# Abstract

Rising energy demands and the environmental impact of fossil fuels have increased the importance of renewable energy, particularly solar photovoltaics (PV), as a sustainable alternative. Recognizing this, the Government of India has introduced several policies and initiatives to accelerate the adoption of photovoltaics energy. However, regional disparities in energy infrastructure and hence its growth, especially in northeastern states like Assam, remain significant challenges. Solar energy uses by decentralized sectors like, residential, agricultural and commercial units have not reached its full potential. A holistic approach for the assessment vis-à-vis planning of decentralized solar energy, incorporating the realistic ground data at lifecycle scale is essential. Such assessment vis-à-vis planning is expected to contribute to promotion of solar energy in Assam (India) providing the precise information related to potential benefits of solar energy which is considered as one of the factors against its promotion. However, available tools and know-how to handle several uncertainties including spatial and seasonal variations of solar energy resources, availability of land resources for PV installation, decision of end-uses (*e.g.*, grid or off grid, individual or community, domestic or irrigation etc.), appear inadequate.

The current research work is aimed to address the above gap with the development of a geospatial framework that can incorporates the spatial and temporal factors of the region under consideration. The framework is designed to be adaptable and scalable, integrated with modular computational architecture, structured data tagged with spatial and temporal variability, and customization capabilities for region-specific application for solar PV planning. These features ensure its applicability to any region in the world, thereby offering a universal framework for decentralized solar energy planning.

The appropriately tested geo-spatial framework is successfully demonstrated to analyze the solar PV potential and related decarbonising potential across different lifecycle stages, within a representative 10 km² area encompassing 61 villages surrounding Tezpur University, Assam (India). High-resolution spatial data (land use-land cover, and solar irradiation data) are sourced from credible platform (Surface Meteorology and Solar Energy database of NASA and Google Earth Engine) for the spatial and temporal analysis. The methodology integrates advanced GIS methods for precise spatial and temporal analysis using Random Forest Classifier (RFC) and Maximum Likelihood Classification (MLC) techniques to refine LULC mapping, incorporating field survey data for validation aiming improved accuracy. Python

PVLib is used for simulating relevant system parameters (viz., Global Horizontal Irradiance, ambient temperature, and wind speed) which are verified subsequently using field data. Integration of Python PVLib also becomes useful for design of solar PV system and subsequent estimation of power outputs (AC and DC) at spatial and temporal sales. Simulated energy yields for any duration of user choices (viz., daily, monthly, and annually) are used to map performance ratio of the PV system caused by temporally varying temperature coefficients and losses like shading and soiling estimation. The best allocation of available land resources among three prevalent solar PV systems *viz*., Rooftop solar (RTS), Ground-mounted solar (GMS) and Solar photovoltaic water pump (SWP) is achieved by the geo-spatial framework. The ground level data (viz., shading, orientation, structural constraints inherent to rooftop, available barren and fallow lands and its feasibility for GMS, farmland distribution, water demand, and cropping patterns) become useful for the allocation. The simulations provide site-specific insights by modelling solar PV capacity and estimating daily, monthly, and annual energy outputs. Decarbonisation potential based on GHG emissions are quantified across five lifecycle stages viz., (i) Manufacturing phase, including raw material extraction and production of PV panels, inverters, and batteries; (ii) Transportation phase (covering emissions from transporting system components to installation sites); (iii) Installation phase (accounting for energy consumption and emissions during system setup); (iv) Operation and maintenance phase (evaluating emissions related to ongoing maintenance) and (v) End-of-life phase (addressing decommissioning, recycling, or disposal impacts).

The study region comprising 61 villages is potential for 1374 MW of SPV installations comprising of GMS (84%), RTS (15%) and SWP (1%) to contribute 1613 GWh of solar energy annually. Based on the current population of the villages, the above SPV installations would address the inadequate level of per capita energy access of the region. Spatial and temporal variations across the study area are mapped, providing a granular understanding of solar resource potential. A substantial lifetime decarbonization benefit of approximately 23.44 million metric tons (MMT) of $CO_2$ is achieved through the deployment of decentralized solar PV systems in the study area (10 $km^2$), with the largest share contributed by GMS, followed by RTS, and SWP.

Unlike RTS and GMS systems, SWP system often remains idle when irrigation is not required (*i.e.*, no-irrigation-demand period). The comparative potential economic benefits of alternative options viz., electrical vehicle (EV) charging or selling to grid during no-irrigation-demand period are also investigated using ground level data set and considering potential revenue streams under some feasible crop rotations (viz., *sali rice-strawberry-ahu rice*; and *sali rice-mustard-boro rice*) prevalent in study region. The assessment of the financial support provided by Government subsidy schemes to promote SPV is also examined using the geo-spatial framework for financial metrics such as Net Present Value (NPV), payback period (PBP), and cost of irrigation to assess economic viability. Overall, the findings support adoption of SWP and EV charging infrastructure in alignment with sustainability goals. A comparative analysis of SPV irrigation against diesel and grid-electricity-operated pumps demonstrates that although SWP systems have higher initial costs, they offer reduced operational expenses, lower emissions, and potential revenue from surplus electricity for EV charging and grid integration. Sensitivity analysis highlights the influence of crop rotations, subsidy structures, and policy frameworks on SWP adoption. This techno-economic and environmental analysis provides insights into performance, cost-effectiveness, and $CO_2$ emissions. The findings highlight SWP as a viable and sustainable irrigation solution for Assam and similar regions, contingent on appropriate financial incentives and policy support.

Barriers, enablers, and business models for scaling solar photovoltaic (PV) energy systems, focusing on RTS and GMS are also analysed. Incorporating government schemes (*viz*., *PM-Surya Ghar* for RTS and *PM-KUSUM* for GMS), the analysis evaluates financial metrics from both consumer and vendor perspectives. Scalable solutions are identified to promote SPV adoption, optimize energy access, and align with India’s climate and development goals. Key barriers grouped into five categories viz., (i) technical, (ii) financial and economic, (iii) policy and regulatory, (iv) social and awareness-related, and (v) market barriers are analysed with reference to the potential deployment of SPV in study region. Similarly, enablers such as technological advancements, government subsidies, net metering, and favorable policies are analyzed for each system pertaining to the study region.

Business viability for RTS and GMS is assessed through cost and profit analysis considering varying levels of subsidies, electricity bill savings, and net metering benefits for consumers. Vendor is a major stakeholder and therefore, profitability of vendor is also evaluated considering some prevalent scenarios. Lifecycle costs, energy generation, and long-term savings of a typical RTS installation in the study region are assessed provided. Similarly, financial analysis focused on revenue and cost estimations at varying interest rates, tariff rates, capacity utilization factor (CUF) is done for deployable GMS in the study region. Lease, loan,

and subsidy-based strategies, as well as deployment through power purchase agreements (PPAs) and energy sales are evaluated to understand the business opportunity.

In conclusion, this research develops a robust geospatial and techno-economic framework for solar energy planning with universal application. By addressing energy disparities, enhancing sustainability, and supporting policy development, the study contributes to advancing solar PV energy adoption and ensuring equitable energy access. The findings offer valuable insights for policymakers, industry stakeholders, and researchers, facilitating the transition to sustainable energy systems. The study systematically addresses its objectives, yielding significant insights into the potential and scalability of solar energy systems in rural Assam with the inherent variations of solar irradiance, module performance, and system efficiency under real-world conditions.

*Keywords: Solar photovoltaic systems, GIS-based energy planning, python PVLib, GHG emission reduction, Rooftop solar (RTS), Ground-mounted solar (GMS), Solar photovoltaic water pump (SWP), Business model.*