A COMPREHENSIVE GIS-BASED FRAMEWORK FOR PHOTOVOLTAIC ENERGY PLANNING AND MANAGEMENT IN RURAL ASSAM

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CHAPTER 6

SUMMARY AND CONCLUSIONS

This research aimed to investigate a comprehensive photovoltaic energy planning and management framework for rural Assam. The study sought to develop a sustainable, data-driven approach for promoting solar energy deployment, assessing the potential benefits of PV adoption for rural communities, and analyzing the technical, economic, environmental, and policy dimensions necessary for its successful implementation.

The thesis commenced by highlighting the urgent need for sustainable and renewable energy solutions in rural Assam, particularly emphasizing solar PV systems. The region's abundant solar resources, coupled with the limitations of conventional electricity infrastructure, necessitate the adoption of sustainable energy alternatives to ensure long-term energy security, environmental sustainability, and socio-economic development. The integration of solar energy can reduce reliance on fossil fuels, lower carbon emissions, and promote rural electrification. To address these challenges, a multi-objective framework was formulated to achieve three key research objectives. These objectives were systematically pursued and successfully accomplished. A summary of the significant findings are provided below.

6.1 Assessment of solar photovoltaic potential in rural Assam

A Geographic Information System (GIS)-based analysis was conducted in conjunction with Python PVLib to estimate solar potential at the village level. The study encompassed a detailed assessment of rooftop and ground-mounted PV system potential while also evaluating greenhouse gas (GHG) emissions reduction assessment. The findings highlight the immense solar potential available in rural Assam, demonstrating that large-scale PV deployment can significantly contribute to energy accessibility while substantially reducing the region's carbon footprint. GIS played a critical role in identifying optimal locations for PV installations, thereby enabling efficient resource allocation and strategic energy planning.

Key findings from the assessment are summarised as follows:

A 10 km² area encompassing Tezpur University and 61 villages with a total of 24,606 households was analyzed to evaluate the solar energy potential.

A GIS-based land use and land cover analysis was performed using Sentinel-2A imagery, supplemented with field surveys for selected locations. Random sampling was conducted to validate data and to account for clustered spatial variations derived from the LULC analysis.

Three major land use categories were considered for PV installation (i) Rooftop solar (RTS): Household and institutional rooftops; (ii) Ground-mounted solar (GMS): Barren land and fallow land; and (iii) Solar photovoltaic water pump (SWP): Cropland designated for solar irrigation purposes.

The total estimated PV installation capacity in the study area was determined using GIS analysis, field data, and mathematical modeling. Python PVLib was subsequently utilized to compute the corresponding solar energy generation capacity.

The analysis yielded a total solar PV installation capacity of 1,374 MW, with an estimated annual generation potential of 1,612.63 GWh/year. This translates to an approximate per capita energy availability of 13,412 kWh/year, indicating substantial renewable energy potential for the region.

The individual contributions of each PV system category were as follows: (i) RTS: 208 MW; (iii) GMS: 1,153 MW; and (iii) SWP: 13 MW.

Surplus energy from SWP systems during non-irrigation periods was found to be a viable source for electric vehicle charging. Consequently, a GIS-based EV charging infrastructure plan was proposed, utilizing road network analysis to identify optimal charging locations near croplands.

The decarbonization potential of the proposed PV installations was analysed based on standard emissions assessment methodologies. The lifecycle emissions associated with PV system manufacturing, transportation, installation, operation, maintenance, and end-of-life disposal were estimated. Then, the total GHG emissions reduction achieved through PV system deployment was quantified, demonstrating the significant environmental benefits of transitioning to PV-based energy solutions. The deployment of decentralised solar PV systems within the 10 km² study area results in a substantial decarbonisation benefit of approximately 23.44 MMT per annum. Among the different PV system categories, GMS contributed the highest share (84%), followed by RTS (15%) and SWP (1%).

The results indicate that solar PV systems can serve as a sustainable energy solution for rural Assam, facilitating energy security, reducing dependence on fossil fuels, and mitigating environmental impacts through substantial GHG reductions. The integration of GIS and

Python-based modeling has provided a robust framework for solar energy potential assessment, system optimization, and strategic deployment planning.

6.2 Assessment of SWP system with integration of EV charging

Solar photovoltaic water pump (SWP) systems primarily operate during irrigation periods and remain idle when irrigation is not required. This operational characteristic results in significant underutilization of the solar PV system, leading to surplus energy generation. The surplus energy can either be fed into the electricity grid or repurposed for alternative uses, such as charging EVs. This study explores the potential for utilizing surplus solar energy for EV charging in Jhawani-3 village, located within the Bihaguri development block of Sonitpur District, Assam. A combination of realistic assumptions, literature reviews, and field data informs the analysis, providing insights into the feasibility and economic viability of this approach. SWP systems face competition from other irrigation technologies, such as Diesel Water Pumping (DWP) and Electric Water Pumping (EWP). To ensure a comprehensive evaluation, a long-term economic analysis is conducted using key financial metrics, including Net Present Value (NPV), Payback Period (PBP), and levelized cost of irrigation. Furthermore, the impact of government subsidies under initiatives like PM-KUSUM (Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan) is considered to assess the affordability and financial feasibility of SWP systems.

The findings of this study highlight several critical factors influencing the selection and viability of various irrigation pumping options. SWP systems emerge as the most energy-efficient solution because they incur no recurring energy costs, unlike DWP and EWP. In contrast, DWP relies on fossil fuels, leading to higher operational expenses due to fluctuating diesel prices. Additionally, DWP contributes to environmental pollution through greenhouse gas (GHG) emissions, making it less sustainable in the long run. EWP requires grid electricity, which, while cheaper than diesel in some cases, still incurs operational costs and is subject to fluctuations in electricity tariffs. The dependency on an unreliable or limited electricity grid can also be a challenge in rural and remote areas. Despite the operational efficiency of SWP, certain challenges hinder its widespread adoption. One of the primary barriers is the high initial capital cost, which includes PV panel installation, pump equipment, and associated infrastructure. Depreciation, interest costs, and system maintenance further add to the total cost of ownership. While government subsidies help mitigate the upfront costs, unsubsidized SWP systems remain a significant financial burden for small and marginal farmers. Moreover, operational efficiency varies due to solar energy dependency, making SWP vulnerable to weather conditions and seasonal fluctuations in solar irradiance. Unlike DWP and EWP, which can operate continuously with an assured fuel or electricity supply, SWP systems are limited to peak sunshine hours. This intermittency increases the total number of operational days required to meet irrigation demands, particularly during cloudy days or monsoon seasons when sunlight availability is reduced.

A comparative cost analysis between SWP, DWP, and EWP indicates that while DWP has the lowest initial investment, it incurs the highest long-term operational costs due to recurring fuel expenses. EWP is moderately priced but remains susceptible to fluctuating electricity costs. In contrast, SWP offers long-term financial benefits through cost savings on energy, although the high initial investment remains a significant entry barrier. To assess the long-term economic viability, a financial analysis is conducted using NPV, PBP, and LCI metrics. The NPV assessment suggests that subsidized SWP systems offer the highest profitability over the long term, followed by EWP, DWP, and non-subsidized SWP. This is primarily due to the elimination of recurring energy costs in SWP. The payback period for subsidized SWP is significantly lower than that for non-subsidized SWP, making it an attractive option under the current subsidy regime. However, DWP remains the most feasible choice for farmers looking for a low-cost, short-term irrigation solution. While SWP systems have higher capital costs, their LCI is lower than that of DWP over the long term due to zero energy costs and minimal maintenance expenses. However, in the short term, DWP and EWP may appear more cost-effective for small-scale farmers with limited capital investment capabilities.

The implementation of SWP systems in North-Eastern states like Assam faces additional economic and logistical challenges. Factors contributing to the higher benchmark costs of SWP in the region include transportation and installation costs, as the remote locations of villages increase the cost of transporting PV panels and other equipment. Additionally, limited technical expertise in the region means that maintenance and repair services for SWP, particularly DC systems, are not widely available, leading to higher repair costs and downtime. Another significant factor is the region's grid electricity pricing structure, which affects revenue generation from selling surplus PV electricity to the grid. In Assam, grid feed-in tariffs are often lower than the prevailing retail electricity rates, making grid integration a less attractive financial option.

Given the intermittent operation of SWP systems, surplus solar energy is frequently available when irrigation is not required. Instead of allowing this energy to go unused, it can be repurposed for EV charging, thereby supporting renewable energy optimization and sustainable mobility. The feasibility of integrating EV charging with SWP systems depends on several factors, including energy storage solutions, as the adoption of battery storage systems can help store surplus solar energy, ensuring that it is available for EV charging even when sunlight is not present. Additionally, favorable policies promoting net metering or feed-in tariffs can enable farmers to sell excess electricity to the grid at competitive rates, improving financial returns. Infrastructure development, particularly the establishment of community-based EV charging stations in rural areas, can incentivize farmers and local communities to transition to electric mobility solutions.

To enhance the adoption and financial feasibility of SWP systems, targeted policy interventions are necessary. Increasing capital cost subsidies under PM-KUSUM and similar programs can make SWP systems more affordable, particularly for small and marginal farmers. Establishing better tariffs for selling surplus solar energy to the grid can improve financial viability and encourage farmers to install larger PV capacities. Investing in training programs for local technicians to maintain and repair SWP systems can reduce operational disruptions and lower maintenance costs. For farmers requiring continuous irrigation, hybrid SWP systems with backup diesel or battery storage can provide an alternative, ensuring reliability even in low-sunlight conditions. Encouraging community-based solar-powered EV charging stations can contribute to rural electrification, decarbonization of transport, and increased utilization of surplus PV energy.

SWP systems present a sustainable and energy-efficient solution for irrigation, particularly for long-term and large-scale agricultural operations. However, high upfront capital costs, intermittent operation, and lack of maintenance infrastructure remain key challenges in their adoption. Subsidized SWP systems offer the best long-term financial returns, but for small-scale and short-term farming operations, DWP and EWP may remain more economically viable due to lower initial investment requirements. The integration of EV charging with SWP systems represents an innovative approach to improving renewable energy utilization and rural electrification. However, this requires supporting policies, infrastructure development, and storage solutions to maximize the benefits. A thorough cost-benefit analysis, taking into account regional constraints, subsidy scenarios, and policy frameworks, is essential for informed decision-making regarding SWP adoption. Further research should explore technological advancements in solar storage, hybrid systems, and smart grid integration to enhance the viability of SWP in diverse agro-climatic regions.

6.3 Barriers, enablers, and business models for scaling solar photovoltaic energy systems

This chapter consolidates the key findings on the challenges, facilitating factors, and business models for expanding solar PV deployment in rural Assam, with a focus on RTS and GMS systems. The study identified a range of technical, financial, regulatory, and social barriers that continue to hinder large-scale solar adoption. These include spatial and structural constraints for RTS, land acquisition challenges for GMS, high initial investment costs, limited financing options, and complexities in policy implementation. Furthermore, gaps in public awareness, resistance to technology adoption, and inadequate local technical expertise present additional obstacles to widespread deployment.

Despite these challenges, several enablers were identified that can drive the growth of solar PV systems. Government-backed incentives, such as subsidies under PM Surya Ghar and PM-KUSUM Component A, have proven instrumental in making solar energy financially viable. Additionally, improvements in PV technology, including high-efficiency modules and energy storage solutions, enhance system reliability and optimize energy generation. Financial innovations such as concessional loans, pay-as-you-go models, and community-based financing mechanisms further improve affordability and accessibility for rural consumers.

The business models formulated in this study provide structured pathways for scaling RTS and GMS deployment, ensuring economic feasibility and long-term sustainability. For RTS, the models integrate cost-reduction strategies, net metering benefits, and tariff-based financial planning to enhance revenue generation. The GMS framework, aligned with PM-KUSUM Component A, highlights opportunities for Power Purchase Agreements (PPAs), government-backed incentives, and carbon credit monetization. Sensitivity analyses on key parameters such as Capacity Utilization Factor (CUF), tariff structures, and financing terms underscore the critical role of optimized financial strategies in reducing payback periods and maximizing investment returns.

A crucial takeaway from this analysis is the necessity of stakeholder collaboration and institutional capacity building. Engaging local communities through participatory approaches, strengthening skill development programs, and leveraging digital platforms for subsidy disbursement can significantly enhance adoption rates. Furthermore, agrivoltaics offers a promising solution for addressing land constraints associated with GMS while enabling dual land use for agriculture and clean energy generation.

To ensure the successful scaling of RTS and GMS, a multi-pronged approach is required. Simplified approval processes, dynamic tariff structures, and long-term power purchase agreements can mitigate investment risks and attract private sector participation. Financial instruments such as green bonds, public-private partnerships (PPPs), and concessional financing mechanisms can further strengthen market penetration. Additionally, investments in grid modernization and energy storage technologies will be critical to enhancing grid stability and integrating decentralized solar power generation.

In summary, this study highlights a roadmap for overcoming barriers and leveraging enabling factors to scale solar PV deployment in rural Assam. The proposed business models and policy recommendations aim to support India's renewable energy ambitions while fostering economic development in under-electrified regions. Future research should focus on localized deployment strategies, innovative financing mechanisms, and emerging technologies such as blockchain and artificial intelligence (AI) for optimizing energy management and addressing climate-induced variability in solar energy generation.

6.4 Major findings of the research

The following are the major findings derived from the comprehensive analyses conducted across the different phases of this research:

- A total of 1374 MW of solar photovoltaic (SPV) potential has been estimated across 61 rural villages in Assam, comprising Ground-Mounted Solar (GMS: 84%), Rooftop Solar (RTS: 15%), and Solar-Powered Water Pumps (SWP: 1%).

- Annual solar energy generation potential from these installations is projected at approximately 1613 GWh, significantly improving per capita energy availability in the study region.

- High-resolution spatial and temporal modeling using GIS and PVLib Python has enabled village-level solar resource mapping and system simulation, accounting for local meteorological and technical variables.

- Integration of SPV with electric vehicle (EV) charging was found to be technically feasible, with SWP systems capable of generating surplus electricity for such applications.

- Life Cycle Assessment (LCA) reveals that substantial greenhouse gas (GHG) emissions can be mitigated through deployment of SPV systems in place of diesel-based or grid-based alternatives.

- The techno-economic analysis indicates favorable performance metrics (e.g., Net Present Value, Levelized Cost of Electricity) for decentralized solar solutions under current and projected policy regimes.

- Field-specific constraints such as intermittency, seasonal variability, and socio-technical barriers remain critical in the design and deployment of SPV systems.

6.5 Significant contributions to literature and practice

This research makes several contributions to both academic literature and practical energy planning:

To academic literature

- Development of an integrated spatial-temporal modeling framework using GIS and PVLib Python for village-level solar potential assessment.

- Extension of lifecycle GHG accounting methods for decentralized rural energy planning in India.

- Novel combination of solar PV for multiple end-uses (RTS, GMS, SWP) including surplus utilization in EV charging, contributing to multidimensional sustainability frameworks.

To practice

- Provides replicable methodology and open-source modeling framework for policymakers and practitioners targeting energy access in underserved regions.
- Demonstrates the feasibility and benefits of decentralized, hybrid energy solutions aligned with government schemes such as PM-KUSUM and PM Surya Ghar.
- Offers an approach to assess and visualize energy equity by mapping per capita energy availability, aiding targeted intervention in energy-deficit areas.

6.6 Recommendations to stakeholders (policy makers, practitioners, and consumers)

Based on the research outcomes, the following recommendations are proposed for key stakeholders:

Policy makers

- Strengthen financial and regulatory support under schemes such as PM-KUSUM and PM Surya Ghar to fast-track decentralized solar deployment.
- Facilitate development of regional energy plans using geospatial tools and real-time weather data integration.
- Introduce incentive structures for grid-integration of surplus energy from SWP and RTS systems, including net-metering support.

Practitioners (developers, NGOs, local bodies)

- Prioritize site-specific feasibility studies incorporating temporal and spatial modeling tools to optimize PV system design.
- Promote integration of energy storage and smart load management to mitigate temporal intermittency.
- Engage local communities in the planning and implementation phases to enhance system acceptability and longevity.

Consumers

- Raise awareness about the long-term cost savings, environmental benefits, and government incentives available for adopting SPV technologies.

- Encourage consumer participation in rooftop solar adoption under schemes like PM Surya Ghar.

- Promote local entrepreneurship in installation and maintenance of decentralized energy systems.

6.7 Limitations of present work

Despite the comprehensive nature of this study, several limitations exist due to constraints in data availability, modeling assumptions, technological factors, financial feasibility, infrastructural challenges, policy implementation, and climatic variability. These limitations are categorized as follows:

Data availability and quality

- The study relies on satellite-based and secondary datasets for solar radiation modeling due to the limited availability of high-resolution ground-measured solar radiation data for rural Assam.
- Discrepancies in dataset resolution and accuracy may affect the precision of solar potential estimations.

Modelling assumptions

- The Python PVLib and GIS-based methodologies incorporate certain assumptions that may introduce minor deviations in real-world system performance.
- Simplified assumptions regarding solar panel efficiency, degradation rates, and climatic conditions may not fully capture dynamic environmental interactions.
- The study does not incorporate real-time variations in system efficiency, which could influence long-term performance assessments.

Technological constraints

- The absence of real-time monitoring systems for solar PV and SWP installations limits the ability to validate performance under actual field conditions.

- Limited integration of advanced battery storage systems restricts surplus energy management, which could improve self-consumption and grid independence.

Climate variability

- The performance of solar PV systems is influenced by seasonal variations, cloud cover, and unpredictable weather conditions, which may reduce overall energy yield.
- Extreme weather events, such as heavy monsoons, could further impact solar energy generation and system reliability.

While these limitations present challenges, they also offer opportunities for future research, including real-time monitoring integration, enhanced modeling accuracy, and policy frameworks to improve financial accessibility and adoption in rural regions.

6.8 Conclusion and suggestions for future work

The overarching conclusions drawn from this research highlight that solar PV systems hold substantial potential for enhancing energy security and sustainability in rural Assam. The developed GIS-based framework has effectively demonstrated its capability in identifying and optimizing locations for solar energy installations, ensuring efficient resource utilization. Furthermore, the integration of SWP systems and EV charging has been found to be both feasible and beneficial, fostering synergies between the energy, agriculture, and rural transportation sectors. This study also emphasizes that addressing non-technical barriers, such as financial constraints, policy gaps, and social resistance, is crucial for the large-scale adoption of solar PV technologies. To this end, strategic recommendations include targeted government interventions, capacity-building initiatives, increased awareness campaigns, and financial support mechanisms tailored to rural communities. By offering a holistic perspective that encompasses technical, economic, and social dimensions, this study contributes significantly to the strategic planning and implementation of solar PV energy systems, which is applicable not only in rural Assam but also in other similar geographical and socio-economic contexts. The findings serve as a valuable reference for policymakers, stakeholders, and researchers seeking to advance sustainable development through renewable energy integration in underserved communities.

Future research should focus on refining solar potential modeling by incorporating real-time meteorological data, advanced satellite imagery, and AI-driven predictive models to enhance accuracy. The integration of energy storage solutions, such as advanced battery technologies and hybrid renewable energy systems combining solar PV with locally available renewable energy sources, should be explored to improve energy reliability and management. Further feasibility assessments should incorporate sensitivity analysis to evaluate the impact of policy changes and technology costs. Additionally, the potential of integrating vehicle-to-grid (V2G) technologies should be assessed to enhance grid interaction and energy efficiency. Furthermore, policy recommendations should be proposed to facilitate the scaling of solar energy adoption under dynamic market conditions. These future directions will contribute to the further evolution of the GIS-based framework, enabling a more robust, adaptive, and sustainable energy planning approach for rural regions..