Novel Decentralized Solar-DC Systems for Community Energy Self-Sufficiency: A Validated Case Study

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https://doi.org/10.5109/7363479

出版情報：Evergreen. 12 (2), pp.851-862, 2025-06. 九州大学グリーンテクノロジー研究教育センター
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Novel Decentralized Solar-DC Systems for Community Energy Self-Sufficiency: A Validated Case Study

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(Received September 19, 2024; Revised May 18, 2025; Accepted June 09, 2025)

Abstract: This paper explores a novel decentralized approach to energy generation using low-voltage DC solar systems, aiming to enhance community participation and self-sufficiency in energy production. The approach capitalizes on recent advancements in power electronics and promotes the adoption of energy-efficient DC appliances, thereby eliminating the complexity associated with traditional inverters and streamlining both the implementation and maintenance of solar power systems. The study details the developmental journey and testing phases of innovative low-voltage DC solar systems deployed across standalone homes and multi-storey residential buildings. Initial experiments conducted in standalone houses utilizing a 24V DC configuration for ceiling fans, LED lights, and batteries have demonstrated robust performance over a span of five years, consistently maintaining optimal battery conditions across diverse weather conditions. Subsequent implementations in standalone houses with varying load requirements further validated the efficacy and adaptability of the design. Furthermore, the approach successfully scaled to a five-storey residential building context, showcasing significant strides in achieving energy self-sufficiency across multiple households. This was made possible through strategic utilization of shared terrace spaces for solar panel installations, illustrating the practicality and scalability of decentralized energy generation models. The observed achievement of 40% to 50% energy self-sufficiency for basic household needs underscores the model's potential to meet substantial energy demands while promoting sustainability and resilience within communities. Overall, this research contributes valuable insights into decentralized energy solutions, highlighting their capacity to empower communities and accelerate progress towards achieving global sustainability goals.

Keywords: community energy self-sufficiency; decentralized solar power; energy-efficient DC appliances; low-voltage DC systems; sustainable development goal 7 (SDG 7)

1. Introduction

1.1. Setting the Stage

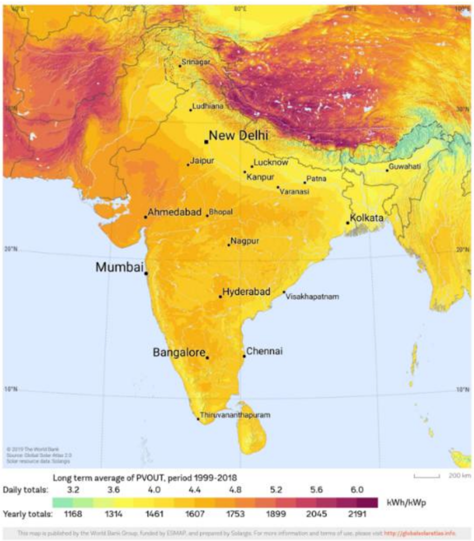
Electricity is indispensable in our daily lives, yet the current centralized model of electricity generation[1,2], primarily dependent on coal-fired thermal power plants, poses significant environmental challenges[3,4]. These plants, while effective in mass energy production, contribute heavily to CO2 emissions, exacerbating climate change[5]. As the Paris Agreement underscores, limiting the global temperature increase to well below 2°C, with efforts to cap it at 1.5°C, is critical. Human activities have already driven a 1.1°C increase, and the impacts are evident worldwide[6]. Thus, reducing reliance on coal and adopting sustainable energy generation methods, such as solar photovoltaic systems, is imperative[7].

Solar power generation can be broadly categorized into on-grid and off-grid systems[8]. Both approaches have seen increased adoption in urban and rural areas, respectively. On-grid systems are suitable for urban environments with reliable grid power[9,10], while off-grid systems are essential in areas with frequent power outages[11–13]. These systems have brought significant benefits, making solar energy more accessible and reducing reliance on fossil fuels. Despite the growing acceptance and implementation of on-

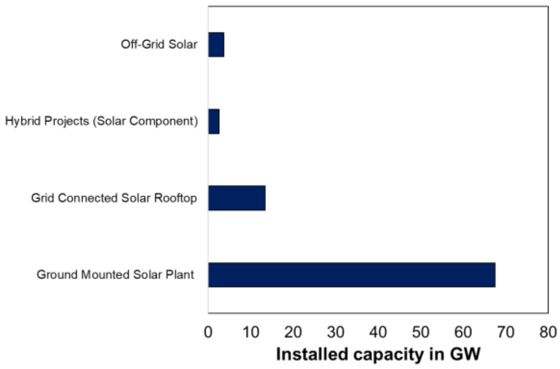
Cite: R. Oza, K. Mehta, A. Bavarva, "Novel Decentralized Solar-DC Systems for Community Energy Self-Sufficiency: A Validated Case Study". Evergreen, 12 (02) 851-862 (2025). https://doi.org/10.5109/7363479.

grid and off-grid solar power systems[14], further exploration is needed to empower individual families to generate their own power[15,16], enhancing energy self-sufficiency and addressing specific household energy needs[17].

According to the data, India's solar power installed capacity was 87.21 GW as of 31 July 2024[18]. India is the third largest producer of solar power globally due to its enormous potential of solar irradiation[19]. Out of this, only 3.70 GW is off-grid solar system. Figure 1 shows the solar potential of India and the distribution of installed solar capacity in India.



(a)



(b)

Fig. 1: (a) solar potential of India (b) Installed solar capacity

While on-grid systems connect to the public electricity grid and provide surplus power back to the grid, and off-grid systems operate independently of the grid, both models often still rely on complex installations and maintenance that can be barriers for individual households[20–22]. Moreover, these systems typically involve the use of inverters to convert DC power generated by solar panels into AC power used by most household appliances, which adds to the cost and complexity[23].

To achieve true energy self-sufficiency at the household level, it is crucial to develop systems that are not only efficient and sustainable but also simple and cost-effective for individual families to adopt and maintain[24–26]. This is where low voltage Solar-DC systems come into play. Here low voltage DC means 48V/24V/12V DC system. It is simple and less complex design. These systems can directly power low voltage DC appliances, such as LED (light-emitting diode) lights, fans, and chargers, without the need for inverters, making them easier to install, use, and maintain. By simplifying the technology and focusing on low voltage applications, these systems can reduce both initial setup costs and ongoing maintenance requirements[27,28], making solar power generation more accessible to a broader range of households[29].

In this work, we focus on 'low-voltage' DC in the 12 V–48 V range, which is widely adopted for off-grid and small-scale PV systems. At 12 V, common loads include LED lighting and USB-charging ports; at 24 V, small BLDC fans and pumps; and at 48 V, higher-power appliances such as refrigerators. Operating at higher DC voltage reduces I^2R cable losses (by up to 75 % when moving from 12 V to 48 V for the same power and distance), lowers conductor cost, and enables use of standardized DC busbars. However, safety clearances and component costs rise with voltage, setting an upper practical bound near 60 V DC. By targeting the 12 V–48 V window, we optimize the trade-off between efficiency, cost, and safety for residential micro-grids. This research proposes the development of off-grid low voltage DC solar systems designed to harness the potential of low voltage DC home appliances.

Such systems eliminate the need for complex inverters, simplifying both implementation and maintenance. By enabling each family to generate their own power, this approach not only contributes to individual energy independence but also significantly reduces CO2 emissions, aiding in the fight against climate change. The potential impact of widespread adoption of decentralized low voltage DC solar systems is profound. It fosters community participation in energy generation, reduces the strain on centralized power grids, and contributes directly to the global effort to mitigate climate change. This study aims to validate the feasibility of these systems through practical implementation in standalone homes and multi-storey residential buildings, evaluating their efficiency, scalability, and overall contribution to SDG-7.

1.2. Problem Statement

The majority of existing solar PV installations incorporate inverters, which are necessary for converting DC (direct current) generated by solar panels to AC (alternating current) used by most home appliances. However, as energy-efficient home appliances increasingly operate on DC, the presence of inverters introduces inefficiencies that need to be addressed. Specifically, inverters necessitate both DC to AC and subsequent AC to DC conversions, resulting in energy losses[30)].

Commercial string inverters in the 1–5 kW range exhibit peak efficiencies of 96–98 % at rated load, but drop to 85–90 % at 20 % loading and incur 2–5 W of standby draw even when no PV is feeding them. For example, a 1 kW inverter operating at 50 % load converts 500 W DC to 480 W AC, wasting 20 W plus idle losses. Over a year, this idle draw alone can add up to 17 kWh which equivalent to powering two LED lights for 12 h every night. Removing the inverter stage thus raises overall system yield by 8–12 %[30)].

Inverters consume power even when no load is present, representing a constant energy loss. Additionally, the conversion efficiency of inverters—the ratio of output energy to input energy—is less than 100%, leading to further energy loss during the conversion process from low voltage DC to higher voltage AC. To mitigate these issues, it is essential to explore solutions that eliminate the need for inverters.

One viable alternative is to design systems that operate directly on low voltage DC for at least partial fulfilment of household energy needs. Here major advantage is that at no load condition batteries do not discharge as compare to inverter-based design where batteries discharge even under no load condition. This improves the system efficiency compare with inverter-based designs. This approach not only improves energy efficiency by eliminating conversion losses but also simplifies system design. Inverters are complex devices requiring sophisticated electronics, which complicates maintenance and increases the likelihood of failures. High technical skills are required for troubleshooting, making technology transfer to society more challenging[23)].

In contrast, simple low voltage DC designs, made possible by the availability of energy-efficient DC appliances, facilitate easier technology transfer to the community. This simplicity enhances the feasibility of achieving community self-sufficiency in energy generation, which is crucial for sustainable development.

Moreover, inverters cause continuous battery discharge even under no-load conditions, as the inverter remains on[31)]. This unnecessary discharge can be avoided with low voltage DC designs, where batteries discharge only when the load is active. Therefore, focusing on low voltage DC solutions can significantly enhance energy efficiency, reliability, and sustainability in solar PV installations[32,33)].

1.3. Gap in the Research

Despite significant advancements in renewable energy generation, particularly through solar photovoltaics (PV), several gaps remain in the current approaches[34)]. Solar PV systems are primarily deployed through two methods: on-grid and off-grid generation. On-grid solar energy generation integrates with the existing grid infrastructure, requiring synchronization of the generated power with the grid, typically facilitated by grid-connected inverters. This technology has seen widespread adoption and substantial growth in installations.

Off-grid solar power generation, on the other hand, provides an essential solution for areas without grid access or with unreliable grid power. This approach, which also relies on inverters to convert DC generated by solar panels to AC for conventional appliances, has been crucial for remote and underserved regions. Both on-grid and off-grid systems have contributed significantly to the adoption of solar energy[35)].

Recent advancements in the development of energy-efficient home appliances that operate on DC voltage present a new opportunity[36)]. Solar panels naturally generate DC power, and with the availability of DC appliances, it becomes possible to design systems that bypass the need for DC to AC (and vice versa) conversions. Conventional off-grid systems necessitate inverters to power AC appliances, introducing conversion inefficiencies and inverter losses. By using DC appliances, these losses can be avoided, enhancing overall system efficiency[37)].

A notable effort in this direction is the 48V DC solution for residential buildings developed by IIT Madras. This centralized approach provides DC power to multiple residential units, reducing energy consumption through the use of energy-efficient DC appliances. However, this model involves a centralized DC module, which can introduce operational challenges and complexity in distribution and maintenance[30)].

The potential for solar DC design is vast, especially with a bottom-up approach that empowers individual families to contribute to energy generation. By designing decentralized, low voltage solar-DC systems for partial energy needs in homes, each family can independently generate and manage their power[22)]. This method involves using commercially available single 330W solar panels to charge 24V battery systems for individual households. Such a decentralized approach simplifies installation and maintenance, reduces complexity, and mitigates operational issues associated with centralized systems.

Therefore, this research proposes a low voltage solar-DC decentralized distributed power system aimed at partial fulfilment of household energy requirements. This system promises to be more general, less complex, and conducive to community participation in energy generation, thus fostering partial self-reliance and contributing to sustainable development goals.

2. Research Design

2.1. Research Question and Objective

This study aims to explore the viability and effectiveness of low voltage solar-DC decentralized power systems for household energy needs. The primary objective is to design a system that maximizes energy efficiency, minimizes complexity, and promotes community participation in sustainable energy generation. To guide this exploration, the following research questions are posed:

What are the technical specifications and design requirements for implementing low-voltage DC solar power systems in standalone homes?

How can energy-efficient DC appliances be integrated into decentralized solar power systems to optimize energy use and eliminate the need for inverters?

What are the challenges for scaling decentralized solar-DC systems in multi-story residential buildings?

2.2. Research Method

To achieve the objectives and address the research questions, this study employed a systematic methodology aimed at implementing solar-DC systems for achieving energy self-sufficiency in residential buildings. The methodology was structured into several key steps, detailed below and illustrated in Figure 2.

To achieve objectives and address the research questions, this study employed a rigorous and systematic approach aimed at implementing solar-DC systems for enhancing energy self-sufficiency in residential buildings. The methodology was structured into several key steps, beginning with community engagement and culminating in the evaluation of system performance and scalability.

The research began by engaging residents within the target community to introduce the concept of energy self-sufficiency. This involved structured discussions and surveys with homeowners across various types of housing units, including standalone houses and multi-story buildings with configurations such as 1BHK, 2BHK, and 3BHK. These interactions were crucial for understanding the diverse energy needs, preferences, and constraints of the community members.

As discussions progressed, it became evident that achieving complete energy self-sufficiency for high-power appliances, such as air conditioners and refrigerators, would require substantial battery capacities and larger solar arrays, posing significant logistical and economic challenges. Consequently, the focus shifted towards achieving partial energy self-sufficiency for essential household loads, such as ceiling fans, lighting, and mobile charging, which are critical for daily living. This strategic shift aimed to balance feasibility with impact, addressing core energy needs while minimizing complexity and cost.

Based on the identified energy needs and feasibility considerations, initial solutions were proposed and accepted by the community. These solutions included the replacement of traditional AC-operated ceiling fans with low-power Brushless DC (BLDC) ceiling fans (28W/35W) and AC tube lights with energy-efficient LED tube lights (20W). The design and prototypes were developed to cater to the specific energy consumption patterns observed during initial assessments, ensuring that each system was both effective and practical for the target users.

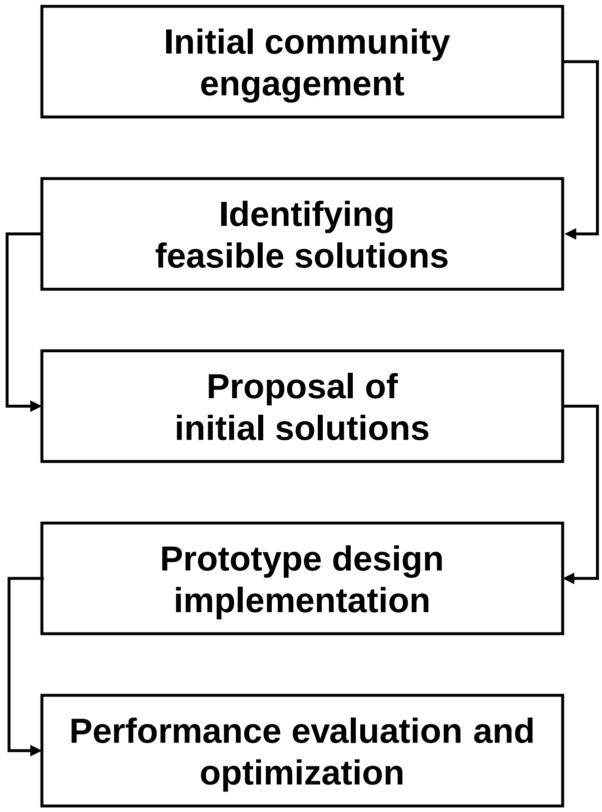


Fig. 2: Research methodology flow of the presented article

The subsequent phase involved the customization and implementation of prototype designs tailored to different house sizes and configurations within the community. This customization ensured that each system was appropriately sized in terms of battery capacity, solar panel requirements, and wiring specifications to optimize performance and efficiency. The installations were carefully tailored to the structural and energy needs of each residence, ensuring reliable operation under varying conditions.

Following the installation of the systems, rigorous performance monitoring and evaluation were conducted to assess the effectiveness of the implemented solar-DC systems. Data on battery charging and discharging currents, as well as voltage measurements at critical points such as solar panel terminals and battery terminals, were systematically collected using digital multimeters. This evaluation phase was crucial for validating system reliability across various weather conditions and operational scenarios, providing insights into the system's performance under real-world conditions.

To support the methodology proposed in this study, a fundamental understanding of the relationship between technology and society is essential. Technology operates within a framework defined by the utilization of available resources, methods of production, consumption patterns, and management of waste—these constitute the core attributes shaping technological systems. Rather than passive consumers, individuals are recognized as active contributors within this framework, engaging in social activities that sustain and maintain these technological cycles. A successful technological society continuously seeks to balance and optimize the interplay between resources, production capabilities, consumption patterns, and waste management. This holistic approach ensures sustainability by minimizing environmental impact and maximizing societal benefit.

The approach advocated here is rooted in social mechanisms that foster cooperation and collaboration within communities for sustainable development. It champions a decentralized model aligned with principles of mass production, empowering each family as a responsible contributor to overall societal development. In contrast, prevailing societal mechanisms often follow a commercial approach characterized by centralized production and planning. This top-down process, while efficient in mass production, can lead to negative consequences such as increased unemployment, environmental degradation, and mass migration. The proposed bottom-up approach aims to mitigate these issues by promoting local entrepreneurship and enhancing community resilience through decentralized energy generation.

Central to this methodology is the adoption of a bottom-up approach to energy generation, focusing initially on meeting basic human energy needs. Emphasis is placed on community participation to achieve self-reliance and foster sustainable development goals, particularly SDG-7 for affordable and clean energy. In this paradigm, the family unit serves as the foundational unit of order, driving the localization of production units to fulfill societal needs sustainably. Implementation and execution of this approach involve practical steps informed by these concepts. The initial implementation phase commenced with a pilot in a standalone house utilizing a 24V DC solar system. This system included specific components such as two 24V BLDC ceiling fans, two 24V DC LED tube lights, and one 24V DC LED lamp, demonstrating satisfactory performance over nearly five years. System maintenance, including the regulation of tubular battery discharge levels and continuous monitoring of battery and solar panel parameters using digital multimeters, ensured optimal performance across varying weather conditions.

Building on this success, the 24V DC design was further deployed in four additional standalone houses with diverse load and environmental conditions, all of which have operated effectively. Encouraged by these outcomes, the methodology was extended to a multi-story building context, where the design successfully achieved energy self-sufficiency in four out of five houses using shared terrace spaces for solar panel installations. Detailed assessments, including calculations of voltage drop in wiring configurations, validated the system's reliability and efficiency. For instance, in a five-story building scenario with an average height of 20 meters, meticulous planning ensured that maximum wire lengths and cross-sectional areas were optimized to maintain acceptable voltage drops, thereby ensuring consistent energy delivery. Ultimately, this methodology supports community participation through localized energy self-sufficiency, contributing to sustainable development goals and mitigating climate change impacts. By fostering a decentralized approach to energy generation, it empowers communities to actively contribute to their energy needs while promoting environmental stewardship and resilience.

2.3. Novelty of Research

The novelty of this research lies in its innovative application of a bottom-up approach to energy generation, targeting partial energy self-sufficiency at the family level and extending to the broader community. This method begins with verifying and implementing solar-DC systems at the household level, ensuring practicality and effectiveness before generalizing the technology for wider societal use. By simplifying the design and maintenance of solar-DC systems and eliminating inverters, the research fosters active community involvement, reduces design complexity, and makes the systems easier to understand and maintain. The proposed design engages complex electronics only during peak sunlight hours, enhancing battery efficiency and lifespan compared to traditional inverter-based systems. Additionally, the elimination of inverters significantly lowers overall system costs, making the technology more accessible and scalable. This approach integrates seamlessly with top-down strategies to achieve Sustainable Development Goal 7 (affordable and clean energy for all), promoting community-wide sustainable energy solutions through a practical, cost-effective, and easily adoptable methodology. Moreover, the research leverages recent advancements in energy-efficient DC appliances, addressing the inefficiencies associated with multiple energy conversions (DC to AC and back to DC), thus minimizing energy losses. This methodological innovation is grounded in the principles of sustainable development, emphasizing the importance of localized energy solutions that can be tailored to diverse residential contexts. By reducing reliance on centralized power systems and encouraging localized energy production, this research contributes to a more resilient and adaptable energy infrastructure, capable of meeting the dynamic needs of modern society while mitigating environmental impacts. The simplified electronics design not only lowers the barrier to entry for adoption but also facilitates easier technology transfer and community training, essential for broad-based implementation and long-term sustainability.

3. System sizing based on consumer typology

This section details the methodology for implementing and evaluating solar-DC systems in various residential settings. The approach is categorized into three types based on house size: small, medium, and large. The methodology encompasses detailed energy calculations, battery requirements, solar panel specifications, and wire sizing for each house type. Practical implementation, customization options, and results from initial prototypes are also discussed. We define three consumer classes—Small (< 500 ft²), Medium (500–800 ft²), and Large (> 800 ft²)—based on a door-to-door survey of 45 rural households in Gujarat. The survey recorded dwelling area, appliance count, and daily usage hours. From the household survey and interaction with the consumers, there three typologies were created for consumers 1) small house 2) medium house and large house.

Household Categories Referenced in the Study:

Small house: Area less than 500 sq ft; equipped with 1 fan and 1 light.

Medium house: Area between 500-800 sq ft; includes 2-3 fans, 2-3 LED lights, and additional LED lamps.

Large house: Area greater than 800 sq ft; outfitted with 2 solar panels (250 Watts), 4-6 fans, 4-6 LED tube lights, and additional lamps.

The prototype implementation starts with a comprehensive analysis of energy requirements for different house sizes: small, medium, and large. Customization is possible in all designs based on actual requirements. The energy calculations, battery requirements, and solar panel specifications for each house type are described below.

To ground our daily-energy budgets in real user behavior, we conducted a door-to-door survey of 45 rural homes in Gujarat, grouped into Small (< 500 ft²), Medium (500–800 ft²), and Large (> 800 ft²) typologies. Respondents reported both the number of appliances in use and their average daily operating hours. Table 1 summarizes the key inputs.

Table 1: Basic of the energy requirements for each typology

Appliance	Nominal Power	Small house Usage [h/day]	Medium house Usage [h/day]	Large house Usage [h/day]
LED	8	4	6	8
Phone charging	10	0.5	1	1.5
BLDC fan	20	2	4	6
TV	60	0	2	4
Refrigerator	100	0	0	3
Misc load	15	1	1.5	2

Aggregating these yields average daily consumptions of 450 Wh for Small, 1100 Wh for Medium, and 1900 Wh for Large households. These Figures align within ±10 % of earlier studies in similar climates[14,25,27], confirming that our typology thresholds reflect real - world usage patterns.

3.1. Consumer typology and system sizing

3.1.1. Small house

For small houses, the proposed design includes essential DC-powered appliances to ensure energy efficiency and sufficiency. The small house design includes one BLDC ceiling fan (12V, 35W) running 12 hours daily, one DC LED tube light (12V, 20W) running 4 hours daily, one DC LED lamp (24V, 12W) running 4 hours daily, and mobile charging for 2 hours (c.f. Figure 3).

The energy requirement for the ceiling fan is calculated as 35W multiplied by 12 hours, resulting in 420 watt-hours (Wh). The LED tube light consumes 20W for 4 hours, totalling 80 Wh. The LED lamp consumes 12W for 4 hours, totaling 48 Wh. Mobile charging for 2 hours requires 10 Wh. The total energy consumption for a small house is therefore 558 Wh per day. To ensure battery longevity, a depth of discharge (DOD) of 50% is considered. Thus, the required battery capacity is double the daily energy consumption, amounting to 1116 Wh. A 12V, 100Ah battery with a capacity of 1200 Wh is deemed suitable. Alternatively, a 12V, 75Ah battery with a capacity of 900 Wh can also be considered based on specific needs.

The daily energy consumption of 558 Wh necessitates solar panels capable of generating more power than required. The installation is done in Gujarat, India. Gujarat receives an average of 5.5 to 6 kWh/m^2/day of solar radiation for more than 300 days a year. Consider solar radiation less than 5.5 KWh/m^2/day so average of 5 hours of sunshine per day, a 150W solar panel can generate 750 Wh per day, which is adequate for the energy needs of a small house.

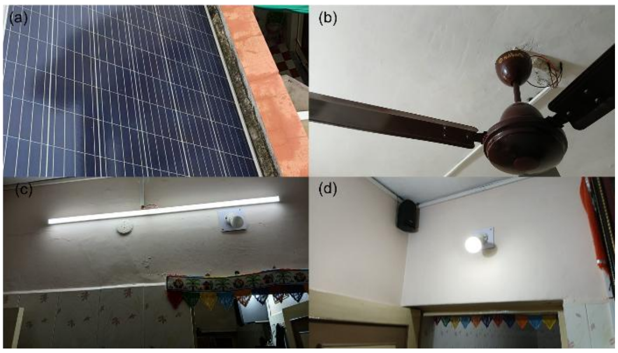


Fig. 3: Installation at small house (a) single solar panel; (b) and (e) DC ceiling fan;(c) LED tube light and (d) Battery

3.1.2. Medium house

For medium-sized houses, the design accommodates a higher load while maintaining energy efficiency. The medium house design includes three BLDC ceiling fans (24V, 28W) each running 8 hours daily, three DC LED tube lights (24V, 20W) each running 4 hours daily, one DC LED lamp (24V, 12W) running 4 hours daily, and mobile charging for 2 hours.

The energy requirement for the ceiling fans is calculated as 28W multiplied by 8 hours multiplied by 3 fans, resulting in 672 Wh. The LED tube lights consume 20W for 4 hours multiplied by 3 lights, totaling 240 Wh. The LED lamp consumes 12W for 4 hours, totaling 48 Wh. Mobile charging for 2 hours requires 10 Wh. The total energy consumption for a medium house is thus 970 Wh per day. Considering a 50% DOD, the required battery capacity is double the daily energy consumption, amounting to 1940 Wh. Two 12V, 75Ah batteries connected in series, providing a total capacity of 1800 Wh, are deemed suitable. The daily energy consumption of 970 Wh requires solar panels capable of generating more power than required. With 5 hours of sunshine per day, a 300W solar panel can generate 1500 Wh per day, which is adequate for the energy needs of a medium house (c.f. Figure 4).

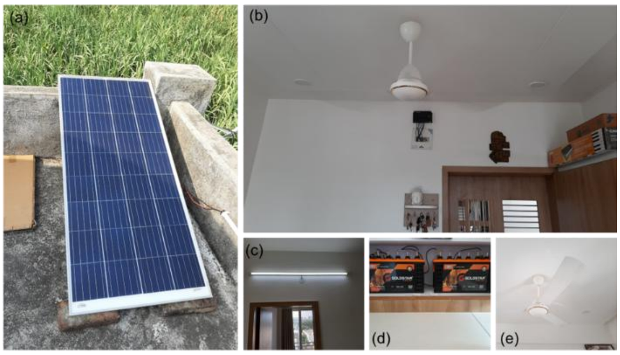


Fig. 4: Installation at medium house

3.1.3. Large house

For large houses, the design addresses a significantly higher load while ensuring efficiency. The large house design includes five BLDC ceiling fans (24V, 28W) each running 8 hours daily, five DC LED tube lights (24V, 20W) each running 4 hours daily, two DC LED lamps (24V, 12W) running 4 hours daily, and mobile charging for 2 hours (c.f. Figure 5).

The energy requirement for the ceiling fans is calculated as 28W multiplied by 8 hours multiplied by 5 fans, resulting in 1120 Wh. The LED tube lights consume 20W for 4 hours multiplied by 5 lights, totaling 400 Wh. The LED lamps consume 12W for 4 hours multiplied by 2 lamps, totaling 96 Wh. Mobile charging for 2 hours requires 20 Wh. The total energy consumption for a large house is thus 1636 Wh per day. With a 50% DOD, the required battery capacity is double the daily energy consumption, amounting to 3272 Wh. Two 12V, 150Ah batteries connected in series, providing a total capacity of 3600 Wh, are deemed suitable. The daily energy consumption of 1636 Wh requires solar panels capable of generating more power than required. With 5 hours of sunshine per day, two 250W solar panels can generate 2500 Wh per day, which is adequate for the energy needs of a large house.

Fig. 5: Installation at Large house

3.2. Wire Sizing and Voltage Drop Considerations

Determining the appropriate wire cross-section area is a critical design parameter to minimize voltage drop across the wire length. Accurate calculations require knowledge of the approximate wire lengths from the solar panel to the charge controller and within the house. Standard copper wire sizes typically used include 1.5mm², 2.5mm², 4.00mm², 6.00mm², and 10.00mm².

For the wire from the terrace to the location of the solar charge controller, assume a length of 50 meters and use a wire with a cross-section area of 10mm². From standard resistance tables, the resistance for a 10mm² copper wire is approximately 0.1Ω for 50 meters. Calculating the maximum voltage drop for a current of 10A using Ohm's Law ($V = IR$), the voltage drop will be 10A x 0.1Ω = 1V, which is acceptable. Conductor size is chosen to limit voltage drop to ≤ 3 %. For a 24 V bus carrying 10 A over 10 m, the minimum CSA is 6 mm² (resistance ≈ 3 mΩ/m drop = 10 A×20 m×3 mΩ/m = 0.6 V, 2.5 %).

For internal house wiring, use a wire with a cross-section area of 2.5mm². The resistance for a 2.5mm² copper wire over 20 meters is approximately 0.16Ω. For a maximum current of 2A, the voltage drop will be 2A x 0.16Ω = 0.32V, which is also acceptable.

These calculations ensure that the voltage drop is minimized, maintaining system efficiency and performance. Accurate wire sizing is essential to reduce power losses and ensure reliable operation of the solar-DC system.

3.3. Battery Charging and Discharging Considerations

An effective approach to battery charging and discharging is crucial for optimizing battery life and system efficiency.

Typically, C/10 and C/20 batteries are available in the market, where C-rate represents the rate at which a battery is charged or discharged relative to its maximum capacity. For a C/10 battery, 10% of the battery's ampere-hour (Ah) capacity is considered. For instance, a 75Ah battery at C/10 would have a maximum charging and discharging current of 7.5A (10% of 75Ah). Similarly, for a C/20 battery, 20% of the battery's capacity is considered, resulting in a maximum charging and discharging current of 3.75A (20% of 75Ah). Maintaining these currents below the specified limits is essential for prolonging battery life. The battery charging current is constrained by the solar panel's capacity, while the discharging current is determined by the load operated during non-sunshine hours. This ensures that the battery is neither overcharged nor excessively discharged, maintaining optimal performance.

4. Practical Implementation and Customization

The practical implementation of prototype solar-DC systems involved a structured and detailed process aimed at ensuring effective customization and widespread adoption. The process began with direct engagement with homeowners, where detailed discussions were conducted to thoroughly understand their specific energy needs and preferences. This initial assessment was crucial in identifying the types of appliances in use, daily energy consumption patterns, and any unique household requirements. These tailored consultations allowed for the design of energy solutions that were highly customized to each household's needs.

Following these assessments, customized prototype designs were developed for three categories of houses: small, medium, and large. These designs took into account factors such as the number of rooms, types of appliances used, and estimated energy consumption. For example, the small house design included one BLDC ceiling fan, one LED tube light, one LED lamp, and a mobile charging facility, while the medium house design accommodated three BLDC ceiling fans, three LED tube lights, one LED lamp, and a mobile charging facility. The large house design was more extensive, featuring five BLDC ceiling fans, five LED tube lights, two LED lamps, and a mobile charging facility. Each design was carefully crafted to meet the specific energy demands of the respective household categories.

The installation phase was critical and involved setting up solar panels, batteries, and DC appliances according to the customized designs. Special attention was given to several key aspects to ensure the system's effectiveness and longevity. Solar panels were properly sized to generate sufficient power based on local sunlight hours, ensuring that daily energy consumption needs were met or exceeded. Batteries were selected with the appropriate depth of discharge (DOD) to ensure long-term performance, with capacities calculated to handle the specific energy requirements of each house category. Additionally, the DC wiring was meticulously designed to minimize voltage drop, with wire cross-sections chosen based on the length of wiring and expected current loads.

After installation, a robust monitoring and evaluation phase was implemented to ensure the systems operated optimally. This phase involved tracking energy consumption for each appliance to confirm alignment with the design specifications, regularly checking battery performance to maintain an optimal depth of discharge, and making system adjustments as necessary. Adjustments might include optimizing the angles of solar panels or fine-tuning appliance usage patterns to enhance efficiency.

This systematic approach, from the initial assessment through to installation, regular monitoring, and ongoing adjustments, ensured that the solar-DC systems were effectively customized and optimized for each household. The iterative nature of this process facilitated the successful implementation of these systems and encouraged broader adoption within the community, ultimately contributing to the achievement of energy self-sufficiency at the community level.

5. Results and Discussion

5.1. Feedback from the consumers

A detailed survey involving a sample size of 10 homeowners was conducted to gather feedback on their experience with the solar DC system. The interviews were structured to collect insights on energy consumption, system performance, and user satisfaction. The findings revealed that before the installation of the solar DC system, homeowners reported an average monthly energy consumption from the grid around 94.5 kWh. After installation, this consumption dropped to 63.1 kWh, indicating a significant 33% reduction in energy usage.

Homeowners observed a notable decrease in their monthly energy bills, with average savings amounting to approximately Rs.220. This financial benefit was largely due to the reduced dependency on grid electricity. Regarding the performance of home appliances, all homeowners reported smooth operation of their devices. In terms of reliability, all 10 homeowners appreciated the consistent power availability provided by the solar DC system. Unlike grid-tied solar systems, the solar DC setup ensured uninterrupted power even during grid outages, greatly enhancing user satisfaction. Maintenance and fault issues were minimal, with all homeowners reporting no critical faults.

The system's performance across different weather conditions, particularly during the monsoon season, was satisfactory according to all homeowners. They reported that with careful use of appliances, the system continued to perform well even during adverse weather conditions. Overall, the feedback was overwhelmingly positive, with all 10 homeowners expressing strong satisfaction and willingness to recommend the solar DC system to others. They cited its reliability, efficiency, and maintenance-free design as key benefits, contributing to their overall high level of contentment with the system.

Beyond hardware, demand-side measures further cut consumption. Replacing 60 W AC fans with 20 W BLDC fans reduces fan load by 67 %. In our survey, 78 % of participants reported routinely switching off lights and chargers when not in use, yielding an additional 10–15 % reduction. Future work could integrate simple feedback displays to drive further savings.

5.2. Energy self-sufficiency achievement

The customer feedback was validated through the analysis of measurement data. Table 1 provides a summary of the energy self-sufficiency achieved for small, medium, and large households. For small households, with a total energy requirement of 2000 Wh, the designed system generated 558 Wh, resulting in an energy self-sufficiency of 27.90% per day. For medium households, where the total energy requirement was 3000 Wh, the system generated 890 Wh, achieving 32.33% energy self-sufficiency per day. For large households, with a total energy requirement of 4500 Wh, the system generated 1636 Wh, yielding 36.36% energy self-sufficiency per day.

Interviews were conducted with 10 homeowners to assess their experiences with energy self-sufficiency. In addition to standard appliances like ceiling fans and lights, other significant loads such as refrigerators, televisions, washing machines, and flour mills were also considered. The daily usage of these appliances varied among consumers, leading to an estimated energy self-sufficiency range of 30% to 40% per day. In cases where the additional load was higher, energy self-sufficiency could be around 20%. This implies that approximately 20% to 40% of the total energy requirements within a household can be met by the system. These estimates were derived by comparing the total energy requirements and monthly energy bills before and after the installation of solar-DC systems.

The reduction in CO2 emissions was also analyzed, with small to large households seeing reductions ranging from approximately 163 kg to 478 kg per year when energy-efficient home appliances were used. When compared to conventional, less energy-efficient appliances, the reduction in CO2 emissions ranged from 326 kg to 956 kg per year.

Feedback from all homeowners was overwhelmingly positive. They reported that the design required minimal maintenance and ensured the smooth operation of various home appliances. The uninterrupted availability of power throughout the day and night was particularly appreciated, especially in contrast to grid-tied solar rooftop designs, which fail to provide power when the grid is down during the day. The solar-DC design, on the other hand, provided consistent power regardless of the time of day or night. Homeowners expressed high levels of satisfaction with the system's performance, noting the absence of any critical faults. Additionally, the system performed satisfactorily across all weather conditions, including during the monsoon season, when careful use of appliances ensured continued reliability. Table 2 presents the results of self-sufficiency achieved through the integration of the novel DC system, categorized by house type, based on measurement data.

Table 2: Energy Self-Sufficiency Achieved in Small, Medium, and Large Households Using Customized Solar-DC Systems

House typology	Total daily energy requirement in Wh	Total daily energy requirement for DC appliances in Wh	Validated energy self-sufficiency achieved
Small house	2,000	558	27.90%
Medium house	3,000	970	32.33%
Large house	4,500	1,636	36.36%

5.3. Challenges for scaling decentralized solar-DC systems

Based on the performed study as well as understanding the consumer aspect, scaling decentralized solar-DC systems face a range of challenges that must be addressed to ensure broader adoption and effectiveness.

Technical standardization is a significant hurdle. These systems often require customized designs to meet the unique needs of different households. However, the absence of standardized components and system designs complicates scaling efforts. Without uniform standards, it becomes challenging to streamline production, reduce costs, and ensure compatibility across various systems.

Cost and affordability also pose substantial barriers. While solar-DC systems offer long-term savings, the initial setup costs—covering solar panels, batteries, and DC appliances—can be prohibitively expensive for many households. Reducing these upfront costs through subsidies, financing options, or economies of scale in production is essential for scaling. Infrastructure and supply chain limitations further complicate scaling efforts. The widespread adoption of solar-DC systems relies on a dependable supply chain for components and the availability of skilled technicians for installation and maintenance. In many regions, particularly remote or underdeveloped areas, these resources are scarce, hindering large-scale deployment.

Policy and regulatory barriers can either support or hinder the scaling of decentralized solar-DC systems. Inconsistent policies, a lack of incentives, or restrictive regulations create significant obstacles. Coordinated policy frameworks that promote renewable energy adoption, provide financial incentives, and simplify regulatory processes are crucial for successful scaling.

Energy storage challenges are critical for the reliability of solar-DC systems, especially in decentralized setups without grid backup. Current battery technologies face issues related to cost, lifespan, and environmental impact. Advancements in battery technology are necessary to improve affordability, efficiency, and sustainability, which are vital for scaling these systems.

Consumer awareness and acceptance is another key challenge. Widespread adoption of solar-DC systems is often hindered by a lack of consumer awareness or scepticism regarding the technology's reliability and benefits. Educational campaigns, demonstrations, and pilot projects are essential for building trust and encouraging broader acceptance.

Maintenance and technical support are crucial for ensuring the long-term success of decentralized solar-DC systems. Providing consistent technical support across a wide geographic area is challenging, especially in remote regions. Developing robust maintenance networks and training local technicians are critical steps in scaling these systems. Integration with existing energy systems poses additional challenges. Scaling decentralized solar-DC systems involves integrating them with existing energy infrastructure, which can be complex. Compatibility issues with current AC-based systems, grid connections, and the need for hybrid solutions must be addressed to facilitate scaling.

Addressing these challenges requires a coordinated effort involving technological innovation, policy support, financial mechanisms, and community engagement to realize the full potential of decentralized solar-DC systems on a large scale.

6. Conclusion

In closing, this study confirms that decentralized low-voltage DC solar systems can deliver meaningful energy independence and environmental benefit in rural households. As summarized in Table 1, daily self-sufficiency ranges from 27.9 % in small homes (2 000 Wh/day) to 36.4 % in large homes (4 500 Wh/day), with medium-sized homes (3 000 Wh/day) achieving 32.3 %. These Figures closely match homeowner reports—typically 30 %–40 % of needs met directly, though heavy usage can lower this to around 20 %. Beyond the numbers, user interviews highlight the system's real-world value: minimal upkeep, uninterrupted power (even during grid failures or monsoon rains), and a sense of autonomy rarely felt with conventional grid-tied setups. Environmentally, annual CO_2 reductions span 163 kg in the smallest homes up to 478 kg in the largest, and reach as much as 956 kg when compared against traditional appliance loads. Still, widespread rollout depends on overcoming hurdles: lowering upfront costs, establishing technical standards, strengthening DC-storage technology, simplifying installation infrastructure, and enacting supportive policies. By tackling these barriers—through targeted R¥&D, financing schemes, and community outreach—decentralized solar-DC networks can play a pivotal role in achieving localized energy self-sufficiency and advancing global sustainability goals.

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