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# Integration of Roof Top Hybrid Connected Solar PV System

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**ABSTRACT:** The rapid growth of the energy and transport sectors has led to an increase in fuel consumption, resulting in a significant rise in greenhouse gas emissions. Switching to renewable energy sources and replacing internal combustion engines with electric vehicles (EVs) can significantly reduce greenhouse gas emissions. In recent years, the electrification of the transportation sector has become a primary focus of research and development efforts. However, if EVs are charged using conventional energy sources, we are unable to fully capitalize on their potential to reduce emissions. Charging EVs using renewable energy sources is the optimal solution. Otherwise, the increased number of EVs on the roads can significantly impact the stability of existing electric grids. As a result, smart homes with EV charging stations are becoming increasingly popular worldwide. This review focuses on the concept of grid-connected rooftop solar photovoltaic (PV) smart homes integrated with EVs and energy management systems in Australia. Australia can reduce emissions in the building and transport sectors by electrifying a range of vehicles and ultimately powering them with 100% renewable energy sources. The benefits of EV integration alongside rooftop solar systems for smart homes with house-to-vehicle or vehicle-to-house, as well as vehicle-to-grid or grid-to-vehicle (bidirectional EV charging) capabilities are also explored in this article. By adopting these systems, these smart homes can provide energy schemes for commercial use, ultimately contributing to the owner's economic benefit.

**KEYWORDS:** electric vehicle; greenhouse gas; home energy management system; renewable energy source; smart home

## I. INTRODUCTION

Over the past years, housing and electricity infrastructural deficiencies in the Global South have significantly affected both the standard of living and environmental conditions [1]. Rapid urbanization has led to a rise in slum populations, with approximately 24.8 % of the urban population in developing regions—totalling around 1.12 billion people—living in informal settlements by 2022 [2]. These areas often lack essential services such as clean water, sanitation, and electricity, adversely impacting residents' health and well-being. The energy deficit is particularly alarming, with close to 700 million people worldwide lacking access to electricity in 2021 and over 80 % of whom were in sub-Saharan Africa [3,4]. This shortfall hampers economic activities, education, and healthcare services, perpetuating poverty and limiting development opportunities. Additionally, around 2.3 billion people still rely on polluting fuels and technologies for cooking, contributing to household air pollution that causes approximately 3.2 million premature deaths annually [5,6].

Inadequate infrastructure and poor waste management systems have further intensified environmental challenges. In regions like The Gambia, plastic pollution has escalated due to insufficient waste disposal infrastructure, contaminating beaches and waterways while contributing to air pollution through uncontrolled burning [6]. Similarly, lack of drainage systems and resilient urban planning has heightened vulnerability to climate-induced disasters.

Beyond its direct impact on livelihoods, infrastructure deficiencies have exacerbated environmental degradation and contributed to climate change. Limited access to modern energy infrastructure forces many communities to rely on traditional biomass fuels, such as wood and charcoal, leading to deforestation and increased greenhouse gas emissions. Additionally, the lack of investment in renewable energy perpetuates reliance on fossil fuels, hindering sustainable

energy transitions [7]. These practices coupled rapid growth in population, industrialisation, and urbanisation contribute are mainly responsible for climate change, a natural phenomenon. While natural factors contribute to climate variability, the overwhelming scientific consensus is that human activities are the primary cause of climate change, particularly due to greenhouse gas (GHG) emissions. Climate change is already causing noticeable changes in the environment and weather patterns.

The signs of climate change are visible worldwide, affecting ecosystems, economies, and human health. In 2024, heavy rains led to devastating floods affecting over 8.5 million people across 20 countries in West and Central Africa. Such disasters highlight how fragile infrastructure exacerbates climate risks, leading to repeated rebuilding efforts without sustainable improvements. The vulnerability of health infrastructure, as seen in Pacific Island countries, further underscores the urgent need for climate-resilient development strategies [10]. Reports from the Intergovernmental Panel on Climate Change (IPCC) consistently warned of the severe consequences of unchecked global warming, including rising sea levels, extreme weather events, and biodiversity loss. The 2014 IPCC Fifth Assessment Report provided strong evidence that human activities, especially burning fossil fuels, were driving climate change, pushing policymakers to take decisive action [11]. As a response to the growing urgency of addressing climate change and limiting global temperature rise, the Paris Agreement emerged and was adopted in December 2015 at the 21st Conference of the Parties (COP21) of the United Nations Framework Convention on Climate Change (UNFCCC) in Paris, France. The Paris Agreement, adopted in 2015 at the United Nations Framework Convention on Climate Change (UNFCCC) Conference of the Parties (COP21), seeks to combat climate change [12]. This is to limit the global temperature rise to well below 2 °C above pre-industrial levels, with efforts to cap it at 1.5 °C, while strengthening resilience and promoting sustainable development [13,14].

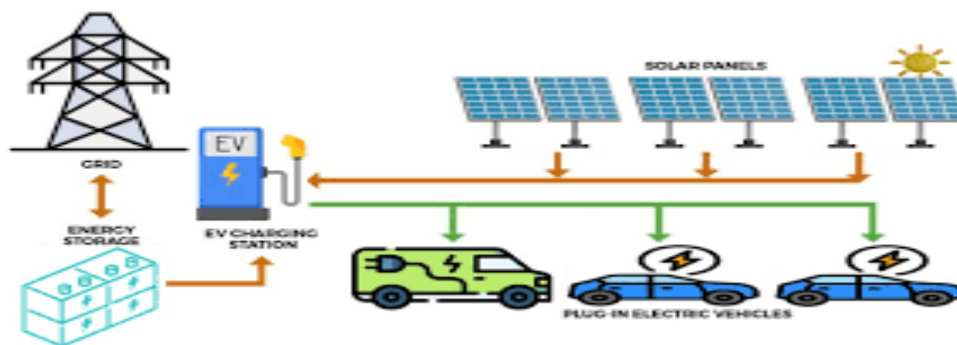


Fig 1: Rooftop Solar Power System

To combat these growing threats requires global efforts in urgent mitigation (reducing emissions) and adaptation (building resilience) [15]. The absence of robust infrastructure hampers effective adaptation to climate change. For instance, inadequate water and sanitation infrastructure can lead to increased health risks under changing climate conditions. Moreover, the lack of climate-resilient infrastructure in urban areas exacerbates the impacts of extreme weather events, leading to greater economic and social losses. The need for building climate-resilient cities in the Global South has been emphasized as a critical step toward sustainable development. Addressing these infrastructure deficiencies is crucial for mitigating climate change and enhancing the resilience of communities in the Global South are essential components of this endeavour [16].

Renewable energy (RE) is pivotal in achieving these goals, offering key benefits, such as decarbonizing energy systems, supporting electrification, enhancing energy security, and fostering innovation and green jobs. Renewable sources, such as solar, wind, and hydropower replace fossil fuels, significantly reducing GHG emissions and supporting sustainable development [17]. Expanding RE infrastructure enhances energy security, stabilizes economies, and reduces dependence on volatile fossil fuel markets. Electrifying sectors like transportation and industry with RE further cut emissions in traditionally high-pollution areas, while decentralized systems, such as solar microgrids, improve access to clean electricity in underserved regions. Integrating energy storage ensures a reliable, stable power supply, addressing intermittency issues.

## II. RELATED WORK

In the Global South (GS), access to affordable, reliable electricity remains challenging, particularly in low-income housing. Solar PV emerges as the most suitable RE option, leveraging high solar irradiance and scalability to meet rural and urban energy needs. It enables flexible deployment, from individual homes to community microgrids, supporting socioeconomic development. However, there are limitations in deploying PV systems, as in many GS regions, there's limited mapping of rooftop area, orientation, or shading potential. Many projects ignore local climatic, architectural, or cultural considerations in system design. Real-world issues like dust, heat, or load profiles are often neglected in performance predictions. However, solutions must be tailored to local conditions, potentially incorporating mixed technologies for maximum impact.

Infrastructure deficiencies of basic amenities, such as water supply, sanitation, roads, and public transport, including unreliable electricity access, are significant challenges in low-cost housing developments in the GS. These issues affect residents' quality of life, economic opportunities, and overall development outcomes. Health risks, economic exclusion, and social inequality [18]. Electricity accessibility refers to the ability of residents to access reliable, affordable, and sufficient electricity for their needs. Many areas in remote, rural, and peri-urban regions lack prioritisation and have limited grid coverage, unreliable supply, and high costs. Even when available, electricity may be too expensive for low-income households, forcing them to rely on alternatives like kerosene or biomass. Consequently, this impacts low-income housing residents with indoor air pollution and respiratory diseases; small businesses hindrances, productivity reduction, and increases reliance on manual labour; lack of power limits communication, information access.

Amid a worsening climate crisis, the global shift toward low-carbon development is accelerating. In China, rural revitalization efforts are improving living standards but also increasing carbon emissions, challenging sustainable ecological progress. Under the “dual carbon” strategy, achieving net-zero goals while enhancing rural living quality necessitates adopting low-carbon, efficient, and sustainable development models. Rooftop solar PV systems play a key role in this transition. Rooftop PV systems offer decentralized, reliable electricity, supporting energy access, socioeconomic development, and environmental sustainability in off-grid rural and remote areas. Benefits include cost-effectiveness and reduced environmental impact, though challenges persist, such as high upfront costs, maintenance needs, energy storage limitations, and policy gaps. Innovative solutions include pay-as-you-go models for affordability, hybrid systems for enhanced reliability, and IoT-enabled smart grids for optimization and remote monitoring.

Solar energy's dependence on sunlight limits its availability during cloudy weather and at night, necessitating investment in costly energy storage solutions. Inadequate grid infrastructure in many countries hinders the integration of solar PV into national energy systems. Poor-quality installations and a lack of trained technicians for maintenance can reduce the efficiency and lifespan of solar PV systems. Many rural areas lack grid access, requiring off-grid or standalone solar PV systems, which can be expensive and challenging to manage. Poor infrastructure for transporting solar components increases costs and complicates installations in remote areas. The limited availability of affordable and efficient battery technologies poses a barrier to consistent energy supply. High dust levels and harsh climates in some areas reduce solar panel efficiency and increase cleaning and maintenance costs. Frequent floods, storms, or other climatic extremes can damage solar infrastructure.

## III. METHODOLOGY

The study employs a mixed-methods approach, integrating both qualitative and quantitative analysis to evaluate the integration of rooftop PV systems. This approach ensures a comprehensive assessment of technical, economic, and environmental aspects. Primary and secondary data sources were utilised for this research. Primary data was collected through theoretical designs and simulation while secondary data was obtained from published literature, international organisation and government reports, and industry standards related to rooftop PV systems. A case study methodology was adopted, focusing on specific locations with significant solar potential. Selection criteria included solar irradiance levels, rooftop availability, and regional energy consumption patterns. The study employed PV system design and simulation tools such as PV\*SOL, to model energy generation. Input parameters included – solar irradiance data, panel efficiency, roof tilt and orientation, and local weather conditions.

The PV roof load-bearing capacity refers to the ability of a rooftop structure to support the additional weight of a PV system without compromising its integrity. Determining this capacity involves several key steps such as analysis of

building's design, construction materials, and existing loads. Other considerations include PV system weight calculation, wind and seismic, deflection and stress analysis, and building code compliance. Structural reinforcements or alternative mounting solutions, such as lightweight PV panels or ground-mounted systems, may be necessary if the roof's load-bearing capacity is insufficient.

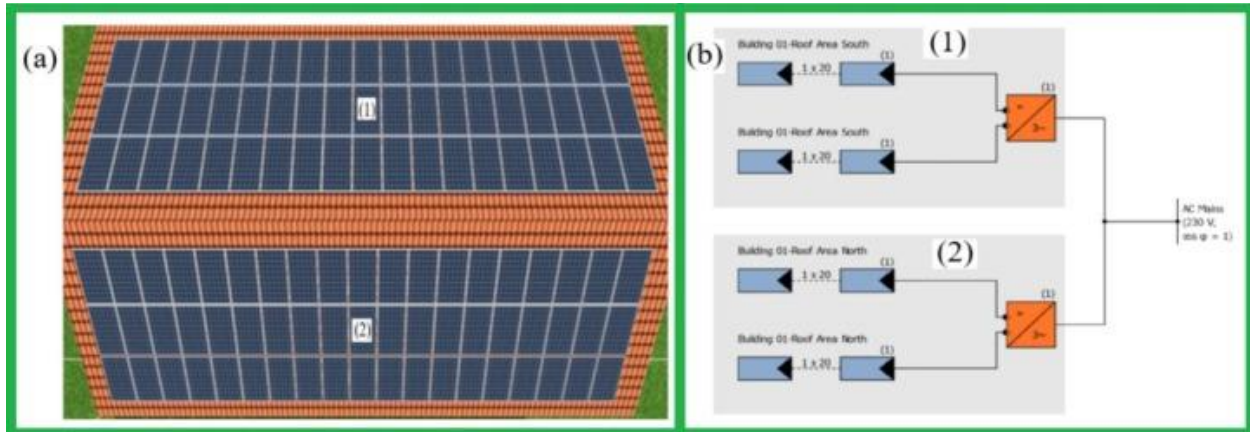


Fig 2: Integrating rooftop PV system in low-cost building

As an initial step in assessing the techno-economic feasibility of PV, the rooftop area available for PV deployment has been estimated. Primarily, there are approaches for evaluating rooftop PV potential at a large scale: the constant value method, manual selection, and GIS-based analysis. The constant value method is the simplest, relying on broad assumptions. The GIS-based approach, though highly detailed and replicable, is resource-intensive, requiring high-resolution data, such as Light Detection and Ranging (LiDAR), which is often not publicly accessible. This study employs the GIS method, as it offers reasonable accuracy and faster than other methods. Despite the manual selection method precision, is time-intensive and lacks scalability, posing challenges for large-scale (nationwide) applications. Solar radiation analysis tools estimate insolation across landscapes or at specific points by employing methodologies derived from the hemispherical viewshed algorithm developed. These tools calculate total solar radiation—referred to as global irradiance—at each location, enabling spatially resolved assessments of solar resource availability. The process involves separate computations of direct, diffuse, and global irradiance for every grid point on a topographic surface, resulting in comprehensive insolation maps of the area under study. Direct Normal Irradiance is critical for concentrated photovoltaic (CPV) and concentrating solar power (CSP) technologies and GHI serves as a key metric for comparing solar potential across climatic zones and for calculating irradiance on tilted surfaces. The solar radiation analysis tools compute insolation throughout a landscape or for locations, centre on techniques from the hemispherical view-shed algorithm. The total radiation is computed for a specific location is given as global radiation. The computation of direct, diffuse, and global insolation is replicated for every featured location on the topographic surface, creating insolation maps for the total geographical area.

#### IV. RESULT ANALYSIS

Mathematical modelling of solar radiation estimation employs various approaches to predict the amount of solar energy reaching a surface—typically horizontal—based on factors, such as geographical location, time of the year, and atmospheric conditions. These models use mathematical equations and relevant parameters to calculate solar irradiance, which represents the solar energy received per unit area. Accurate estimation of solar radiation is fundamental to the design, simulation, and optimization of PV systems. Over the years, numerous mathematical models have been developed to estimate solar irradiance based on varying input parameters and assumptions. Solar resource assessment involves evaluating data, such as solar irradiance and sun hours, to determine solar energy potential.

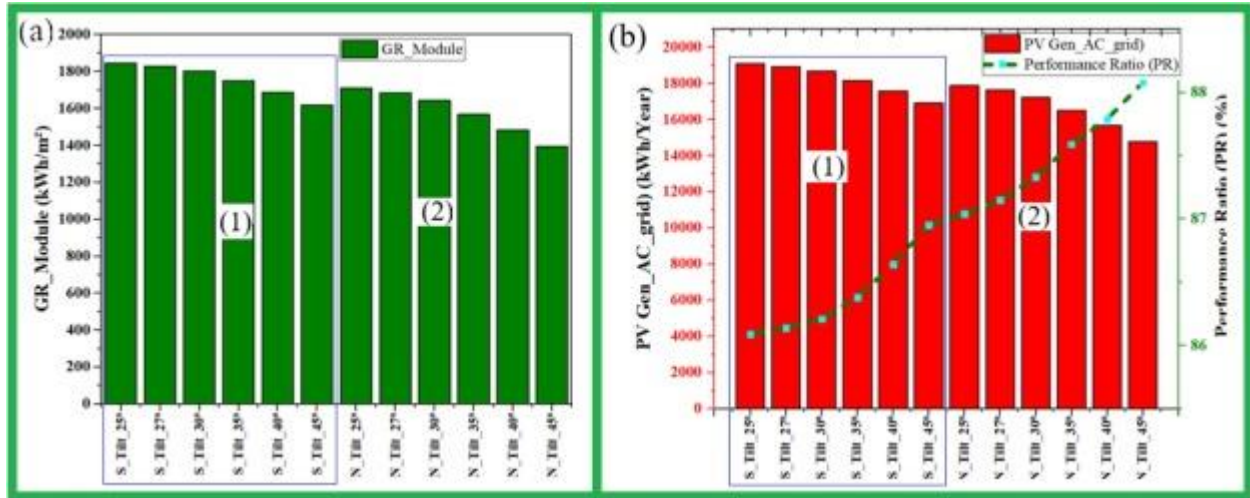


Fig 3: Integrating rooftop PV system in low-cost building plan

The performance ratio (PR) represents the ratio between the actual energy output of a PV system and its theoretical maximum energy output. It is largely independent of the PV plant’s orientation and the incident solar irradiation. PR serves as a key indicator of system efficiency, accounting for meteorological influences, such as solar irradiation, climate variations, relative humidity (RH), and temperature. Mathematically, PR is defined as the ratio between the specific alternating current (AC) electricity output of a PV system and the global tilted irradiation (GTI) received by the PV array surface.

The impact of gable angle was investigated, and the study finds that the roof gable plays a significant role in determining the tilt angle and number of PV modules in a rooftop PV system. The slope of the roof is predefined by the angle of the roof’s pitch and its angle often dictates the tilt angle of the PV modules when installed flush with the roof, as the modules are typically mounted parallel to the roof surface. The tilt of the roof gable affects how much usable area is available for PV module installation, especially on steeply pitched roofs. The optimised fixed tilt for maximising annual energy production at this location is 5.67°

### V. CONCLUSION

This study aimed to enhance the integration of PV systems through efficient design and an innovative system scheme. It highlights the importance of roof geometry and orientation in maximising PV system efficiency while contributing to sustainability goals. Therefore, the study investigated the impacts of roof pitch angles (25°–45°) and two-sided gable PV module mounting on system performance and PV potential using PVSOL, a computational modelling tool that simulates shading and calculates reduced irradiance.

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