19]. Studies indicate that integrating PV with EV charging can enhance grid stability by reducing peak demand and promoting distributed energy resources (DER). Moreover, the combination of solar PV, battery energy storage systems (BESS), and vehicle-to-grid (V2G) technologies can significantly improve the energy efficiency and economic viability of EV infrastructure [20]. The levelized cost of electricity (LCOE) for solar-powered EV charging has been estimated at $0.118 per kWh in Sokoto, making it competitive with conventional grid electricity prices in many regions [21].

Despite the benefits, challenges such as intermittency of solar power, land and space constraints for PV installations, and initial capital costs hinder large-scale deployment. However, advancements in bidirectional charging, demand response strategies, and policy incentives, such as tax credits and subsidies, are fostering the expansion of solar-integrated EV charging infrastructure globally [22].

2.3 Tools for solar energy assessment

2.3.1 Mathematical modelling techniques for solar PV systems

Empirical models for solar energy forecasting

Empirical models, such as the Angstrom-Prescott model, employ historical weather data and site-specific solar radiation measurements to predict PV output [23]. These models rely on regression analysis to establish correlations between solar radiation and meteorological parameters. Physical models, including the Perez model and Bird model, incorporate atmospheric conditions, solar angles, and spectral characteristics to simulate solar radiation with higher accuracy [24].

Machine learning and artificial intelligence-based modelling approaches

These models have recently gained prominence in solar energy forecasting. Techniques such as artificial neural networks (ANN), support vector machines (SVM), and deep learning algorithms are being used to improve the accuracy of solar power predictions by analyzing large datasets of weather patterns and PV performance [25]. Studies indicate that AI-based models can achieve prediction accuracies exceeding 90%, making them valuable tools for real-time energy management and grid integration [26].

2.3.2 Geographic information system (GIS) for solar energy planning

GIS supports solar energy planning by combining spatial analysis and data-driven decision-making to refine site selection, resource assessment, and energy potential mapping, leading to more reliable feasibility studies. By incorporating meteorological data, land use patterns, and topographical features, GIS improves the precision of solar PV system evaluations. GIS-based modelling enables the assessment of direct normal irradiance (DNI), global horizontal irradiance (GHI), and diffuse horizontal irradiance (DHI), which are key factors in estimating the performance and output of solar PV installations [27].

Role of GIS in spatial analysis and site selection

GIS supports spatial analysis for identifying optimal locations for solar PV installations by integrating multiple factors, including solar radiation levels, land characteristics, and grid accessibility. Studies indicate that GIS-based site selection methods enhance feasibility, lower land acquisition costs, and minimize environmental impacts [28, 29].

Land suitability assessments within GIS consider slope, aspect, and infrastructure proximity. Advanced tools such as multi-criteria decision analysis (MCDA) and analytical hierarchy process (AHP) help prioritize sites based on economic and technical factors [30]. The integration of remote sensing further improves solar potential assessments, aiding decision-making in large-scale solar PV deployment [31].

GIS-based solar radiation assessment techniques

GIS-based techniques analyze solar potential by combining high-resolution spatial data, meteorological inputs, and solar radiation models. Tools such as the Solar and Wind Energy Resource Assessment (SWERA) and the Heliostat model utilize satellite imagery and ground-based measurements to estimate irradiance with an accuracy of ±5% [32]. Digital Elevation Models (DEM) refine these assessments by correcting shading effects caused by terrain, improving mapping precision [33].

Platforms like ArcGIS, QGIS, and GRASS GIS incorporate specialized methodologies such as the Solar Analyst tool and the r.sun model to calculate direct, diffuse, and global solar radiation [34]. Research suggests that GIS-based solar radiation assessments improve site selection efficiency, reduce installation costs, and enhance energy yield predictions compared to conventional methods [35].

2.3.3 PVLib Python for solar performance modelling

PVLib Python is an open-source library that provides tools for modeling and simulating the performance of PV systems. Developed and maintained by the PV research community, PVLib enables detailed calculations for solar position, irradiance modeling, and power output estimation. It integrates multiple algorithms, including the Ineichen and Perez models for irradiance decomposition and the Sandia Array Performance Model (SAPM) for module performance analysis [36, 37].

Capabilities and applications of PVLib Python in energy prediction

PVLib Python offers a framework for modeling and forecasting the energy output of photovoltaic (PV) systems under different environmental conditions. It includes various irradiance models, such as the Ineichen and Perez decomposition models, to estimate solar radiation availability with precision. These models help researchers assess the influence of cloud cover, atmospheric conditions, and seasonal changes on PV system performance, achieving an accuracy of ±5% compared to ground-based measurements [38].

A key application of PVLib is in time-series simulations, where it processes meteorological data from sources like the National Solar Radiation Database (NSRDB) and satellite-derived datasets to predict PV system output on an hourly and daily basis [39]. The library also enables the calculation of module temperature effects, performance ratio (PR), and capacity utilization factor (CUF), providing a detailed evaluation of PV system efficiency [40].

2.3.4 Decentralized energy planning and geospatial modelling

Decentralized energy planning has become a cornerstone of sustainable rural electrification strategies, particularly in regions with limited or unreliable grid access. Unlike centralized systems that rely on large-scale infrastructure, decentralized models prioritize locally available renewable energy sources, especially solar PV to meet community-specific energy demands. This approach enhances system resilience, reduces transmission losses, and supports participatory energy governance. Recent studies emphasize that decentralized energy systems are essential for achieving universal energy access under SDG 7, particularly in rural contexts [41].

Geospatial modelling serves as a vital tool in decentralized energy planning by enabling spatially explicit analyses of renewable resource availability, infrastructure feasibility, and socio-demographic demand patterns. GIS, in particular, have been employed for site suitability analysis, spatial prioritization, and infrastructure layout optimization. For instance, Sinha and

Chandel [42] conducted a GIS-based multi-criteria decision analysis (MCDA) for optimal solar PV site selection in India. Similarly, Moner-Girona et al. [43] developed an open-source geospatial toolkit for off-grid energy planning across Sub-Saharan Africa, integrating demand mapping and least-cost electrification pathways. Palit and Bandyopadhyay [44] highlighted the potential of decentralized solar mini-grids for remote Indian villages, stressing the role of spatial energy modelling in decentralized policy formulation.

In India, significant progress has been made in leveraging geospatial tools for decentralized solar deployment. For example, Jain et al. [45] integrated GIS and remote sensing data to map techno-economic solar potential across Indian districts. However, limitations remain: many studies continue to focus on either a single application (e.g., rooftop or ground-mounted systems) or lack high-resolution temporal modelling. Additionally, there is limited integration of GIS-based planning with real-time simulation tools such as Python PVLib, and inadequate consideration of life cycle environmental impacts or seasonal variation in solar output.

To address these limitations, the present research adopts an integrated, high-resolution spatio-temporal approach for decentralized solar energy planning using Python PVLib and GIS. This includes the modelling of seasonal and diurnal solar generation patterns, regional life cycle GHG emissions, and optimization of solar applications across multiple energy services—rooftop systems, ground-mounted arrays, and solar-powered water pumps—within rural Assam.

2.4 Greenhouse gas (GHG) emissions and lifecycle assessment (LCA)

2.4.1 GHG emission reduction through solar PV

The deployment of solar photovoltaic (PV) systems significantly reduces greenhouse gas (GHG) emissions by displacing fossil fuel-based power generation.

Carbon footprint of solar PV systems

Solar PV systems have a much lower carbon footprint compared to burning of oil. It was found that PV systems produce carbon footprint emission between 14-73 gCO_2-eq/kWh, while burning of oil emits around 742 gCO_2-eq/kWh [46]. These emissions vary based on factors such as PV technology type, manufacturing methods, installation location, and system lifespan.

Crystalline silicon PV modules, the most widely used in the solar industry, generate approximately 201.4 kg CO_2 per square meter over their entire life cycle, whereas the same area of thin-film technologies like cadmium telluride (CdTe) produces lower emissions, around 115.04 kg CO_2. [47]. Improvements in recycling processes and material efficiency are expected to further decrease emissions in the future.

Comparative analysis with fossil fuel-based energy sources

Research demonstrates that solar PV systems significantly reduce carbon emissions by displacing fossil-fuel-based electricity generation. A megawatt-scale solar installation contributes to substantial CO_2 mitigation, whereas coal-fired power plants of similar capacity result in considerably higher emissions [48]. Solar PV also avoids emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_x), which contribute to air pollution and acid rain. In contrast, fossil fuel power plants emit large amounts of these pollutants, leading to negative health and environmental effects [49].

Although fossil fuel plants provide continuous electricity generation, their long-term environmental and economic drawbacks surpass the challenges posed by the intermittent nature of solar energy. Advances in battery storage and grid integration are making solar PV systems increasingly practical as a primary energy source, delivering clean power at competitive costs [50].

2.4.2 Lifecycle GHG assessment of solar PV systems

Methodologies for conducting LCA

Life-cycle assessment (LCA) methodologies for solar photovoltaic (PV) systems follow standardized frameworks such as ISO 14040 and ISO 14044, ensuring systematic evaluation of environmental impacts throughout a system's lifecycle. LCA typically consists of four key phases: goal and scope definition, life cycle inventory (LCI), impact assessment (LCIA), and interpretation [51].

In the inventory analysis phase, data on material extraction, manufacturing, transportation, installation, operation, and end-of-life disposal are collected Research highlights that PV module manufacturing contributes significantly to lifecycle emissions, with silicon refinement and wafer fabrication being among the most energy-intensive stages [52].

Sensitivity and uncertainty analyses are applied to improve the accuracy of life cycle assessment (LCA) results, highlighting critical factors influencing system efficiency and end-of-life management. The adoption of circular economy strategies, including closed-loop recycling of silicon wafers and module components, enhances resource recovery and minimizes environmental impact throughout the lifecycle [53].

Environmental impact assessment of PV modules, inverters, and BOS (Balance of System) components

PV modules contribute significantly to the environmental footprint of solar energy systems, with impacts arising from raw material extraction, energy-intensive manufacturing, and end-of-life disposal. While advancements in recycling and material efficiency help mitigate these effects, optimizing production processes remains a key focus for reducing emissions and resource consumption [54].

Inverters, which convert DC power from PV modules into AC power, contribute around 5-10% of the total system emissions, largely due to semiconductor processing and electronic component manufacturing. The average lifetime of inverters ranges from 10-15 years, necessitating periodic replacements that add to the environmental burden [55].

The BOS components, including mounting structures, wiring, and transformers, contribute to the overall emissions of solar energy systems, with their impact varying based on material choices and system design. Aluminum and steel-based mounting structures are particularly energy-intensive, with recycling strategies capable of reducing emissions [56]. Advanced grid integration solutions, such as smart inverters and improved BOS designs, are being developed to enhance energy efficiency and reduce environmental impacts.

2.5 Barriers and enablers for large-scale deployment of solar PV

Policy, financial, and regulatory barriers

Inconsistent policies, absence of long-term incentives, and bureaucratic obstacles have slowed the growth of solar PV in various regions. Financial barriers, such as high initial capital investment, limited access to low-cost financing, and uncertainty in return on investment, further restrict solar deployment. Studies indicate that financing costs can account for up to

60% of the total project cost in developing nations, making government-backed subsidies and incentives crucial for accelerating adoption [57].

Technological and infrastructural constraints

Integrating large-scale solar PV into the grid presents challenges due to the intermittent nature of solar power. Advancements in battery energy storage systems (BESS) and smart grid technology are needed to address these issues. Research indicates that incorporating battery storage can improve grid stability and increase solar energy penetration. Upgrading transmission and distribution infrastructure is also necessary to support higher renewable energy input [58].

Enablers and strategies for scaling solar PV

Feed-in tariffs (FiTs), net metering, and renewable energy auctions have been effective in supporting solar PV growth. Countries such as Germany and China have expanded solar deployment through stable policy frameworks and financial incentives. Business models like solar leasing, power purchase agreements (PPAs), and community solar projects have also helped make solar PV more accessible to both consumers and businesses [59].

2.6 Economic analysis and business models for solar PV systems

2.6.1 Techno-economic assessment of solar PV systems

A techno-economic assessment of solar PV systems examines their financial feasibility, energy efficiency, and long-term sustainability. Economic viability is evaluated using key financial metrics such as net present value (NPV), levelized cost of electricity (LCOE), and payback period (PBP) [60]. As of 2025, the global LCOE for utility-scale solar PV has dropped to approximately $0.04/kWh, making it competitive with traditional energy sources. Rooftop solar PV systems generally have payback periods between 5 and 10 years, influenced by installation costs, local electricity rates, and available financial incentives [61].

Beyond economic considerations, system efficiency is assessed through performance indicators like PR and CUF. Well-maintained PV systems typically achieve PR values between 75% and 85%, reflecting effective energy conversion. CUF, which represents the actual energy output relative to installed capacity, ranges from 12% to 24%, depending on location, solar irradiance, and system design [62].

2.6.2 Business models for solar PV deployment

Business models for rooftop solar (RTS)

RTS business models primarily include self-owned systems, third-party leasing models, and power purchase agreements (PPAs). In self-owned systems, consumers invest upfront and benefit from long-term electricity savings. Leasing models allow third-party investors to install and maintain PV systems on consumer rooftops, while PPAs enable consumers to purchase electricity from solar providers at a fixed rate, often lower than grid tariffs [63].

Ground-mounted solar (GMS)

Large-scale solar farms function under diverse financing and operational models, including Independent Power Producer (IPP) agreements, corporate Power Purchase Agreements (PPAs), and government-facilitated auction mechanisms. IPPs supply electricity to utilities through long-term contracts, ensuring financial stability and predictable revenue streams. Corporate PPAs have gained traction, allowing commercial and industrial consumers to source solar power directly, reducing reliance on conventional energy sources. Competitive bidding in government-backed auctions has further optimized project costs, fostering wider adoption and cost-effective deployment of solar energy infrastructure [64].

Solar water pumping (SWP) systems

SWP models are primarily driven by government subsidies, microfinance initiatives, and pay-as-you-go (PAYG) mechanisms. Programs such as India's PM-KUSUM scheme have enabled farmers to transition from diesel-powered pumps to solar-powered systems, reducing operational costs and carbon footprints. PAYG models allow users to pay in small installments, making solar irrigation accessible to smallholder farmers [65].

Role of government schemes and financial incentives in business viability

Government policies and financial incentives have been key drivers of solar PV adoption. Measures such as feed-in tariffs (FiTs), net metering, and capital subsidies have supported both grid-connected and off-grid solar expansion. Countries like Germany and China have implemented FiTs to provide stable returns for solar investors. In developing regions, subsidy programs and concessional financing have helped make solar energy more accessible to low-income households and businesses [66]. Carbon credit mechanisms and green bonds also offer additional revenue sources, strengthening the financial viability of solar projects.

New financing approaches, such as crowdfunding and blockchain-based energy trading platforms, are emerging to support decentralized solar markets. As solar technology continues to improve and costs decline, evolving business models will play a key role in meeting global renewable energy targets and increasing energy access in underserved areas.

2.7 Summary and identification of research gaps

This chapter has reviewed the key aspects of solar PV energy systems, including technological advancements, tools for solar energy assessment, environmental impact analysis, mathematical modeling techniques, scalability challenges, and economic feasibility. The review highlights significant research gaps, particularly in the integration of GIS-based solar assessment, techno-economic evaluation of solar-powered water pumping with EV charging, and the development of business models aligned with policy frameworks. These gaps establish the foundation for the research objectives of this study, which aim to enhance solar PV deployment strategies in rural Assam while ensuring economic and environmental sustainability.

2.7.1 Identified research gaps

Despite significant progress in solar energy planning tools and methodologies, several specific research gaps persist in the context of decentralized solar deployment in rural India, particularly in Assam. These gaps are categorized as follows:

(a) Conceptual/theoretical gaps:

- Most studies lack a holistic conceptual framework that integrates spatial, temporal, environmental, and socio-economic factors for decentralized energy planning.
- There is insufficient emphasis on integrated modelling of multiple decentralized solar PV technologies (RTS, GMS, SWP) in a unified platform.
- Limited attention has been given to evaluating solar PV options in terms of life cycle greenhouse gas (GHG) emissions within regional contexts.

(b) Methodological gaps:

- Few studies employ combined GIS and Python PVLib-based frameworks that model both spatial variability and temporal generation dynamics for RTS, GMS, and SWP systems.
- Most existing models do not incorporate real-time meteorological data or adaptive modelling for climate and weather variability.
- Lack of methodological integration between solar energy potential modelling and demand-side applications, such as electric vehicle (EV) charging and water pumping.

(c) Application/implementation gaps:

- Many models fail to account for rural-specific constraints in Assam such as poor grid connectivity, land availability, and seasonal irrigation loads.
- There is a paucity of studies aligning decentralized solar PV planning with government schemes like PM-KUSUM and PM Surya Ghar in a context-sensitive manner.
- Limited development of business models that are tailored to rural energy consumers and vendors under policy-enabled environments.

The present research aims to address these gaps by developing a comprehensive geospatial tool incorporating real-world spatial and temporal data, applying it to diverse solar technologies, and aligning outcomes with existing policy frameworks to guide practical implementation in rural Assam.

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