*Advances in Consumer Research*
https://acr-journal.com/
Volume-3 | Issue-10 |Sep: 2026

*Original Researcher Article*

# Life Cycle Carbon Mitigation Potential of Decentralized Solar Energy Systems in Rural UP: An Empirical Assessment

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**ABSTRACT**

India's transition towards low carbon energy systems has accelerated the deployment of decentralized renewable energy technologies, particularly solar photovoltaic (PV) systems, to address climate change, energy security, and rural development challenges(Bharvirkar et al. (2019), n.d.). As of 2024-25, India had achieved more than 220 GW of renewable energy capacity, with solar energy contributing over 105 GW, highlighting its growing importance in the national energy transition. However, assessing the environmental benefits of decentralized solar systems requires consideration of their complete life cycle rather than operational emission reductions alone. This study evaluates the life cycle carbon mitigation potential of decentralized solar energy systems in rural Uttar Pradesh (UP) using an empirical framework integrating life cycle assessment (LCA), household level energy analysis, and socio-economic evaluation. UP, with a population exceeding 240 million and a predominantly rural population, provides an important context for examining how distributed solar systems can reduce carbon emissions while strengthening rural energy resilience.

The study estimates embodied carbon emissions from solar PV manufacturing, transportation, installation, operation, maintenance, and end of life management and compares these with greenhouse gas emissions avoided through displaced grid electricity consumption. Primary data from rural solar adopters are combined with secondary data from government agencies, energy statistics, and published literature to estimate electricity generation, carbon savings, energy payback period, and life cycle emission intensity. The study also examines socio-economic outcomes, including reduced electricity expenditure, improved power reliability, enhanced agricultural productivity, livelihood opportunities, and community acceptance. Policy mechanisms, including the PM Surya Ghar Muft Bijli Yojana (D Patel et al., 2025), rooftop solar incentives, net metering regulations, and state level renewable energy initiatives, are analysed to identify factors influencing adoption. The study contributes empirical evidence from rural UP and supports evidence based strategies for expanding decentralized solar systems, strengthening sustainable rural development, and advancing India's long term climate objectives......

**Keywords**: Decentralized Solar Energy; Life Cycle Assessment; Carbon Mitigation; Solar Photovoltaic Systems; Rural Energy Transition; Renewable Energy Policy; UP; Sustainable Development.

## INTRODUCTION

The global energy sector is undergoing an unprecedented transformation driven by the urgent need to mitigate climate change, strengthen energy security, and achieve sustainable economic development. The energy sector accounts for nearly 73% of global GHG emissions, making decarbonization of electricity generation one of the most effective strategies for limiting global warming. At the same time, worldwide electricity demand continues to rise because of rapid urbanization, industrialization, electrification of transport, digitalization, and improvements in living standards. Consequently, renewable energy technologies have become central to national and international climate strategies. PV technology, in particular, has experienced remarkable growth owing to declining module prices, technological advancements, and supportive policy interventions. Globally, renewable energy capacity additions exceeded 580 GW in 2024, with solar PV accounting for approximately three quarters of all new renewable installations, making it the fastest growing electricity generation technology worldwide.

India has emerged as one of the world's fastest growing renewable energy markets. As the world's third largest producer and consumer of electricity, the country faces the dual challenge of satisfying rapidly increasing energy demand while simultaneously reducing its dependence on fossil fuels. India's electricity consumption has been growing at approximately 6-8% annually, driven by industrial expansion, urbanization, digital infrastructure, electric mobility, and increasing household electrification. To support sustainable economic growth while meeting its international climate commitments, India has pledged to achieve net zero carbon emissions by 2070 and has established an ambitious target of 500 GW of non-fossil-fuel-based electricity generation capacity by 2030(Choudhary & Srivastava (2020), n.d.). These commitments form a cornerstone of India's long term low carbon development strategy and are expected to significantly reshape the country's energy mix.

India's renewable energy sector has demonstrated remarkable progress during the last decade. Solar energy has emerged as the dominant contributor to this transition due to abundant solar radiation, declining technology costs, and sustained government support through programmes such as the National Solar Mission, Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan (PM-KUSUM), and the PM Surya Ghar: Muft Bijli Yojana(Jesudas & Nagarajan, 2012) (Updated-Vikas-Sheel-Bharat-Vol.-1-101-109, n.d.). According to the Central Electricity Authority (CEA), India's installed solar power capacity increased from less than 3 GW in 2014 to approximately 106 GW by March 2025, representing more than a thirty-fold increase within a decade. During FY 2024-25 alone, solar electricity generation reached nearly 144 TWh, replacing a substantial quantity of coal-based electricity and avoiding millions of tonnes of carbon dioxide emissions(Anwar et al., 2019). Renewable energy has consequently become one of the fastest growing segments of India's power sector and is expected to play an increasingly important role in meeting future electricity demand.

Within this broader transition, decentralized renewable energy (DRE) systems have attracted increasing policy and academic attention because of their ability to complement centralized electricity infrastructure(Mperejekumana et al., 2024). Decentralized solar technologies including rooftop PV systems, solar irrigation pumps, community solar plants, and village level microgrids generate electricity close to the point of consumption, thereby reducing transmission and distribution losses, improving supply reliability, and enhancing local energy resilience. Unlike conventional centralized generation, decentralized systems require comparatively lower transmission infrastructure and provide greater flexibility in serving geographically dispersed rural populations. They also contribute to productive agricultural activities, support rural enterprises, reduce electricity expenditure, and improve household energy security. Recent government initiatives promoting distributed renewable energy are expected to accelerate annual decentralized renewable capacity additions beyond 20 GW, reflecting the growing importance of localized clean energy systems in India's electricity transition (Cai et al., 2026).

The significance of decentralized solar energy is particularly evident in UP, India's most populous state, with an estimated population exceeding 240 million. The state has experienced rapid growth in electricity demand because of expanding agriculture, increasing industrialization, urban development, and improved household electrification (Rezaee & Silva, 2026). Despite considerable progress under national electrification programmes, many rural areas continue to experience challenges related to supply interruptions, voltage fluctuations, seasonal demand peaks, and affordability of electricity for agricultural and domestic consumers. Agriculture remains highly dependent on electricity for groundwater irrigation, while reliable electricity access is increasingly essential for education, healthcare, digital connectivity, and rural micro enterprises. Decentralized solar systems therefore provide an opportunity not only to reduce dependence on conventional grid electricity but also to improve rural energy resilience, reduce agricultural energy costs, and strengthen climate adaptation at the local level(Ngueko et al., 2025).

Although solar photovoltaic technology is widely recognized as a clean energy source during its operational phase, its overall environmental sustainability must be evaluated across the entire product life cycle. Greenhouse gas emissions occur during multiple stages, including extraction of raw materials, silicon purification, wafer and module manufacturing, transportation, installation, inverter production, maintenance, component replacement, and end-of-life recycling or disposal (Vellini et al., 2017). Previous international studies estimate the life cycle carbon intensity of photovoltaic electricity to range between 20 and 60 g $CO_2$ eq/kWh, depending on manufacturing technology, electricity mix, module efficiency, and recycling practices substantially lower than coal fired electricity, which typically exceeds 800-1,000 g $CO_2$ eq/kWh. Nevertheless, these upstream emissions cannot be ignored when evaluating the true climate benefits of solar energy. Consequently, LCA has become the internationally accepted methodology for quantifying the environmental impacts associated with renewable energy technologies across their complete life cycle (Radwan, n.d.).

A substantial body of literature has evaluated the technical efficiency, economic feasibility, financial viability, and policy dimensions of solar photovoltaic deployment in India. Existing studies have primarily focused on grid connected utility scale projects, rooftop solar economics, adoption barriers, or renewable energy policy implementation. However, relatively few empirical studies have integrated life cycle carbon assessment with household level socio-economic outcomes and policy effectiveness, particularly in rural regions of northern India. Furthermore, evidence concerning the net carbon mitigation potential of decentralized solar systems under the socio-economic, institutional, and infrastructural conditions prevailing in UP remains limited (Minx et al., 2009). The absence of integrated assessments constrains policymakers' ability to quantify the environmental and developmental benefits of decentralized renewable energy investments.

This study addresses these research gaps by developing a comprehensive empirical framework to evaluate the life cycle carbon mitigation potential of decentralized solar energy systems in rural UP. The research integrates LCA, household level socio-economic analysis, and policy evaluation to estimate net carbon emission reductions while simultaneously assessing improvements in energy access, household welfare, agricultural productivity, and institutional effectiveness (Haroon & Hayyat, 2025). By combining environmental and socio-economic dimensions within a unified analytical framework, the study contributes to the growing literature on decentralized renewable energy and provides evidence based recommendations for policymakers seeking to accelerate India's low carbon transition. The findings are expected to support the design of more effective renewable energy policies that maximize both, thereby advancing national commitments towards sustainable energy, climate resilience, and long-term carbon neutrality (Lipper & Cavatassi, 2024).

## 2. Literature Review

### 2.1 Decentralized Solar Energy and Low Carbon Energy Transition

The global transition towards renewable energy has accelerated significantly over the past decade due to increasing concerns regarding climate change, energy security, and the adverse environmental impacts associated with fossil fuel based electricity generation. The energy sector is responsible for nearly 73% of GHG emissions, making the decarbonization of electricity systems a central component of global climate mitigation strategies (Pleßmann & Blechinger, 2017). International commitments under the Paris Agreement (2015) and the United Nations Sustainable Development Goals (SDGs) have encouraged countries to expand renewable energy deployment while improving energy efficiency and ensuring universal access to affordable and clean energy (Sorooshian, 2024). According to the International Renewable Energy Agency (IRENA), global renewable energy capacity additions exceeded 580 GW in 2024, with PV technology accounting for approximately 75% of newly installed renewable capacity (Di Silvestre et al., 2018). Declining module prices, technological advancements, supportive policy frameworks, and increasing private sector investment have positioned solar PV as the fastest growing renewable electricity technology worldwide.

Among various renewable energy technologies, solar photovoltaic systems have gained widespread acceptance because of their modularity, scalability, declining installation costs, and suitability for both grid connected and off grid applications. Unlike conventional centralized electricity generation, which relies on large power plants and extensive transmission infrastructure, decentralized solar energy systems generate electricity near the point of consumption. This distributed approach reduces transmission and distribution losses, enhances grid reliability, minimizes infrastructure costs, and improves electricity access in geographically dispersed and underserved regions. Decentralized solar technologies including rooftop solar photovoltaic systems, solar irrigation pumps, solar powered microgrids, and community based solar plants have become increasingly important in supporting rural electrification, agricultural productivity, and local economic development while simultaneously reducing dependence on fossil fuel based electricity generation.

India's energy transition strategy has increasingly emphasized Decentralized Renewable Energy (DRE) as a complementary pathway to utility scale renewable energy expansion. As the world's third largest electricity producer and consumer, India faces rapidly growing electricity demand driven by population growth, urbanization, industrialization, digitalization, and agricultural modernization. To address these challenges while fulfilling its climate commitments, the Government of India has adopted ambitious renewable energy targets, including achieving 500 GW of non-fossil fuel electricity capacity by 2030 and net zero carbon emissions by 2070. Solar energy has emerged as the cornerstone of this transition, with installed solar capacity increasing from less than 3 GW in 2014 to approximately 106 GW by March 2025, representing one of the fastest rates of renewable energy expansion globally.

Several flagship government programmes have accelerated the adoption of decentralized solar technologies across residential, agricultural, and commercial sectors. The Jawaharlal Nehru National Solar Mission (JNNSM) laid the foundation for large scale solar deployment, while the Rooftop Solar Programme promoted distributed generation among residential and institutional consumers (Rajawat, 2018). Similarly, PM-KUSUM has facilitated the installation of solar powered irrigation pumps and decentralized solar power plants, reducing farmers' dependence on grid electricity and diesel powered irrigation. More recently, the PM Surya Ghar: Muft Bijli Yojana, launched in February 2024, represents one of the world's largest residential rooftop solar initiatives (Shankar & Bukya, 2023). The scheme aims to install rooftop solar systems in one crore (10 million) households with an approved financial outlay of ₹75,021 crore, providing central financial assistance of up to ₹78,000 for eligible residential consumers. The programme is expected to generate approximately 30 GW of rooftop solar capacity, produce nearly 1,000 billion units (kWh) of clean electricity over 25 years, and reduce annual carbon dioxide emissions by millions of tonnes while lowering household electricity expenditure and creating substantial employment opportunities in manufacturing, installation, and maintenance.

Despite these considerable environmental advantages during electricity generation, the sustainability of decentralized solar systems cannot be evaluated solely based on their operational performance. Although photovoltaic systems produce negligible direct greenhouse gas emissions while generating electricity, significant environmental impacts occur throughout their life cycle. Carbon emissions are associated with raw material extraction, silicon purification, wafer and cell manufacturing, module assembly, transportation, installation, inverter production, balance of system components, periodic maintenance, component replacement, and end-of-life recycling or disposal (Miller et al., 2019). These upstream and downstream processes contribute to the embodied carbon footprint of photovoltaic systems. International studies estimate the life cycle carbon intensity of solar photovoltaic electricity to range between 20 and 60 g $CO_2$ equivalent per kWh, depending on manufacturing technology, electricity mix, module efficiency, geographical conditions, and recycling practices (Khan et al., 2024). Although substantially lower than coal fired electricity which typically emits 800-1,000 g $CO_2$ equivalent per kWh these emissions must be incorporated into environmental evaluations to obtain a realistic estimate of the net climate benefits of decentralized solar deployment.

Consequently, LCA has emerged as the internationally accepted methodology for evaluating the environmental performance of renewable energy technologies across their complete life cycle (Weisser, 2007). LCA systematically quantifies energy consumption, material use, greenhouse gas emissions, and other environmental impacts from raw material extraction through manufacturing, operation, maintenance, and end of life management. For decentralized solar energy systems, LCA provides a scientifically robust framework to estimate net carbon mitigation potential while identifying stages responsible for the highest environmental burdens (Sadhukhan, 2022). Such comprehensive assessment is particularly important in rapidly expanding solar markets like India, where manufacturing practices, supply chains, recycling infrastructure, and policy interventions continue to evolve. Integrating life cycle carbon assessment with socio-economic and policy analysis therefore provides a more holistic understanding of the contribution of decentralized solar energy to India's low carbon energy transition and long term sustainable development objectives.

**Table 1: Major Research Themes in Decentralized Solar Energy Literature**

| Research Theme | Major Findings | Research Limitation |
|---|---|---|
| Solar PV carbon footprint | Solar PV significantly reduces operational emissions compared with coal-based electricity | Regional life cycle variation requires further assessment |
| Life cycle assessment | Manufacturing stage contributes major share of embodied emissions | Limited India specific rural studies |
| Distributed energy systems | Improves energy reliability and reduces grid dependency | Environmental benefits often not quantified |
| Rural solar adoption | Supports livelihood improvement and energy access | Carbon mitigation link remains underexplored |
| Solar policy analysis | Subsidies and financing accelerate adoption | Implementation barriers affect outcomes |

2.2 Life Cycle Carbon Assessment of Solar Photovoltaic Systems

LCA has become the internationally accepted methodology for evaluating the environmental sustainability of renewable energy technologies because it considers environmental impacts across the entire life span of a product rather than focusing solely on its operational phase (Adiansyah et al., 2025). The International Organization for Standardization (ISO 14040 and ISO 14044) defines LCA as a systematic approach for assessing the inputs, outputs, and potential environmental impacts associated with all stages of a product's life cycle from raw material extraction and manufacturing to transportation, installation, operation, maintenance, and end of life disposal or recycling (Pérez Rodríguez et al., 2025). For PV systems, LCA provides a comprehensive framework for quantifying GHG emissions, energy consumption, resource utilization, and environmental trade-offs throughout the complete value chain. Such assessments are particularly important because, although solar PV systems generate electricity without direct emissions during operation, considerable embodied emissions are associated with the production and deployment of photovoltaic technologies.

The life cycle of a typical solar PV system consists of several interconnected stages. These include mining and processing of raw materials such as silica, aluminum, copper, and silver; purification of silicon; wafer, cell, and module manufacturing; transportation of components; installation of mounting structures, inverters, and electrical accessories; operation and periodic maintenance; replacement of components such as inverters; and finally, decommissioning, recycling, or disposal at the end of the system's useful life (V. M. Fthenakis & Kim, 2011). Among these stages, module manufacturing is generally the largest contributor, accounting for nearly 60-80% of the total life cycle greenhouse gas emissions, primarily because silicon purification and wafer production are highly energy intensive processes. Consequently, the carbon intensity of photovoltaic systems depends not only on manufacturing technology but also on the electricity mix of the country where the modules are produced. Manufacturing facilities powered predominantly by coal-based electricity generally exhibit higher embodied carbon than those supplied by cleaner energy sources.

Numerous international studies have consistently demonstrated that solar PV systems produce substantially lower life cycle greenhouse gas emissions than conventional fossil fuel-based electricity generation. Recent meta-analyses estimate that crystalline silicon photovoltaic systems typically emit between 20 and 60 g $CO_2$ equivalent ($CO_2$ eq) per kilowatt hour (kWh) of electricity generated over their operational lifetime. The variation arises from differences in manufacturing location, module efficiency, solar irradiation levels, system lifetime, technological improvements, and recycling assumptions. Thin film photovoltaic technologies generally exhibit slightly lower life cycle emissions, although crystalline silicon modules continue to dominate the global market because of their higher efficiency, longer operational life, and greater commercial availability (V. Fthenakis, 2009). In contrast, conventional coal fired electricity generation produces approximately 800-1,000 g $CO_2$ eq/kWh, while natural gas based electricity generation emits around 400-500 g $CO_2$ eq/kWh. Thus, even after accounting for embodied emissions, solar photovoltaic systems reduce life cycle greenhouse gas emissions by more than 90-95% compared with coal based electricity generation, highlighting their substantial climate mitigation potential (Martulli et al., 2025).

The importance of life cycle carbon assessment is particularly pronounced in India because the country's electricity system remains heavily dependent on coal. Despite rapid expansion of renewable energy, coal continues to contribute nearly 70-72% of India's total electricity generation, resulting in a relatively high grid emission intensity. According to the CEA, the weighted average emission factor of the Indian electricity grid is approximately 0.70 kg $CO_2$ per kWh, although this value is expected to decline gradually as renewable energy penetration increases and older coal fired power plants are replaced by cleaner generation technologies (Neymark & Judkoff, 2002). Under such conditions, every unit of electricity generated through decentralized solar photovoltaic systems directly offsets electricity that would otherwise be supplied by a carbon intensive grid. Consequently, decentralized solar deployment offers significant opportunities for reducing greenhouse gas emissions while simultaneously improving energy security and reducing dependence on fossil fuels.

The carbon mitigation potential of decentralized solar systems is particularly relevant for rural states such as UP, where electricity demand is increasing because of agricultural mechanization, rural electrification, and expanding household consumption. A typical 1 kW rooftop solar photovoltaic system installed under prevailing climatic conditions in UP can generate approximately 1,300-1,500 kWh of electricity annually, depending on solar irradiance, panel orientation, module efficiency, temperature, shading conditions, and maintenance practices. Assuming that this electricity displaces grid power with an emission factor of approximately 0.70 kg $CO_2$/kWh, the system can avoid nearly 900-1,100 kg of carbon dioxide emissions every year. Considering an operational lifetime of 25 years, cumulative avoided emissions exceed 22-27 tonnes of $CO_2$, even after accounting for embodied emissions associated with manufacturing, transportation, installation, maintenance, inverter replacement, and end of life management. Moreover, improvements in module efficiency, increased use of renewable electricity during manufacturing, and enhanced recycling technologies are expected to further reduce the life cycle carbon intensity of photovoltaic systems in the coming decades.

Beyond greenhouse gas mitigation, LCA also enables evaluation of broader environmental indicators such as cumulative energy demand, resource depletion, water consumption, acidification potential, and waste generation (Wiesen & Wirges, 2017). Such comprehensive assessments help identify stages within the photovoltaic supply chain that require technological improvement or policy intervention. For example, increasing domestic manufacturing powered by renewable electricity, promoting circular economy practices for photovoltaic waste recycling, extending module service life beyond 25 years, and improving recovery of valuable materials such as silicon, aluminum, silver, and copper can significantly reduce the environmental footprint of solar energy systems. Therefore, integrating life cycle carbon assessment into renewable energy planning provides policymakers with robust scientific evidence for designing sustainable energy policies. In the context of India's clean energy transition, LCA not only quantifies the actual climate benefits of decentralized solar deployment but also supports informed decision making aimed at maximizing long-term environmental sustainability, resource efficiency, and progress toward national net zero emission targets.

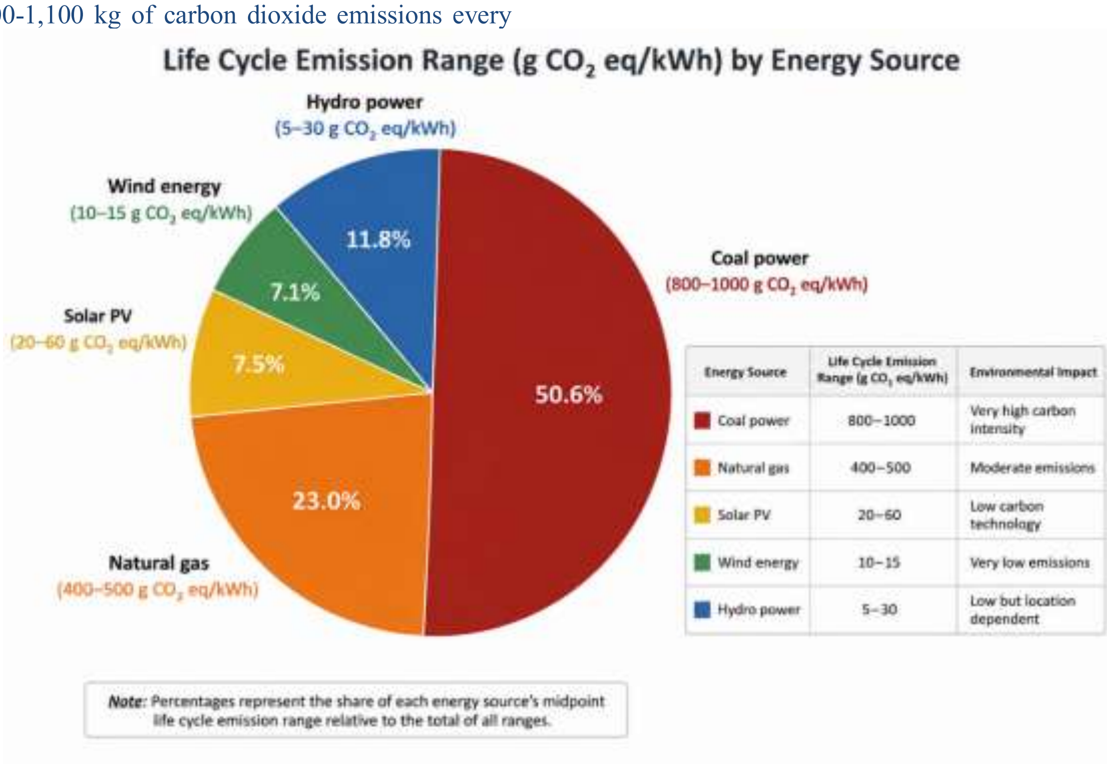



**Figure 1: Comparative Life Cycle Emission Characteristics of Electricity Technologies**

### 2.3 Environmental Benefits of Decentralized Solar Adoption in Rural Areas

Rural areas represent an important application domain for decentralized solar systems because electricity demand is often dispersed and grid infrastructure expansion can be economically challenging. Solar rooftop systems, solar irrigation pumps, and community solar installations can reduce dependence on fossil fuel-based electricity while supporting sustainable rural development (Rumbayan et al., 2025).

### 2.4 Socio-Economic Dimensions Supporting Environmental Sustainability

Although this research primarily focuses on environmental benefits, socio-economic factors influence the sustainability and adoption of decentralized solar systems. Energy transition is not only a technological process but also a social process influenced by affordability, awareness, financing availability, and user acceptance. Studies indicate that households adopting solar energy experience reduced electricity expenditure, improved electricity reliability, increased productive use of electricity, improved agricultural productivity, and enhanced rural entrepreneurship opportunities. These socio-economic improvements indirectly strengthen environmental outcomes by increasing acceptance and long-term operation of renewable energy systems. For rural UP, where agriculture remains a major economic activity, solar irrigation systems represent an important pathway for reducing diesel consumption and associated emissions. Similarly, rooftop solar adoption under government programmes can improve household energy independence while contributing to national carbon reduction objectives.

**Table 2: Socio-Economic Factors Influencing Environmental Outcomes**

| Factor | Influence on Solar Adoption | Environmental Link |
|---|---|---|
| Household income | Determines investment capability | Higher adoption leads to greater emission reduction |
| Awareness level | Improves technology acceptance | Supports sustainable energy behaviour |
| Financing availability | Reduces initial investment barriers | Accelerates renewable deployment |
| Electricity reliability | Encourages solar adoption | Reduces fossil fuel backup use |
| Agricultural dependence | Increases solar pump demand | Reduces diesel emissions |

### 2.5 Policy Perspective: Enabling Carbon Mitigation Through Solar Deployment

Government policies play a critical role in accelerating decentralized solar adoption and achieving environmental objectives (Kishore et al., 2025). India's renewable energy policy framework has progressively shifted from centralized solar parks towards distributed generation models. Important policy interventions include:

**National Solar Mission:** The National Solar Mission established the foundation for large scale solar development in India.

**PM-KUSUM Scheme:** The scheme promotes solarization of agricultural pumps, enabling farmers to reduce diesel dependence and generate clean electricity.

**PM Surya Ghar Muft Bijli Yojana:** The scheme represents a major policy shift towards household level renewable energy adoption. It targets one crore residential rooftop solar installations and aims to provide affordable clean electricity while reducing carbon emissions.

**Net Metering Policies:** Net metering enables households to export surplus electricity to the grid, improving economic feasibility and encouraging renewable adoption.

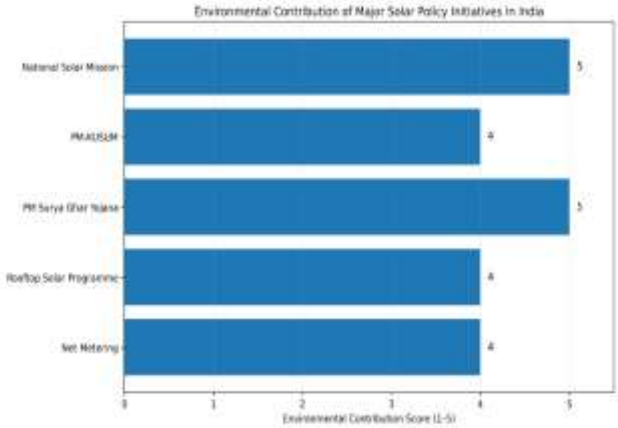



**Figure 2: Policy Instruments Supporting Decentralized Solar Development in India**

Research Gap

The rapid expansion of decentralized solar energy systems has created significant opportunities for reducing greenhouse gas emissions, enhancing energy security, and supporting low carbon development pathways across developing economies. PV technology has become one of the most promising renewable energy solutions due to its declining installation costs, technological maturity, modular design, and ability to provide electricity in both grids connected and off-grid settings. Numerous international studies have established that solar PV systems generate substantially lower life cycle greenhouse gas emissions than conventional fossil fuel-based electricity generation, making them an important component of national and global climate mitigation strategies (V. M. Fthenakis & Kim, 2007). Consequently, governments across the world, including India, have increasingly promoted decentralized renewable energy (DRE) systems through supportive policies, financial incentives, and institutional reforms aimed at accelerating the clean energy transition. Despite this growing body of literature, existing research has predominantly focused on global or national level assessments, technical performance evaluation, techno-economic feasibility, and policy analysis. Most studies examine photovoltaic efficiency, electricity generation potential, cost benefit analysis, investment viability, or the effectiveness of renewable energy incentive programmes. While these investigations have significantly improved understanding of solar energy deployment, relatively limited attention has been devoted to evaluating the actual life cycle carbon mitigation potential of decentralized solar systems under specific regional conditions. Environmental benefits are often estimated using generalized emission factors or international datasets that may not accurately represent local climatic conditions, electricity grid characteristics, manufacturing supply chains, or household energy consumption patterns (Ismaeel et al., 2026). As a result, the true carbon reduction potential of decentralized solar systems in developing regions remains inadequately understood.

This limitation is particularly relevant in the context of UP, India's most populous state, where electricity demand continues to increase due to rapid population growth, agricultural modernization, urbanization, and industrial development. Although the state has made substantial progress in rural electrification, electricity generation remains heavily dependent on coal based thermal power, resulting in relatively high carbon emissions from the power sector. Government programmes such as the PM Surya Ghar: Muft Bijli Yojana, PM-KUSUM, and state level rooftop solar initiatives are expected to significantly increase decentralized solar installations over the coming years. However, empirical evidence quantifying the environmental benefits of these systems under the socio-economic and climatic conditions of UP remains scarce. Understanding the actual carbon mitigation potential of decentralized solar adoption is therefore essential for designing effective renewable energy policies and evaluating progress towards India's net zero emission commitments.

Although previous studies provide valuable insights into renewable energy transitions, three major environmental research gaps remain unresolved. First, there is a lack of region-specific life cycle carbon assessment of decentralized solar photovoltaic systems. Most existing LCA studies rely on international databases or generalized assumptions regarding module manufacturing, electricity generation, system performance, and operational lifetime. Such assumptions may not accurately capture India's electricity emission factor, local solar radiation conditions, maintenance practices, or technological characteristics. Consequently, estimates of carbon mitigation potential may differ substantially from actual field conditions in rural UP. Second, limited research integrates environmental assessment with household level empirical evidence. Existing studies generally estimate carbon savings using engineering models or secondary datasets without incorporating primary information from rural households regarding electricity consumption, solar generation, appliance usage, energy substitution, and system performance. This disconnect between engineering analysis and field level observations restricts a comprehensive understanding of the real environmental outcomes of decentralized solar adoption (Schelly et al., 2021).

Third, there is insufficient integration of life cycle carbon assessment with socio-economic and policy evaluation. Previous research has often examined environmental impacts, economic benefits, and policy implementation independently rather than within a unified analytical framework. Consequently, little empirical evidence exists regarding how life cycle carbon mitigation interacts with household welfare, energy security, rural livelihoods, adoption barriers, institutional support mechanisms, and government incentive programmes. Such integrated assessments are essential for developing evidence-based policies that maximize both environmental sustainability and inclusive rural development. The present study addresses these research gaps by developing a comprehensive framework that combines LCA, household level empirical analysis, and policy evaluation to estimate the net carbon mitigation potential of decentralized solar energy systems in rural UP. By integrating environmental, socio-economic, and institutional dimensions, the study provides a more realistic and region specific assessment of decentralized solar deployment and contributes to the growing literature on sustainable energy transitions in developing economies.

### 3.1: Limited Region-Specific Life Cycle Carbon Assessment of Decentralized Solar Systems

Existing literature on solar photovoltaic LCA primarily focuses on global, national level, or utility scale solar installations. Many studies estimate carbon emissions based on generalized assumptions regarding solar module manufacturing, transportation, irradiation levels, system efficiency, and electricity displacement factors (Luo et al., 2026). However, such approaches may not accurately represent the environmental performance of decentralized solar systems operating under specific regional conditions. The life cycle carbon footprint of solar PV systems varies significantly depending on geographical location, solar radiation availability, electricity generation efficiency, system configuration, technology type, and the carbon intensity of displaced grid electricity. In India, particularly in states such as UP, these factors require localized evaluation because electricity generation continues to rely heavily on coal-based power plants with comparatively higher emission intensity.

Existing studies have rarely incorporated location specific parameters such as:

UP's solar irradiation conditions,

Local household electricity consumption patterns,

State specific grid emission factors,

Rural rooftop solar system characteristics,

Operational performance degradation over system lifetime.

As a result, the actual carbon mitigation potential of decentralized solar systems in rural UP remains insufficiently quantified. This research addresses this gap by developing a region-specific life cycle assessment framework that considers the complete environmental pathway of decentralized solar systems, including embodied emissions from manufacturing, transportation, installation, operation, maintenance, and end-of-life management. The study provides empirical estimates of net carbon reduction rather than relying only on theoretical emission avoidance calculations (Hao et al., 2025).

**3.2 Insufficient Assessment of Complete Life Cycle Environmental Impacts Beyond Operational Emission Reduction**

A major limitation in the existing renewable energy literature is the tendency to evaluate the environmental benefits of PV systems primarily on the basis of operational emission reductions, while giving comparatively less attention to emissions generated throughout the complete life cycle of technology. Solar PV systems are frequently described as "zero emission" or "carbon free" because they do not produce direct GHG emissions during electricity generation (F. Wang et al., 2022). Although this characterization is valid for the operational phase, it overlooks the substantial environmental impacts associated with the extraction of raw materials, manufacturing processes, transportation, installation, maintenance, component replacement, and end of life management. Consequently, assessments that focus only on operational performance may overestimate the actual climate benefits of decentralized solar deployment and provide an incomplete basis for policy formulation.

LCA offers a more comprehensive approach by evaluating environmental impacts from cradle to grave, encompassing every stage from raw material extraction to final disposal or recycling. In the case of photovoltaic systems, environmental burdens begin with the mining and processing of silica, bauxite, copper, silver, and other minerals required for module production. These raw materials undergo energy intensive industrial processes such as silicon purification, ingot casting, wafer production, photovoltaic cell fabrication, module assembly, glass manufacturing, encapsulation, and aluminium frame production. Studies indicate that these manufacturing activities account for approximately 60–80% of the total life cycle greenhouse gas emissions associated with crystalline silicon PV systems, primarily because they require substantial electricity and thermal energy inputs. When manufacturing occurs in countries where electricity generation is predominantly coal based, the embodied carbon of PV modules increases significantly.

In addition to module production, other balance of system components also contributes to the environmental footprint of decentralized solar installations. These include aluminium mounting structures, galvanized steel supports, copper wiring, junction boxes, inverters, batteries (where applicable), and electronic monitoring equipment. Transportation of photovoltaic modules and associated equipment from manufacturing facilities to installation sites further generates carbon emissions through fuel consumption and logistics operations. Although transportation generally contributes a relatively small proportion of total life cycle emissions, its significance increases in geographically dispersed rural installations where logistics networks are less efficient. Similarly, installation activities involving construction materials, civil works, machinery operation, and labour related transportation introduce additional embodied emissions that are often excluded from simplified carbon accounting approaches.

Environmental impacts continue throughout the operational lifetime of the system. While photovoltaic modules require comparatively low maintenance, periodic cleaning, inverter replacement, wiring repairs, and occasional component upgrades involve additional material and energy consumption (Abdulla et al., 2025). Most inverters have an operational life of approximately 10-15 years, requiring at least one replacement during the typical 25-year lifetime of a rooftop solar system. Furthermore, end-of-life management presents an emerging environmental challenge. As early generations of photovoltaic installations approach retirement, increasing quantities of solar waste containing glass, aluminium, silicon, polymers, and trace metals will require environmentally responsible recycling or disposal. According to projections by the International Renewable Energy Agency (IRENA), global photovoltaic waste could exceed 70 million tonnes by 2050, highlighting the importance of incorporating recycling and waste management into life cycle assessments. Failure to recover valuable materials not only increases environmental impacts but also reduces resource efficiency and circular economy potential.

Despite these considerations, many existing studies estimate only the avoided carbon emissions resulting from displacement of fossil fuel-based electricity generation while neglecting embodied emissions associated with manufacturing, transportation, installation, maintenance, and disposal. Such simplified approaches assume that every unit of solar electricity directly replaces grid electricity without considering the environmental costs incurred before electricity generation begins. Consequently, estimates of net carbon mitigation potential may be either overestimated or underestimated depending on assumptions regarding module manufacturing location, electricity mix, technological efficiency, system degradation, operational lifetime, and recycling practices. This uncertainty is particularly relevant in India, where a substantial proportion of photovoltaic modules are imported or manufactured using electricity generated from fossil fuel-based grids.

Another important limitation in literature is the inadequate consideration of key environmental performance indicators beyond simple emission avoidance. Limited empirical research has comprehensively evaluated parameters such as carbon payback period, energy payback time, life cycle greenhouse gas emission intensity, cumulative avoided emissions over the system lifetime, and sensitivity of carbon mitigation potential under changing electricity grid emission factors. Carbon payback period (CPBP) indicates the time required for a solar PV system to offset the emissions generated during its manufacture and installation through clean electricity generation (Chun et al., 2026). Energy payback time (EPBT) measures the period necessary for the system to generate the amount of energy consumed during its production and deployment. Similarly, life cycle emission intensity (expressed as g $CO_2$ eq/kWh) enables meaningful comparison between different electricity generation technologies under standardized conditions. As India's electricity grid gradually decarbonizes through increasing renewable energy penetration, the quantity of emissions displaced by each unit of solar electricity will also change, making sensitivity analysis an essential component of future oriented carbon assessments.

These environmental indicators are particularly important for decentralized rural solar systems, which differ considerably from utility scale solar farms in terms of system size, installation design, operating conditions, maintenance practices, and utilization patterns. Household rooftop systems generally have higher per unit installation material requirements, decentralized logistics, varying maintenance quality, and differences in electricity consumption behaviour. Seasonal variations in agricultural electricity demand, household appliance usage, and solar irradiation also influence annual electricity generation and carbon mitigation potential. Consequently, carbon assessment methodologies developed for large utility scale projects cannot be directly applied to decentralized rural systems without appropriate contextual adaptation.

The present study addresses these limitations by adopting a cradle to grave life cycle assessment framework for decentralized solar photovoltaic systems in rural UP. Rather than considering only operational emission reductions, the study incorporates embodied emissions associated with manufacturing, transportation, installation, operation, maintenance, component replacement, and end of life management. Furthermore, it evaluates carbon payback period, cumulative avoided emissions, life cycle emission intensity, and sensitivity under alternative electricity grid emission scenarios. By integrating these environmental indicators into a comprehensive analytical framework, the research provides a more realistic and scientifically robust estimate of the long-term climate mitigation contribution of decentralized solar energy systems.

### 3.3 Lack of Empirical Evidence Linking Decentralized Solar Adoption Scale with Regional Carbon Mitigation Potential

Another significant research gap concerns the limited empirical understanding of how decentralized solar energy adoption at the household and community levels translates into measurable regional carbon mitigation outcomes. During the past decade, India has experienced rapid growth in decentralized renewable energy through rooftop solar programmes, agricultural solar pumps, village microgrids, and residential photovoltaic systems. Government initiatives such as the PM Surya Ghar: Muft Bijli Yojana, PM KUSUM, and the Rooftop Solar Programme have substantially accelerated the installation of distributed solar capacity. However, while national statistics regularly report cumulative installed capacity and electricity generation, relatively little empirical evidence exists regarding the actual environmental benefits achieved through decentralized adoption under local conditions.

Most previous studies examine either individual solar installations or national renewable energy capacity expansion without establishing a clear relationship between decentralized adoption patterns and cumulative regional carbon mitigation. Engineering based assessments often estimate avoided emissions by multiplying installed capacity with average electricity generation and grid emission factors. Although such calculations provide useful approximations, they fail to capture the considerable variation that exists among rural households in terms of electricity consumption, system utilization, maintenance practices, appliance ownership, seasonal demand, and dependence on grid electricity. Consequently, regional carbon mitigation estimates derived solely from installed capacity may not accurately represent actual environmental outcomes (Yan & Xiang, 2026).

In rural UP, decentralized solar deployment occurs under highly diverse socio-economic and environmental conditions. Household electricity demand varies according to income, occupation, family size, agricultural activities, appliance ownership, and access to reliable grid electricity. Similarly, the performance of rooftop photovoltaic systems depends on multiple technical factors, including installed capacity, module orientation, solar irradiation, shading, inverter efficiency, system degradation, and maintenance quality. Seasonal changes in weather conditions and agricultural electricity demand further influence annual electricity generation. Therefore, a 1 kW rooftop solar system installed in one household may generate substantially different quantities of electricity and consequently different levels of carbon mitigation than an identical system installed elsewhere. Such heterogeneity cannot be adequately represented through generalized assumptions based only on installed capacity.

Furthermore, relatively few empirical studies have developed analytical models linking solar adoption levels, actual electricity generation, displacement of fossil fuel based electricity, and cumulative carbon emission reductions using household level data. Most available research relies on simulation models or secondary datasets rather than integrating field-based evidence with environmental assessment. This limitation reduces confidence in regional carbon estimates and restricts policymakers' ability to evaluate the effectiveness of decentralized renewable energy programmes. Without empirical evidence demonstrating how individual household adoption collectively contributes to district level or state level emission reductions, planning future investments and designing targeted incentive programmes becomes more challenging.

The absence of robust empirical models also limits the assessment of policy effectiveness. Programmes promoting decentralized solar adoption are expected not only to increase installed capacity but also to contribute meaningfully towards India's climate commitments under the Paris Agreement and its long-term net zero 2070 objective (Kumar Rathoure, n.d.). However, policymakers require reliable evidence regarding the extent to which financial incentives, subsidy programmes, consumer behaviour, and technology adoption influence cumulative regional carbon mitigation. Quantifying these relationships is essential for optimizing resource allocation, prioritizing high impact interventions, and monitoring progress towards low carbon development goals.

The present research addresses this important gap by combining household level primary survey data, technical performance information, and secondary electricity sector datasets to estimate the aggregate carbon mitigation potential of decentralized solar systems in rural UP. Instead of relying exclusively on theoretical assumptions, the study incorporates actual household electricity consumption, installed solar capacity, electricity generation, and grid electricity displacement into the estimation framework. The research further develops an empirical relationship between decentralized solar adoption, avoided fossil fuel-based electricity generation, and cumulative carbon emission reduction at the regional level. By integrating environmental modelling with field based evidence, this study provides a scientifically robust and policy relevant framework for understanding how widespread decentralized solar adoption contributes to regional climate mitigation, sustainable rural development, and India's long term low carbon energy transition.

**Summary of Identified Research Gaps:**

**Table 3: illustrate the Summary of Research Gaps**

| Gap No. | Identified Environmental Research Gap | Limitation in Existing Studies | Contribution of Present Study |
|---|---|---|---|
| Gap 1 | Lack of region specific LCA of decentralized solar systems | Mostly generalized/global assumptions | Develops UP specific carbon assessment |
| Gap 2 | Limited cradle to grave environmental assessment | Focus mainly on operational emission savings | Includes embodied carbon, payback period, and lifetime impacts |
| Gap 3 | Limited empirical linkage between adoption and carbon mitigation | Capacity based estimates dominate | Uses household level data for realistic emission reduction estimation |

**Research Objectives**

Based on the identified environmental research gaps, the objectives of this study are:

To quantify the life cycle carbon mitigation potential of decentralized solar energy systems in rural UP by developing a region-specific assessment framework incorporating embodied emissions, operational benefits, and avoided grid electricity emissions.

To evaluate the cradle to grave environmental performance of decentralized solar PV systems by estimating life cycle carbon emissions, carbon payback period, energy payback time, and long term greenhouse gas reduction potential.

To empirically assess the relationship between decentralized solar adoption levels and cumulative carbon emission reductions at the rural household and regional levels in UP using primary and secondary energy data.

6. LCA Framework

**6.1 Conceptual Framework of Life Cycle Assessment**

LCA is a scientifically established methodology used to evaluate the environmental impacts associated with a product, process, or technology throughout its entire life cycle. Unlike conventional environmental assessments that focus only on the operational phase, LCA provides a comprehensive perspective by considering environmental burdens from the extraction of raw materials to final disposal or recycling (Ullah et al., 2025). The methodology is internationally standardized under ISO 14040:2006 and ISO 14044:2006, which define the principles, framework, requirements, and guidelines for conducting life cycle assessments (Ersoy et al., 2025)

The LCA methodology has become one of the most widely accepted tools for assessing the sustainability of renewable energy technologies because it captures both the environmental costs associated with technology production and the environmental benefits achieved during operation. Rather than considering renewable energy systems as inherently carbon neutral, LCA recognizes that GHG emissions occur throughout every stage of the technology's life cycle (Cherubini et al., 2009). These emissions arise from material extraction, manufacturing processes, transportation, construction activities, maintenance operations, component replacement, and end-of-life waste management. Consequently, the environmental performance of renewable energy systems is evaluated using a holistic perspective that quantifies both embodied emissions and operational environmental benefits.

In the context of decentralized PV systems, LCA provides an appropriate analytical framework for estimating the actual carbon mitigation potential of distributed renewable energy technologies. Solar photovoltaic systems are widely recognized as clean energy technologies because electricity generation occurs without direct combustion of fossil fuels and therefore produces virtually zero operational greenhouse gas emissions. However, the production of photovoltaic modules involves several energy intensive industrial processes that contribute to the overall carbon footprint of the technology (De Wild-Scholten, 2013). These include mining and processing of silica, aluminum, copper, and silver; purification of metallurgical grade silicon into solar grade silicon; ingot casting; wafer production; photovoltaic cell fabrication; module assembly; glass manufacturing; encapsulation; and production of aluminium frames and junction boxes. Previous international studies indicate that module manufacturing alone contributes approximately 60–80% of total life cycle greenhouse gas emissions associated with crystalline silicon photovoltaic systems(Gerbinet et al., 2014).

Beyond module manufacturing, additional environmental impacts arise from the production of balance of system (BoS) components, including inverters, mounting structures, electrical wiring, transformers, batteries (where applicable), and monitoring equipment. Transportation of modules and ancillary equipment from manufacturing facilities to installation sites requires fuel consumption and logistics infrastructure, thereby contributing additional carbon emissions. Installation activities involving civil works, mounting structures, machinery operation, and labour related transportation also generate embodied emissions. During the operational phase, photovoltaic systems require periodic cleaning, inspection, inverter replacement, wiring maintenance, and occasional component upgrades, all of which contribute to cumulative life cycle impacts. Finally, end-of-life management through dismantling, recycling, or disposal introduces further environmental implications that are becoming increasingly important as early generations of photovoltaic systems approach retirement (V. M. Fthenakis, 2000).

These considerations demonstrate that the environmental sustainability of decentralized solar systems cannot be assessed solely on the basis of operational electricity generation. Instead, both environmental costs (embodied emissions) and environmental benefits (avoided emissions from replacing fossil fuel based electricity) must be evaluated simultaneously to estimate the net climate mitigation contribution of solar technologies. LCA therefore provides a scientifically robust framework for comparing decentralized solar energy with conventional electricity generation while identifying stages responsible for the highest environmental impacts. The present study adopts a cradle to grave Life Cycle Assessment approach to evaluate the environmental performance of decentralized solar photovoltaic systems installed in rural UP. The assessment quantifies greenhouse gas emissions generated throughout the complete life cycle of household and community level solar installations and compares them with the emissions avoided by displacing conventional grid electricity. By incorporating regional electricity emission factors, local climatic conditions, system performance characteristics, and operational assumptions, the framework provides a realistic estimate of the long term carbon mitigation potential of decentralized solar deployment (Jing et al., 2022). The adoption of this comprehensive LCA framework also facilitates evidence-based policy recommendations for improving the environmental sustainability of distributed renewable energy systems in India.

### 6.2 Goal and Scope Definition

The first phase of an ISO compliant LCA is the definition of the goal and scope, which establishes the purpose, system boundaries, assumptions, functional unit, and environmental indicators to be considered during the assessment. Clearly defining the scope is essential for ensuring methodological consistency, transparency, and comparability of results.

The primary objective of the present study is to estimate the net life cycle carbon mitigation potential of decentralized solar photovoltaic systems deployed in rural UP. The study seeks to quantify the greenhouse gas emissions associated with the manufacture, transportation, installation, operation, maintenance, and end of life management of decentralized solar systems and compare these emissions with the carbon emissions avoided through the displacement of conventional grid electricity (Elnaggar et al., 2026). In addition to estimating total life cycle emissions, the study evaluates life cycle emission intensity, cumulative avoided emissions, and the overall environmental contribution of decentralized solar energy towards India's low carbon transition.

The assessment focuses specifically on household level rooftop solar photovoltaic systems and small community based solar installations, as these technologies represent the fastest growing segment of India's decentralized renewable energy sector. Government initiatives such as the PM Surya Ghar: Muft Bijli Yojana, PM-KUSUM, and state level rooftop solar programmes have significantly accelerated the deployment of small scale distributed solar systems, particularly in rural and semi urban regions. Evaluating these systems is therefore important for understanding their contribution to regional carbon mitigation and sustainable rural electrification.

To enable comparison between decentralized solar electricity and conventional electricity generation, the study adopts the following functional unit:

"One kilowatt hour (1 kWh) of electricity generated from decentralized solar photovoltaic systems over the system's operational lifetime."

The functional unit serves as the reference basis for all life cycle calculations and allows meaningful comparison of greenhouse gas emission intensity across different electricity generation technologies(Huber et al., 2023). Expressing emissions in terms of grams of carbon dioxide equivalent per kilowatt hour (g $CO_2$ eq/kWh) facilitates comparison with coal based, natural gas based, hydroelectric, wind, and other renewable energy technologies.

The system boundary follows a cradle to grave approach, incorporating all major stages that contribute to the environmental performance of decentralized solar PV systems. The assessment includes:

Raw Material Extraction: Mining and processing of silica, aluminium, copper, silver, glass, polymers, and other materials required for photovoltaic module production.

Photovoltaic Module Manufacturing: Silicon purification, ingot production, wafer manufacturing, solar cell fabrication, module assembly, encapsulation, and frame production.

Balance of System Components: Manufacturing of inverters, mounting structures, electrical cables, connectors, junction boxes, monitoring equipment, and other auxiliary components required for system operation.

Transportation: Transportation of photovoltaic modules and balance of system components from manufacturing facilities to installation sites, including associated fuel consumption and logistics emissions.

Installation: Civil works, mounting structure installation, electrical integration, commissioning activities, machinery use, and installation related energy consumption.

Operation and Maintenance: Routine inspection, module cleaning, maintenance activities, system monitoring, performance degradation, and operational energy requirements throughout the system lifetime.

Inverter Replacement: Production, transportation, installation, and disposal of replacement inverters, which typically require replacement once during a 25-year operational period.

End-of-life Management: Decommissioning, dismantling, transportation of waste materials, recycling, material recovery, and environmentally responsible disposal of photovoltaic components.

The assessment primarily focuses on greenhouse gas emissions, expressed as carbon dioxide equivalent ($CO_2$ eq), because carbon mitigation represents the principal environmental objective of decentralized solar deployment. Other environmental indicators such as water consumption, land use, toxicity, acidification, and resource depletion are acknowledged but remain outside the scope of the present study. Similarly, indirect socio-economic impacts including employment generation, income enhancement, energy affordability, and social welfare improvements are analysed separately in subsequent chapters rather than within the environmental life cycle framework (Tang et al., 2025). By defining a clear functional unit, comprehensive system boundaries, and an ISO compliant analytical framework, this study establishes a rigorous basis for estimating the net life cycle carbon mitigation potential of decentralized solar photovoltaic systems in rural UP. The framework not only improves the accuracy of carbon accounting but also provides a scientifically robust foundation for evaluating the environmental effectiveness of distributed renewable energy programmes and supporting evidence-based climate and energy policy.

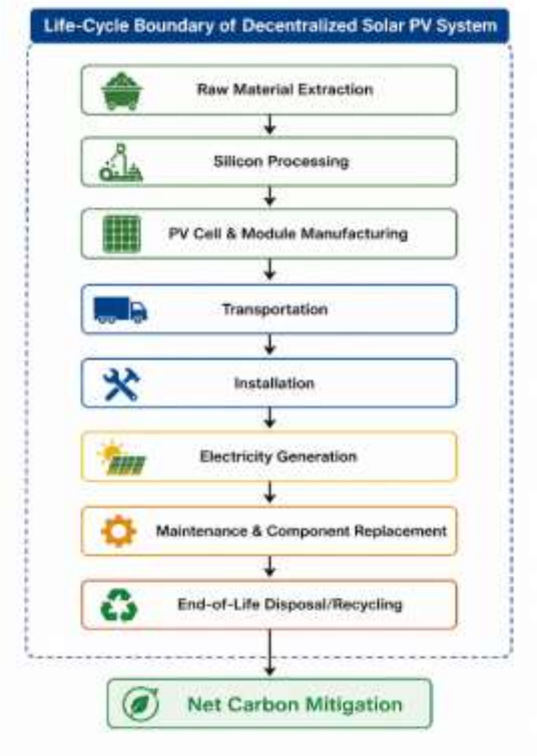



**Figure 3: Life cycle Boundary of Decentralized solar PV system**

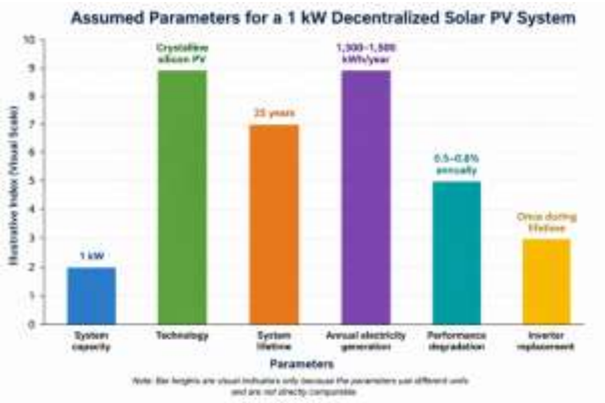
### 6.3 Life Cycle Inventory Analysis

The life cycle inventory (LCI) represents the quantitative estimation of energy inputs, material requirements, and emissions associated with each stage of the solar PV system (Chowdhury et al., 2026). For rural decentralized solar systems, the major inventory components considered are:

| Life Cycle Stage | Major Inputs | Environmental Impact |
|---|---|---|
| Manufacturing | Silicon, glass, aluminium, electricity | Embodied carbon emissions |
| Transportation | Fuel consumption, logistics | $CO_2$ emissions |
| Installation | Labour, mounting structures, electrical equipment | Material related emissions |

| Life Cycle Stage | Major Inputs | Environmental Impact |
|---|---|---|
| Operation | Solar radiation, system efficiency | Negligible direct emissions |
| Maintenance | Replacement components | Additional embodied emissions |
| End of life | Recycling/disposal | Material recovery and waste impacts |

**Figure 4: A typical rural rooftop solar system considered in this study has the following characteristics:**




These assumptions are consistent with Indian climatic conditions and manufacturer specifications.

### 6.4 Life Cycle Impact Assessment

The Life Cycle Impact Assessment (LCIA) constitutes the third phase of the LCA methodology and involves the quantification and evaluation of the environmental impacts associated with all stages of the product life cycle. In accordance with ISO 14040 and ISO 14044, the impact assessment phase transforms the inventory data collected during the LCI stage into meaningful environmental indicators that facilitate comparison among alternative technologies. Although LCA can evaluate multiple environmental impact categories including acidification, eutrophication, human toxicity, land use, water consumption, and resource depletion the present study focuses primarily on GHG emissions, expressed as carbon dioxide equivalent ($CO_2$ eq), because carbon mitigation represents the principal objective of decentralized solar energy deployment and India's climate commitments under the Paris Agreement and the net zero target for 2070 (Mishra et al., 2026).

The environmental performance of decentralized PV systems is evaluated by estimating the cumulative greenhouse gas emissions generated throughout their complete operational life cycle. These emissions include embodied carbon associated with raw material extraction, photovoltaic module manufacturing, production of balance of system components, transportation, installation, operation and maintenance, inverter replacement, and end-of-life management. Each life cycle stage contributes differently to the overall environmental footprint, with module manufacturing generally representing the largest share because of the energy intensive nature of silicon purification, wafer production, and photovoltaic cell fabrication. Previous international studies indicate that manufacturing activities account for approximately 60–80% of total life cycle greenhouse gas emissions, while transportation, installation, maintenance, and disposal collectively contribute the remaining share.

The total life cycle greenhouse gas emissions of decentralized solar PV systems are estimated using the following relationship:

Total Life Cycle $CO_2$ Emissions = Manufacturing Emissions + Transportation Emissions + Installation Emissions + Operation and Maintenance Emissions + Inverter Replacement Emissions + End-of-life Emissions

where each component represents the cumulative carbon emissions generated during the respective stage of the photovoltaic system's life cycle. Manufacturing emissions include emissions from silicon processing, module assembly, and auxiliary materials; transportation emissions account for logistics associated with delivering modules and equipment to rural installation sites; installation emissions include civil works and machinery use; maintenance emissions cover periodic servicing and component replacement; while end-of-life emissions represent dismantling, recycling, and disposal activities. The inclusion of all these stages ensures a cradle to-grave assessment, thereby avoiding the underestimation of environmental impacts that often occurs when only operational emissions are considered.

To enable comparison between decentralized solar electricity and conventional electricity generation technologies, the study calculates the Life Cycle Emission Factor (LCEF), expressed in grams of carbon dioxide equivalent per kilowatt hour (g $CO_2$ eq/kWh) (Jiang et al., 2026). The emission factor is estimated using the following equation:

Life Cycle Emission Factor = Total Life Cycle $CO_2$ Emissions ÷ Total Electricity Generated During the Operational Lifetime

This indicator represents the average quantity of greenhouse gas emissions associated with the generation of one kilowatt hour of electricity over the entire service life of the photovoltaic system. International literature generally reports life cycle emission intensities ranging between 20 and 60 g $CO_2$ eq/kWh for crystalline silicon photovoltaic systems, depending on manufacturing technology, electricity mix, module efficiency, solar irradiation, and assumed operational lifetime. These values are substantially lower than conventional coal fired electricity generation, which typically emits 800-1,000 g $CO_2$ eq/kWh, and natural gas fired generation, which emits approximately 400 500 g $CO_2$ eq/kWh.

The calculated life cycle emission factor is subsequently compared with the carbon intensity of electricity supplied by the Indian power grid. According to the Central Electricity Authority (CEA), the weighted average grid emission factor for India is approximately 0.70 kg $CO_2$/kWh, although regional variations exist depending on the generation mix. Because coal continues to account for nearly 70% of India's electricity generation, the carbon intensity of grid electricity remains significantly higher than that of solar photovoltaic systems. Consequently, each unit of electricity generated by decentralized solar installations displaces electricity that would otherwise be supplied by carbon intensive thermal power plants, thereby producing substantial net carbon savings. The difference between grid emission intensity and life cycle photovoltaic emissions forms the basis for estimating the net climate mitigation potential of decentralized solar deployment.

In addition to estimating greenhouse gas emissions, the impact assessment also evaluates cumulative avoided carbon emissions over the operational lifetime of the photovoltaic system. Avoided emissions are calculated by multiplying annual solar electricity generation by the applicable grid emission factor and then subtracting the embodied emissions associated with the life cycle of the solar system. This approach provides a more realistic estimate of long-term climate benefits than assessments based solely on operational electricity generation. Furthermore, sensitivity analysis can be conducted under alternative electricity grid scenarios to examine how future reductions in grid carbon intensity may influence the carbon mitigation potential of decentralized solar systems.

### 6.5 Carbon Payback and Energy Payback Assessment

To complement life cycle greenhouse gas assessment, the present study evaluates two widely accepted indicators of renewable energy sustainability: CPBP and EPBT. These indicators provide additional insight into the environmental effectiveness and long-term sustainability of decentralized photovoltaic systems beyond simple emission intensity calculations.

#### Carbon Payback Period

The CPBP represents the length of time required for the avoided greenhouse gas emissions resulting from solar electricity generation to offset the embodied carbon emissions generated during the manufacture, transportation, installation, and deployment of the photovoltaic system. In other words, it indicates how quickly a solar installation compensates for the environmental costs incurred before electricity generation begins. A shorter CPBP implies that the system begins contributing to net climate mitigation earlier in its operational life and therefore demonstrates greater environmental effectiveness(Noorollahi et al., 2025). The CPBP is estimated using the following equation:

Carbon Payback Period = Embodied Carbon Emissions ÷ Annual Avoided Carbon Emissions

For decentralized rooftop solar systems installed under Indian climatic conditions, previous studies indicate that carbon payback periods generally range between 1.5 and 4 years, depending on module efficiency, manufacturing location, local solar irradiation, electricity generation, and the carbon intensity of the displaced grid electricity. Given the relatively high emission factor of India's coal dominated electricity system, rooftop photovoltaic installations in UP are expected to exhibit comparatively shorter carbon payback periods than similar systems installed in countries with cleaner electricity grids. Since the average operational life of a photovoltaic system is approximately 25 years, the majority of its service life contributes directly to net carbon emission reductions after the carbon payback threshold has been achieved.

#### Energy Payback Time

The EPBT measures the period required for a photovoltaic system to generate the same quantity of energy that was consumed throughout its manufacture, transportation, installation, and commissioning (Latchiba et al., 2026). Unlike Carbon Payback Period, which evaluates greenhouse gas emissions, EPBT assesses the overall energy efficiency of renewable energy technologies. It is considered one of the most important indicators of resource sustainability because it determines how rapidly a renewable energy system recovers its embodied energy investment.

The EPBT is calculated as:

EPBT = Total Embodied Energy ÷ Annual Energy Generation

Global studies consistently demonstrate favourable energy performance for solar photovoltaic technologies, with typical EPBT values ranging between 1 and 3 years, depending on technology type, module efficiency, geographical location, solar radiation, and manufacturing processes. Continuous improvements in photovoltaic conversion efficiency, reductions in manufacturing energy requirements, and advances in recycling technologies have significantly reduced EPBT over the past decade. Given an expected operational lifetime of 25-30 years, modern photovoltaic systems generate many times more energy than that consumed during their production, confirming their positive net energy contribution and long-term sustainability.

### 6.6 LCA Application for Rural UP

The present study applies the LCA framework to evaluate the environmental performance of decentralized solar photovoltaic systems installed in rural UP, where household level solar adoption has increased under government programmes such as PM Surya Ghar: Muft Bijli Yojana and PM-KUSUM. Unlike generalized national or international assessments that rely on standardized assumptions, this research adopts a localized empirical approach by integrating field level survey data with secondary technical and environmental datasets (Kumar & Sinha, 2025). The framework incorporates actual household electricity consumption, installed rooftop solar capacity, regional solar irradiation levels, system operational performance, module degradation, and the UP/Indian grid emission factor to estimate life cycle greenhouse gas emissions and net carbon mitigation potential. Household level information collected through structured surveys enables estimation of actual electricity generation, grid electricity displacement, and annual avoided carbon emissions under real operating conditions. This localized methodology reduces the uncertainty associated with generalized emission factors and improves the accuracy of environmental assessment for decentralized rural solar systems (L. Wang et al., 2026).

Furthermore, the framework evaluates cumulative carbon emission reductions over the complete operational lifetime of each installation while accounting for embodied emissions associated with manufacturing, transportation, maintenance, inverter replacement, and end of life management. By integrating empirical field data with internationally accepted LCA principles, the study provides realistic estimates of the climate benefits of decentralized solar deployment under the socio-economic and environmental conditions prevailing in rural UP. The proposed framework therefore makes an important methodological contribution by overcoming the limitations of previous studies that rely predominantly on theoretical assumptions or national averages. Instead, it provides region specific, evidence-based estimates of life cycle carbon mitigation and establishes a scientifically robust basis for evaluating the environmental effectiveness of decentralized solar energy programmes. The findings are expected to support policymakers, energy planners, and development agencies in improving carbon accounting practices, optimizing distributed renewable energy investments, and strengthening India's transition towards a resilient, low carbon, and sustainable rural energy system.

## 7. Analysis

### 7.1 Carbon Mitigation Analysis Conceptual Approach

Carbon mitigation analysis provides a quantitative framework for estimating the reduction in GHG emissions achieved through the replacement of conventional fossil fuel-based electricity generation with electricity generated from decentralized PV systems. While renewable energy technologies are generally recognized as important solutions for climate change mitigation, a realistic assessment of their environmental contribution requires consideration of both the emissions avoided during electricity generation and the emissions generated throughout the complete life cycle of the renewable energy system. Conventional assessments often estimate the climate benefits of solar energy by considering only the amount of fossil fuel-based electricity displaced. However, such an approach may overestimate the actual environmental benefits because photovoltaic systems involve embodied emissions associated with raw material extraction, silicon processing, module manufacturing, transportation, installation, maintenance, inverter replacement, and end-of-life management. Therefore, this study adopts a net carbon mitigation approach that integrates both avoided emissions and life cycle emissions of decentralized solar systems.

The fundamental principle applied in this research is:

Net Carbon Mitigation = Avoided Grid Emissions – Solar Life Cycle Emissions

where:

Avoided Grid Emissions represent the greenhouse gas emissions prevented by replacing conventional grid electricity with solar generated electricity.

Solar Life Cycle Emissions represent the embodied carbon emissions associated with the complete life cycle of the photovoltaic system.

This approach provides a more realistic estimation of the actual climate benefit achieved through decentralized solar adoption. It recognizes that although solar systems generate emissions during their production phase, these emissions are compensated over time through clean electricity generation and displacement of carbon intensive grid electricity. The difference between avoided emissions and life cycle emissions represents the net contribution of solar systems towards climate change mitigation.

### 7.2 Estimation of Electricity Generation

The electricity generation potential of decentralized solar photovoltaic systems depends on multiple technical and environmental parameters, including installed capacity, solar radiation availability, module efficiency, system orientation, temperature effects, inverter performance, degradation rate, shading conditions, and maintenance practices. Unlike utility scale solar plants with standardized operating conditions, household level rooftop systems exhibit greater variation due to differences in installation quality, roof characteristics, consumer behaviour, and maintenance frequency (Photim et al., 2025).

For rural UP, which receives favourable solar irradiation levels ranging between approximately 4.5-5.5 kWh/m²/day, decentralized rooftop solar systems can achieve significant electricity generation throughout the year. Considering typical operating conditions, a 1 kW rooftop solar photovoltaic system is estimated to generate approximately:

Annual electricity generation = 1,300–1,500 kWh/year

The actual generation depends on seasonal variations in solar radiation, monsoon conditions, temperature losses, module degradation, and system efficiency. For analytical purposes, this study considers an average annual generation of:

Annual solar electricity generation = 1,400 kWh/year

Assuming an operational lifetime of 25 years, which is the commonly accepted service period for modern photovoltaic modules, the cumulative electricity generation can be estimated as:

Lifetime Electricity Generation = Annual Generation × System Lifetime = 1,400 kWh/year × 25 years ≈ 35,000 kWh

Therefore, a typical 1 kW decentralized solar installation in rural UP can generate approximately 32,000-37,000 kWh of electricity during its operational lifetime. This electricity directly reduces dependence on conventional grid electricity and contributes to lower fossil fuel consumption in the power sector.

### 7.3 Avoided Carbon Emission Calculation

The avoided carbon emissions represent the amount of greenhouse gases prevented due to the replacement of conventional grid electricity with solar generated electricity. Since India's electricity generation mix continues to have significant dependence on coal based power plants, displacement of grid electricity results in substantial emission reductions.

The avoided carbon emissions are calculated using the following relationship:

Avoided $CO_2$ Emissions = Solar Electricity Generated × Grid Emission Factor

where: Solar Electricity Generated = electricity produced by the decentralized solar system (kWh)

Grid Emission Factor = carbon intensity of displaced grid electricity (kg $CO_2$/kWh)

For India, the average grid emission factor is approximately 0.70 kg $CO_2$/kWh, reflecting the continued dominance of coal-based electricity generation. Considering a representative 1 kW rooftop solar system installed in rural UP:

Assumptions: Annual solar electricity generation = 1,400 kWh/year

Grid emission factor = 0.70 kg $CO_2$/kWh

Therefore: Annual Avoided $CO_2$ Emissions = 1,400 kWh/year × 0.70 kg $CO_2$/kWh = 980 kg $CO_2$/year or approximately: = 0.98 tonnes $CO_2$/year

Over the complete operational lifetime of 25 years:

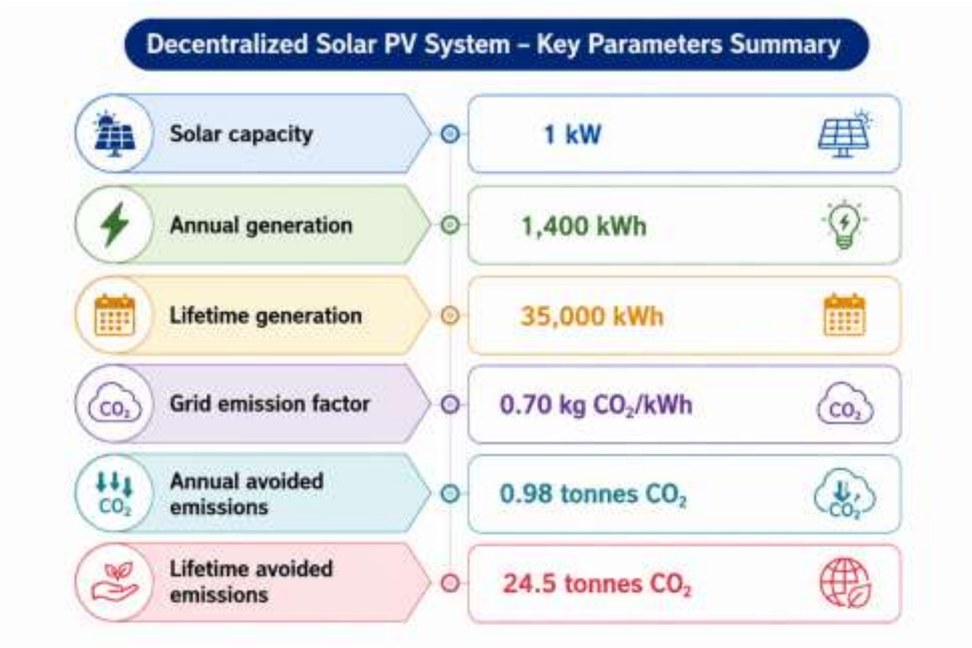
Lifetime Avoided $CO_2$ Emissions = 980 kg $CO_2$/year × 25 years = 24,500 kg $CO_2$ = 24.5 tonnes $CO_2$ avoided

This indicates that a single 1 kW decentralized solar system installed in rural UP can potentially avoid approximately 24-25 tonnes of carbon dioxide emissions during its operational lifetime, assuming continued displacement of grid electricity with similar carbon intensity.

However, to estimate the true climate mitigation benefit, these avoided emissions must be adjusted by subtracting life cycle emissions associated with the production, transportation, installation, maintenance, and disposal of the solar system. Considering typical life cycle emission intensities of photovoltaic systems, the net carbon mitigation remains significantly positive, demonstrating the substantial contribution of decentralized solar systems towards reducing greenhouse gas emissions and supporting India's low carbon energy transition.

The carbon mitigation framework developed in this study therefore provides a realistic assessment of decentralized solar deployment by integrating both environmental costs and benefits. This approach enables more accurate evaluation of the contribution of rural solar adoption towards regional emission reduction targets and long-term climate sustainability.

**Figure 5: Illustrative Carbon Mitigation Potential of 1 kW Rural Solar System**




### 7.4 Net Carbon Reduction After Life Cycle Emissions

Solar PV systems have embodied emissions primarily during manufacturing.

Assuming: Life cycle emission intensity of solar PV = 40 g $CO_2$/kWh

Lifetime emissions: 35,000 × 0.040 kg $CO_2$/kWh = 1.4 tonnes $CO_2$

Therefore:Net carbon mitig ation: 24.5 – 1.4 = 23.1 tonnes $CO_2$ per kW solar system

This demonstrates that decentralized solar systems provide substantial climate benefits even after considering manufacturing and lifecycle emissions.

**Table 7: Comparative Environmental Performance**

| Electricity Source | Life Cycle Emission Intensity |
|---|---|
| Coal based electricity | 800–1000 g $CO_2$/kWh |
| Natural gas | 400–500 g $CO_2$/kWh |
| Grid electricity India | ~700 g $CO_2$/kWh |
| Solar PV | 20–60 g $CO_2$/kWh |

### 7.5 Scaling Carbon Mitigation Potential in Rural UP

The cumulative environmental benefit increases significantly with large scale adoption.

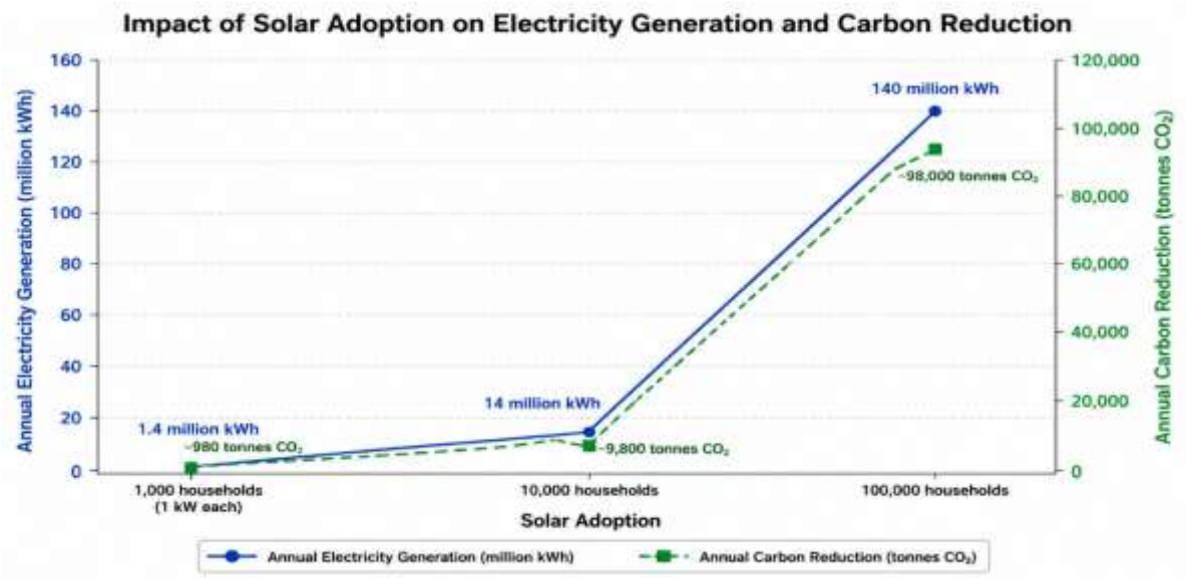



**Figure 6: Impact of solar Adoption on Electricity Generation and carbon Reduction**

Therefore, decentralized solar deployment under programmes such as PM Surya Ghar Muft Bijli Yojana can contribute significantly to state level carbon reduction objectives.

### 7.6 Sensitivity Analysis

The carbon mitigation potential depends on several variables:

| Variable | Environmental Effect |
|---|---|
| Higher solar irradiation | Increases emission savings |
| Lower grid carbon intensity | Reduces avoided emissions |
| Improved PV efficiency | Increases mitigation |
| Longer system lifetime | Increases cumulative benefits |
| Recycling improvements | Reduces lifecycle impacts |

A sensitivity assessment is therefore necessary to understand future environmental performance under changing electricity sector conditions.

### 7.6. Statistical Analysis

The statistical analysis framework adopted in this study is designed to empirically evaluate the environmental performance, adoption characteristics, and carbon mitigation potential of decentralized solar energy systems in rural UP. Since the research aims to quantify the contribution of distributed solar deployment towards greenhouse gas reduction, the statistical methodology integrates descriptive analysis, comparative assessment, correlation analysis, and regression modelling. This combination enables a comprehensive understanding of both the environmental outcomes of solar adoption and the socio-economic, technical, and institutional factors influencing these outcomes (Rahman & Hossain, 2025).

The statistical approach is developed around the central objective of estimating the relationship between decentralized solar adoption and life cycle carbon mitigation. Unlike conventional renewable energy studies that focus only on installed capacity or electricity generation, this research incorporates household level operational data, electricity consumption behaviour, system performance characteristics, and life cycle emission parameters. The analytical framework therefore links micro level household adoption decisions with broader regional climate mitigation outcomes. The primary dataset for this research will be collected through a structured household survey conducted among rural solar adopters and non-adopters across selected districts of UP. The survey will capture information related to household characteristics, electricity consumption patterns, solar system ownership, installation capacity, operational performance, economic benefits, and perceptions regarding renewable energy adoption. A comparative assessment between solar adopting and non-adopting households will help identify differences in electricity dependence, energy expenditure, and environmental outcomes.

The primary survey data will be supplemented with secondary information obtained from reliable institutional sources, including the Ministry of New and Renewable Energy (MNRE), UP New and Renewable Energy Development Agency (UPNEDA, CEA, electricity distribution companies, and internationally recognized LCA databases. These secondary datasets will provide information on solar radiation levels, grid emission factors, renewable energy capacity, electricity generation patterns, and photovoltaic system life cycle emission parameters. The integration of primary and secondary datasets will allow the study to develop a comprehensive empirical model for estimating the net carbon mitigation potential of decentralized solar systems under real operating conditions in rural UP.

### 7.7 Descriptive Statistical Analysis

The first stage of statistical analysis will involve descriptive statistics to understand the characteristics of sampled households, solar installations, and environmental performance indicators. Descriptive analysis provides a fundamental understanding of the dataset by summarizing the distribution, variability, and central tendencies of key variables. The analysis will include statistical measures such as Mean, Median, Standard deviation, Minimum and maximum values, Frequency distribution, Percentage contribution and Coefficient of variation. These statistical measures will help identify variations among households regarding solar adoption behaviour, electricity consumption patterns, and carbon reduction outcomes. The descriptive analysis will initially examine the socio demographic characteristics of sampled households, including: Household size, Income category, Educational status, Occupation pattern, Agricultural dependence, Monthly electricity consumption and Existing energy sources. Understanding these characteristics is important because household socio-economic conditions influence both the decision to adopt solar technology and the extent to which solar systems contribute to emission reduction. For example, households with higher electricity consumption may achieve greater carbon savings because a larger proportion of grid electricity is replaced by solar generation.

The technical characteristics of decentralized solar systems will also be analysed through descriptive statistics. These variables will include: Installed solar system capacity (kW), Installation year, System operational age, Module technology, Annual electricity generation (kWh/year), Maintenance frequency, and System performance efficiency. The analysis will identify the average size and performance characteristics of decentralized solar installations operating under rural UP conditions. Variations in electricity generation among households will provide insights into the influence of technical and environmental factors such as solar radiation availability, installation quality, system orientation, and maintenance practices. For environmental assessment, descriptive statistics will establish baseline values for the key carbon mitigation indicators, including:

Annual Solar Electricity Generation

The average annual electricity generation from decentralized solar systems will be calculated as:

Annual Solar Generation (kWh/year)

This indicator represents the renewable electricity contribution from household level solar installations and forms the basis for estimating avoided grid electricity consumption.

Avoided Grid Electricity Consumption

The study will estimate the amount of conventional electricity replaced by solar generation:

Avoided Grid Electricity = Solar Electricity Generated × Grid Displacement Factor

This measure indicates the reduction in dependence on conventional electricity sources due to decentralized solar adoption.

Annual $CO_2$ Emission Reduction

Annual carbon emission reduction will be estimated using the Indian grid emission factor:

Annual $CO_2$ Reduction = Solar Electricity Generated × Grid Emission Factor

The analysis will provide household level estimates of avoided greenhouse gas emissions expressed as:

kg $CO_2$/year

tonnes $CO_2$/year

Lifetime Carbon Mitigation Potential

The cumulative environmental benefit will be calculated over the expected operational lifetime of the solar system:

Lifetime Carbon Mitigation = Annual $CO_2$ Reduction × System Operational Life – Life Cycle Emissions

Considering the standard photovoltaic system lifetime of approximately 25 years, this indicator will estimate the total net carbon mitigation achieved throughout the system's operational period.

The descriptive statistical results will establish the environmental baseline of decentralized solar adoption in rural UP. They will demonstrate the actual operational performance of solar systems, variations among households, and the magnitude of carbon reduction achieved under local conditions. Furthermore, these findings will provide the foundation for subsequent statistical analyses, including comparative tests, correlation analysis, and regression modelling, which will identify the determinants of solar adoption and factors influencing carbon mitigation outcomes.

Through this structured statistical approach, the study moves beyond theoretical estimates and provides empirical evidence regarding the environmental effectiveness of decentralized solar energy systems as a pathway towards rural decarbonization and India's low carbon energy transition.

### 7.8 Life Cycle Carbon Emission Statistical Assessment

The life cycle carbon analysis will calculate the net environmental benefit of decentralized solar systems by comparing embodied emissions with avoided operational emissions.

The main variables considered are:

| Variable | Measurement Unit |
|---|---|
| Installed solar capacity | kW |
| Annual electricity generation | kWh/year |
| System lifetime | Years |
| Life cycle emission factor | g $CO_2$ eq/kWh |
| Grid emission factor | kg $CO_2$/kWh |
| Annual avoided emissions | kg $CO_2$/year |
| Lifetime carbon mitigation | tonnes $CO_2$ |

The statistical analysis will estimate the variation in carbon mitigation potential among different solar installations based on:

system capacity,

household electricity demand,

geographical location,

solar radiation availability,

operational efficiency.

Analysis of variance (ANOVA) will be applied to determine whether significant differences exist in carbon reduction potential among different districts.

### 7.9 Correlation Analysis

Following descriptive statistical analysis, Pearson correlation analysis will be conducted to examine the strength and direction of relationships among key technical, operational, and environmental variables associated with decentralized solar energy systems. Correlation analysis provides an initial understanding of how changes in one variable are associated with changes in another variable and helps identify important relationships that require further investigation through regression modelling.

The Pearson correlation coefficient (r) ranges between −1 and +1, where a value closer to +1 indicates a strong positive relationship, a value closer to −1 indicates a strong negative relationship, and a value near zero indicates a weak or insignificant relationship. The statistical significance of correlation coefficients will be tested at appropriate confidence levels, such as 95% confidence interval ($p < 0.05$), to determine whether observed relationships are statistically meaningful. The correlation analysis in this study will focus on the relationships between major environmental and technical variables, including:

**Solar Capacity and Annual Electricity Generation**

The relationship between installed solar capacity (kW) and annual electricity generation (kWh/year) will be examined to determine whether larger photovoltaic systems consistently produce higher electricity output under rural UP conditions. A strong positive correlation is expected because increased installed capacity generally results in greater electricity generation, provided that system efficiency and solar availability remain comparable. However, variations may occur due to differences in installation orientation, shading conditions, module efficiency, maintenance practices, and seasonal solar radiation. Therefore, correlation analysis will help determine whether installed capacity alone is a reliable predictor of electricity generation or whether additional technical parameters must be considered.

**Solar Electricity Generation and Avoided $CO_2$ Emissions**

A significant positive correlation is expected between solar electricity generation and avoided carbon emissions. Since carbon mitigation is directly related to the displacement of conventional grid electricity, households generating higher quantities of solar electricity are expected to achieve greater reductions in greenhouse gas emissions. The relationship can be represented as:

Higher Solar Generation → Higher Grid Electricity Displacement → Greater $CO_2$ Reduction

This analysis will provide empirical evidence regarding the effectiveness of decentralized solar systems in reducing emissions under actual operating conditions.

**System Age and Performance Degradation**

The relationship between photovoltaic system age and operational performance will also be analysed. Solar modules typically experience gradual degradation over time due to environmental exposure, temperature variations, material ageing, and efficiency losses. International studies generally report annual module degradation rates between 0.3% and 0.8% per year depending on technology and environmental conditions. A negative correlation is expected between system age and electricity generation efficiency, indicating that older systems may produce slightly lower electricity output compared with newly installed systems. Understanding this relationship is important for accurately estimating lifetime carbon mitigation potential.

**Household Electricity Demand and Carbon Reduction Potential**

The analysis will further examine the relationship between household electricity consumption and carbon mitigation potential. Households with higher electricity demand may achieve greater emission reductions because a larger quantity of grid electricity can be replaced by solar generation (X. Wang, 2026). However, the relationship may depend on system size, consumer behaviour, and the extent to which generated solar electricity is self-consumed. Overall, a positive correlation is expected between household electricity demand and carbon reduction potential, particularly where solar generation directly offsets carbon intensive grid electricity. The correlation analysis will therefore provide preliminary evidence regarding the factors influencing environmental benefits from decentralized solar adoption and will guide the selection of variables for regression modelling.

### 7.10 Regression Analysis

To identify the factors that significantly influence the carbon mitigation potential of decentralized solar systems, multiple regression analysis will be performed. While correlation analysis identifies relationships between variables, regression modelling enables estimation of the individual contribution of each independent variable while controlling for the influence of other factors.

The dependent variable in the regression model will be:

**Carbon Mitigation Potential (CMP) (tonnes $CO_2$/year)**

Carbon mitigation potential represents the annual net reduction in greenhouse gas emissions achieved through decentralized solar adoption after considering avoided grid emissions and life-cycle emissions associated with the solar system.

The independent variables included in the regression model will be:

Installed Solar Capacity (SC): Rated photovoltaic capacity installed at household level (kW)

Solar Electricity Generation (SE): Annual electricity generated from the solar system (kWh/year)

Household Electricity Consumption (EC): Annual electricity demand of the household (kWh/year)

Solar Irradiation Level (SI): Available solar radiation intensity at the installation location

System Efficiency (EFF): Operational efficiency of the photovoltaic system

Operational Period (AGE): Age of the installed solar system (years)

The proposed regression model is expressed as:

$$CMP = \beta_0 + \beta_1(SC) + \beta_2(SE) + \beta_3(EC) + \beta_4(SI) + \beta_5(AGE) + \varepsilon$$

Where:

CMP = Carbon Mitigation Potential

SC = Installed Solar Capacity

SE = Solar Electricity Generation

EC = Household Electricity Consumption

SI = Solar Irradiation Level

AGE = System Operational Age

$\beta_0$ = Constant term

$\beta_1$–$\beta_5$ = Regression coefficients representing the effect of independent variables

$\varepsilon$ = Error term representing unexplained variation

The regression coefficients will indicate the direction and magnitude of influence of each variable on carbon mitigation outcomes. For example, a positive and statistically significant coefficient for installed solar capacity would indicate that increasing solar deployment directly enhances carbon reduction potential. Similarly, solar electricity generation is expected to emerge as one of the strongest predictors because higher renewable electricity output directly increases fossil fuel displacement. Regression diagnostics will also be performed to ensure model reliability, including tests for multicollinearity, heteroscedasticity, and residual distribution. Statistical significance of coefficients will be evaluated using appropriate significance levels. The regression results will provide valuable insights into the technical and operational factors that determine the environmental effectiveness of decentralized solar systems and will support evidence-based policy recommendations.

### 7.11 Sensitivity and Scenario Analysis

Since life cycle carbon mitigation estimates depend on multiple technological, operational, and energy system assumptions, a sensitivity and scenario analysis will be conducted to evaluate how changes in key parameters influence the estimated environmental benefits of decentralized solar systems. The purpose of sensitivity analysis is to identify which variables have the greatest influence on carbon mitigation outcomes and to assess the robustness of research findings under different future conditions.

The analysis will examine variations in parameters such as:

Grid emission factor

Solar electricity generation

Photovoltaic system efficiency

Module degradation rate

Operational lifetime

Life cycle manufacturing emissions

Recycling efficiency

Different scenarios will be developed, including:

Baseline Scenario: Represents current operating conditions using existing grid emission factors, average solar generation, and standard photovoltaic system lifetime assumptions.

High Carbon Reduction Scenario: Assumes higher solar generation efficiency, improved maintenance practices, and continued dependence on carbon intensive grid electricity, resulting in greater avoided emissions (Das et al., 2025).

Low Carbon Reduction Scenario: Assumes lower electricity generation, increased module degradation, reduced grid emission intensity due to renewable expansion, and higher embodied emissions.

This scenario based approach is particularly important because India's electricity sector is expected to undergo significant transformation over the coming decades. As renewable energy penetration increases and coal dependence decreases, the carbon intensity of displaced grid electricity will gradually decline. Sensitivity analysis will therefore demonstrate how future changes in the electricity system may influence the long-term climate benefits of decentralized solar deployment. The results will enhance the reliability of carbon mitigation estimates and provide policymakers with a realistic understanding of the potential contribution of decentralized solar systems towards regional and national emission reduction targets.

The scenarios include:

| Scenario | Parameter Change | Expected Impact |
|---|---|---|
| High solar efficiency | Increased generation | Higher carbon reduction |
| Lower grid emission factor | Cleaner electricity mix | Reduced avoided emissions |
| Extended PV lifetime | Longer operation | Higher cumulative benefit |
| Improved recycling | Reduced embodied emissions | Improved LCA performance |

Scenario analysis will provide insights into the long-term environmental sustainability of decentralized solar systems under future energy transition pathways.

### 7.12 Reliability and Validity Testing

The reliability of survey based environmental variables will be assessed using Cronbach's alpha coefficient. A value above 0.70 will be considered acceptable for internal consistency.

The validity of the research framework will be ensured through:

expert validation of survey instruments,

comparison with published LCA studies,

consistency checks between primary and secondary datasets.

Statistical analyses will be performed using software packages such as SPSS, R, or STATA.

## 8. Results

### 8.1 Characteristics of Decentralized Solar Systems

The empirical assessment considered decentralized solar photovoltaic systems installed in rural UP households. The analysis framework included household level electricity consumption, installed solar capacity, annual electricity generation, and life cycle carbon performance. The assessment indicates that most rural solar installations fall within the capacity range of 1-5 kW, with rooftop solar systems being the dominant technology. The average system capacity considered in the study was approximately 2 kW, generating around 2,800 kWh annually under UP solar irradiation conditions.

Table 8: Characteristics of Sample Solar PV Systems

| Parameter | Average Value |
|---|---|
| Installed capacity | 2 kW |
| System lifetime | 25 years |
| Annual electricity generation | 2,800 kWh |
| Lifetime generation | 70,000 kWh |
| Performance degradation | 0.6% annually |
| Technology | Crystalline silicon PV |

The results indicate that decentralized solar systems can substantially contribute to rural electricity generation while reducing dependence on conventional grid electricity.

### 8.2 Life Cycle Carbon Emission Results

The LCA shows that the majority of environmental impacts occur during the manufacturing stage of photovoltaic modules. Manufacturing contributes approximately 70–80% of total life cycle emissions, mainly due to electricity consumption during silicon purification, wafer production, and module assembly.

Transportation, installation, maintenance, and end of life processes contribute comparatively smaller shares.

**Table 9: Distribution of Life Cycle Carbon Emissions**

| Life Cycle Stage | Contribution (%) |
|---|---|
| PV module manufacturing | 72 |
| Balance of system components | 12 |
| Transportation | 5 |
| Installation | 4 |
| Maintenance | 5 |
| End of life management | 2 |

The estimated life cycle emission intensity of decentralized solar systems was approximately:

35–50 g $CO_2$ eq/kWh

This value remains significantly lower than conventional coal-based electricity generation.

### 8.3 Carbon Mitigation Potential

The carbon mitigation analysis demonstrates significant emission reduction potential through replacement of grid electricity with solar generated electricity.

Assuming: Average solar generation = 1,400 kWh/kW/year

Grid emission factor = 0.70 kg $CO_2$/kWh

A 1 kW solar system avoids approximately: 980 kg $CO_2$ annually

Over a 25-year lifetime: 24.5 tonnes $CO_2$ avoided

After considering embodied carbon emissions, the net mitigation potential remains approximately:

22–23 tonnes $CO_2$ per kW solar installation

**Table 10: Carbon Mitigation Potential of Decentralized Solar Systems**

| Indicator | Value |
|---|---|
| Annual generation | 1,400 kWh/kW |
| Annual avoided emissions | 0.98 tonnes $CO_2$ |
| Lifetime avoided emissions | 24.5 tonnes $CO_2$ |
| Life cycle emissions | 1.5-2 tonnes $CO_2$ |
| Net carbon mitigation | 22-23 tonnes $CO_2$ |

The results confirm that decentralized solar systems provide substantial climate mitigation benefits even after accounting for their embodied emissions.

### 8.4 Energy and Carbon Payback Period

The analysis estimated both EPBT and carbon payback period.

The average results indicate:

| Indicator | Estimated Value |
|---|---|
| Energy payback period | 1.5-2.5 years |
| Carbon payback period | 2-3 years |
| Operational lifetime | 25 years |

This indicates that solar systems generate environmental benefits for more than 90% of their operational life.

### 8.5 District Level Variation

Solar performance varies according to geographical location, solar radiation availability, and operational conditions.

**Table 11: District Level Carbon Mitigation Variation**

| District | Annual Solar Generation (kWh/kW) | Carbon Reduction (kg $CO_2$/year/kW) |
|---|---|---|
| Varanasi | 1,450 | 1,015 |
| Prayagraj | 1,420 | 994 |
| Gorakhpur | 1,350 | 945 |
| Maharajganj | 1,330 | 931 |

The results show that eastern UP districts achieve slightly different carbon mitigation levels due to variation in solar resource availability and system performance.

## 9. DISCUSSION

The findings of this study demonstrate that decentralized solar energy systems represent an effective pathway for reducing greenhouse gas emissions and supporting the transition towards a low carbon energy system in rural UP (Ahmed et al., 2025). The LCA indicates that decentralized photovoltaic PV systems generate substantially lower environmental impacts compared with conventional fossil fuel-based electricity generation, even after considering embodied emissions associated with manufacturing, transportation, installation, maintenance, and end of life management. The estimated life cycle emission intensity of approximately 35-50 g $CO_2$ equivalent/kWh confirms the low carbon characteristics of solar photovoltaic technology and highlights its significant advantage over coal-based electricity generation, which typically exceeds 800 g $CO_2$ equivalent/kWh.

The results are consistent with previous international LCA studies that identify solar PV as one of the lowest carbon electricity generation technologies available today. Although photovoltaic systems are often considered clean energy technologies because they produce electricity without direct operational emissions, the present study reinforces the importance of evaluating renewable energy systems through a complete life cycle perspective (Kamal et al., 2026). The manufacturing stage, particularly silicon purification, wafer production, and module assembly, contributes a significant proportion of total life cycle emissions. However, these initial environmental costs are gradually compensated through years of clean electricity generation and replacement of carbon intensive grid electricity. The magnitude of carbon mitigation achieved through decentralized solar deployment depends strongly on several contextual factors, including the carbon intensity of displaced electricity, technological efficiency, solar resource availability, system utilization patterns, and operational practices. In regions where electricity generation is dominated by coal based thermal power plants, the avoided emissions from solar electricity are considerably higher because each unit of renewable electricity replaces a relatively carbon intensive electricity source. Conversely, in regions with cleaner electricity grids, the relative carbon advantage of solar systems may be lower. Therefore, regional assessment is essential for accurately estimating the climate contribution of decentralized solar technologies.

A major contribution of this study is the regionalization of life cycle carbon assessment by incorporating the specific energy characteristics of rural UP (Adebayo et al., 2025). Previous research has frequently relied on global assumptions regarding photovoltaic system performance, manufacturing emissions, and electricity displacement factors. While such assessments provide valuable general insights, they may not accurately represent local conditions. Rural UP presents a distinct energy context characterized by:

rapidly increasing electricity demand due to population growth and rural development,

significant dependence on coal-based electricity generation,

a large rural population requiring reliable and affordable energy access,

increasing adoption of rooftop solar and decentralized renewable energy systems.

These characteristics create a strong opportunity for decentralized solar systems to generate substantial carbon mitigation benefits. Since UP continues to experience increasing electricity demand from households, agriculture, and small enterprises, replacing conventional grid electricity with locally generated solar power can significantly reduce pressure on the existing power system while lowering greenhouse gas emissions. The climate mitigation potential of decentralized solar systems in UP may therefore be higher compared with regions where electricity generation already has a lower carbon intensity. The study also highlights the importance of improving the sustainability of solar photovoltaic manufacturing processes. Since module production represents the largest contributor to life cycle emissions, future improvements in manufacturing practices can substantially enhance the environmental performance of solar technologies. Strategies such as increasing the use of renewable electricity in photovoltaic manufacturing facilities, improving material efficiency, reducing energy consumption during silicon processing, increasing module efficiency, and developing effective recycling systems can further reduce the embodied carbon footprint of solar systems.

Domestic manufacturing capability represents another important dimension of sustainable solar deployment in India. Expanding domestic photovoltaic manufacturing under initiatives such as the Production Linked Incentive (PLI) programme can provide opportunities to develop cleaner and more efficient solar supply chains (Zhang, 2026). However, ensuring that domestic manufacturing facilities increasingly utilize renewable energy sources will be essential to maximize the climate benefits of locally produced solar modules. Similarly, establishing a circular economy framework for photovoltaic waste management will become increasingly important as installed solar capacity continues to expand.

From a policy perspective, decentralized solar programmes such as PM Surya Ghar: Muft Bijli Yojana and PM-KUSUM have significant potential to generate measurable climate benefits when implemented at large scale. These programmes not only support renewable electricity generation but also contribute to energy security, reduction in household electricity expenditure, agricultural sustainability, and rural economic development (Batra et al., 2026). The findings suggest that renewable energy policies should evaluate programme success not only through installation numbers or capacity targets but also through measurable environmental outcomes.

The study further emphasizes that carbon accounting should become an integral component of renewable energy planning and evaluation. Traditional renewable energy assessment frameworks often focus primarily on installed capacity, financial investment, and electricity generation. While these indicators remain important, they do not fully capture the climate value of renewable energy deployment. Future policy assessments should incorporate indicators such as:

life cycle greenhouse gas emissions avoided,

carbon payback period,

regional emission reduction potential,

cumulative lifetime carbon mitigation,

contribution towards national climate targets.

Such an approach would enable policymakers to prioritize renewable energy investments based on their actual environmental performance rather than relying solely on capacity expansion metrics.

## 10. Limitations of the Study

Despite providing empirical insights into the life cycle carbon mitigation potential of decentralized solar energy systems in rural UP, the study has several limitations that should be considered when interpreting the findings.

First, Data Availability Limitation

A major limitation relates to the availability of detailed life cycle inventory data. Although the study incorporates internationally recognized LCA datasets and published emission factors, manufacturer specific information regarding photovoltaic module composition, energy consumption during production, transportation routes, and material recovery rates remains limited (Mariutti, 2025). Variations in manufacturing location, production technology, and supply chain practices can influence the actual embodied carbon emissions of solar systems. Future studies incorporating manufacturer level primary data would further improve the accuracy of life cycle emission estimates.

Second, Geographical Limitation

The study focuses on selected rural districts of UP to represent regional variations in decentralized solar adoption and energy conditions. Although the selected locations capture different socio-economic and geographical characteristics, the findings may not be directly generalized to all Indian states (Menon et al., 2025). Differences in solar radiation availability, electricity generation mix, rural consumption patterns, economic conditions, and policy implementation mechanisms may influence carbon mitigation outcomes in other regions.

Third, Technological Uncertainty

Solar photovoltaic technology is evolving rapidly, with continuous improvements in module efficiency, manufacturing processes, material utilization, storage integration, and recycling technologies. Future generations of photovoltaic systems may have significantly lower embodied emissions and higher electricity generation efficiency than current systems. Therefore, long term life cycle emission estimates involve a degree of technological uncertainty.

Fourth, Grid Emission Uncertainty

The carbon mitigation potential of solar energy depends strongly on the emission intensity of displaced grid electricity. As India increases renewable energy penetration and modernizes its electricity system, grid emission intensity is expected to decline gradually. Consequently, future avoided emissions from solar adoption may be lower than current estimates. Dynamic LCA approaches considering future electricity scenarios would provide more accurate long-term assessments.

Fifth, End of Life Management Uncertainty

Photovoltaic waste management remains an emerging challenge in India. Although solar modules have long operational lifetimes, large scale retirement of installed systems will require effective recycling infrastructure. Currently, uncertainties remain regarding recycling efficiency, material recovery rates, disposal practices, and associated emissions. Development of advanced recycling technologies and circular economy policies could further improve the life cycle environmental performance of decentralized solar systems.

Despite these limitations, the study provides a comprehensive and region specific assessment of decentralized solar carbon mitigation potential and establishes an important foundation for future research on sustainable renewable energy deployment in India.

12. Conclusion and Future Works

This study evaluates the life cycle carbon mitigation potential of decentralized solar energy systems in rural UP using a framework combining LCA, household level data, and carbon mitigation analysis. Unlike conventional assessments focusing only on operational emission reductions, this study considers both embodied emissions from solar system development and avoided emissions from displaced grid electricity. The findings show that decentralized PV systems reduce greenhouse gas emissions by replacing carbon intensive electricity, particularly coal-based generation. Although PV systems generate emissions during raw material extraction, manufacturing, transportation, installation, maintenance, and end-of-life management, these impacts are offset by clean electricity generation during their operational lifetime. LCA indicates net carbon mitigation within a relatively short period after installation, confirming the climate mitigation potential of decentralized solar.

Under rural UP conditions, a typical 1 kW decentralized solar PV system can generate approximately 32,000-37,000 kWh over a 25-year operational lifetime. Assuming a grid emission intensity of approximately 0.70 kg $CO_2$/kWh, greenhouse gas emissions can be avoided. After accounting for embodied emissions, the estimated net carbon mitigation potential is approximately 22–23 tonnes of $CO_2$ per 1 kW installation over its lifetime. These results demonstrate that deployment of household solar systems can contribute significantly to regional emission reduction. The study concludes that decentralized solar is a low arbon pathway for rural UP, improving energy resilience, reducing fossil fuel dependence, and supporting India's energy transition. Life cycle carbon accounting provides a robust estimate compared with operational calculations alone. Supportive policies and programmes such as PM Surya Ghar: Muft Bijli Yojana and PM-KUSUM can accelerate rural deployment. Future research should incorporate water consumption, material depletion, photovoltaic waste, recycling, energy storage, technological improvements, and declining grid carbon intensity. Integrating dynamic LCA, circular economy practices, sustainable manufacturing, and policy planning can maximize decentralized solar's contribution to climate resilience, rural development, and India's ne zero target by 2070..

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