Journal of Physics: Conference Series

PAPER • OPEN ACCESS

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To cite this article: Brajesh Dhiman *et al* 2019 *J. Phys.: Conf. Ser.* **1343** 012095

Study of small scale photovoltaic applications in rural Indian household context

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Abstract. In India, approximately 240 million people do not have access to electricity. Many suburban and rural parts of the country are either not connected to the grid or are served with an intermittent power supply. In such cases, a dependable source is required to avail the electricity primarily for subsistence. Small-scale solar photovoltaic applications become the most reliable and dependable option to provide electricity, and it could be a solution to compensate electricity for households where the national grid is unreliable, or the population density is too sparse. In this context, a case study is performed in order to investigate the feasibility and usefulness of decentralized small-scale solar photovoltaic applications in the context of Indian rural households. The methodology involves field observations conducted in Sonitpur district of Assam, India. Additionally, a Life-cycle assessment (LCA) is conducted using 'GaBi' educational software to assess the embodied energy and energy payback time (EPBT). The socio-cultural relationship of such small-scale solar photovoltaic applications is studied in the human development context of remote villages in Assam state, India. Two different types of decentralized solar photovoltaic distribution models are considered – Solar photovoltaic home system (SPVHS) model and decentralized DC microgrid distribution model. Context-specific benefits are observed for the DC microgrid model over the SPVHS model. Furthermore, the socio-cultural dimensions and issues identified in ownership and maintenance point towards the acceptance of such systems. To fulfil the energy demand by considering affordability and usefulness of design, the DC microgrid distribution model ensured an optimal design based on the rural user requirements. Hence, such systems would address the subsistent energy needs of Indian villages and propel them towards energy self-sufficiency.

1. Introduction

About 240 million people in India are not connected to the electrical power grid, as reported by the International Energy Agency [1]. As per the Government of India, an electrified village should have at least 10% of households having access to electricity, leaving a gap for the rest 90%. In addition, limitations in technical feasibility and financial resources for the expansion of the electrical grid in rural regions result in a high unemployment rate and minimal industrial growth [2]. This draws attention towards exploring opportunities for off-grid energy solutions in the rural Indian context. The low per-capita energy consumption and low per-capita income in remote and rural regions are appropriate for decentralized small-scale photovoltaic applications. Such small-scale photovoltaic applications have become a promising alternative towards energy reliance in rural India (Figure 1). The photovoltaic systems are economical and could form the entry point for renewable energy applications in India. In addition to fulfilling energy needs, photovoltaic systems provide scope for rural development in the socio-cultural context. In comparison to small scale photovoltaic applications, other renewable energy sources (like ocean thermal energy, wind energy, solar farms, biomass, geothermal energy, and hydro energy) exhibits higher installation and O&M costs (operations and Maintenance), and pose geographical and resource constraints within different rural-urban agglomerations in India [3]. Photovoltaic-based power generation improves the socio-economic status and energy reliability in the Indian rural setup and smaller towns [4-5]. Furthermore, the livelihood of people in the rural region improves by providing them with a clean source of energy in the form of solar photovoltaic applications [6–9]. Small scale solar photovoltaic systems can help in: - a) Extension of study time for students in rural areas; b) increasing the access to information; c) improvement in health scenario of rural family d) extension of working hours and e) increasing the sense of security (Figure 1).

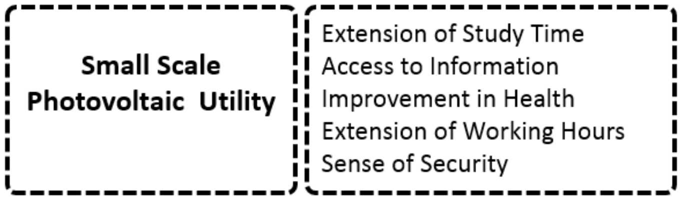

Figure 1. Potential benefits of small-scale photovoltaic applications

2. Advantages of small-scale solar photovoltaic applications

Small-scale solar photovoltaic applications can go beyond meeting daily energy requirements, achieving a deeper social impact in developing countries. A literature review conducted to assess the socio-cultural impacts of small-scale solar photovoltaic applications in the rural context is presented below:

2.1. Health

Applications like solar home system enhanced indoor air quality by significantly reducing the use of fossil-fuel as sources of lighting, resulting in improved health [10]. Samad et al. [11] reported a reduction in the frequency of respiratory disorders due to decreased consumption of kerosene.

2.2. Education

Literature shows that literacy attainment and school enrolment are one of the primary indicators for socio-economic development in rural society [12]. Moreover, the use of solar photovoltaic applications plays an important role in the overall time spent on the education of rural children and enhance the rate of education. Van de Walle et al. [13] observed an enhancement in the overall time-period of schooling for girls.

2.3. Productive usage of solar photovoltaic energy

Samad et al. [14] observed a significant increase in household income with access to electricity. Rud reported the significant impact of solar photovoltaic energy on productive work-hours and increased output, as access to electricity not only resulted in growing activities related to business but also promoted micro-enterprises [15]. A study done in rural Assam in India has shown an improvement in opportunities for income generation and employment after the introduction of the solar photovoltaic home system (SPVHS) [9]. Moreover, Implementation of SPVHS also improves the paid-work opportunities for rural women, as reported in [16].

3. A study outlining the relevance of solar photovoltaic system in rural India

This study is conducted in Sonitpur district of Assam (a state of India) with the help of AEDA (Assam Energy Development Agency). The scope for development of context-specific solar photovoltaic applications is high as rural India has poor access to electricity. This study reported that small-scale photovoltaic energy applications were much preferred as a cost-efficient, clean, and reliable source of energy. It is noteworthy to mention that consideration for socio-economic relevance while designing photovoltaic application like SPVHS indicates an important criterion for user preference.

3.1. A study conducted in the rural setup

Energy-starved villages in district Sonitpur has been identified for the study, considering its poor connectivity to the grid. A qualitative study of 42 families (N=42) is done with the help of AEDA. State nodal agency for energy development installed the SPVHS in the rural villages. In addition, local liaison was done with Chaiduar Rural Development Centre (a local NGO), which works with women weavers of the *Bodo* community (Figure 2a). In this study, a 40-watt peak (Wp) photovoltaic module (having an efficiency of 12%), 12V-40Ah lead-acid tubular flooded battery, and CFLs (3 and 5 watts) are used. In the aforesaid system, the charge controller was absent.

Figure 2. Study in rural setup a) Rural women weavers using solar photovoltaic system for weaving of cloth and b) student making use of solar photovoltaic system for study

Introduction of such systems to womenfolk in the rural community of weavers resulted in the extension of work-hours and increased productivity. Increase in work productivity directly impacted monthly earning of family, resulting in the improved socio-economic condition. It is further observed that tribal families with the intervention of SPVHS can provide a conducive environment and a safe source of domestic lighting for children, which improves their overall study hours (Figure 2b). Furthermore, the intervention of SPVHS reduced the consumption of kerosene, which is a polluting and unhealthy source of energy. This resulted in monthly savings and improved health due to the reduction of kerosene-related emissions. The social acceptance of SPVHS improved due to an increased monthly income of tribal families. The enhanced production of handlooms (due to the introduction of SPVHS) has empowered tribal women towards attaining self-reliance.

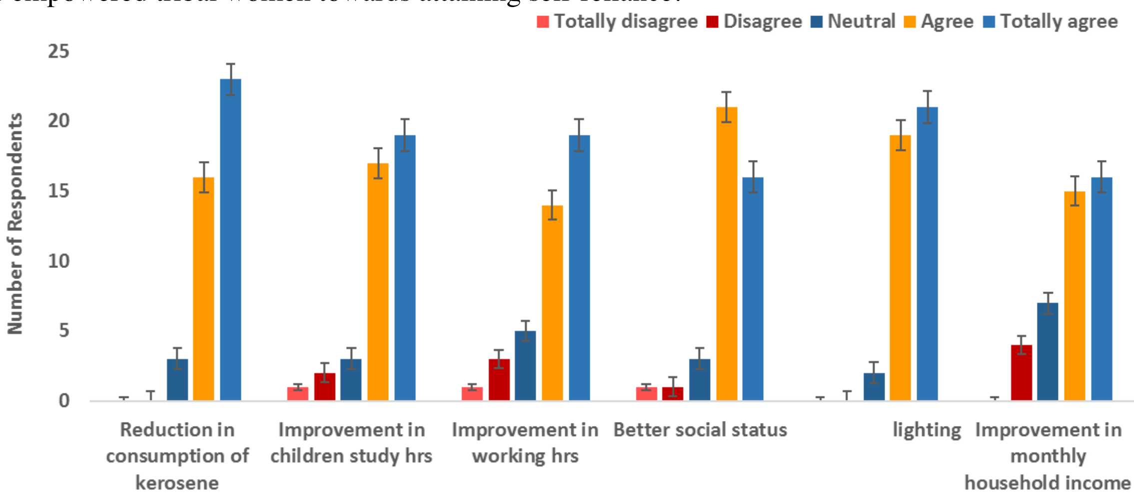

Figure 3. Social impact of small-scale photovoltaic home system as reported during the study

Moreover, the study reported that people in this area show a positive inclination towards SPVHS and are willing to adopt such systems in their homes. In the survey, samples were collected to record the impact of photovoltaic systems, for about six months from March till August 2018. The results obtained are showing the social impact of such systems (Figure 3). Furthermore, the environmental sustainability aspects of such small-scale photovoltaic systems need careful considerations because of the increasing threat of global warming and climate change. Hence, it would be interesting to observe the sustainability aspects of such photovoltaic systems from a life-cycle perspective.

4. Lifecycle Assessment

A simplified lifecycle assessment (LCA) of an SPVHS in the rural context is conducted using GaBi educational software. The life-cycle stages studied are pre-processing (raw materials), manufacturing phase (photovoltaic panel, battery, charge controller, plug loads), transportation phase, installation and use phase, maintenance, and disposal phase. The lifespan of this system is taken as 20 years. The functional unit of this LCA is a *provision of electricity by one multi-silicon solar photovoltaic panel for 20 years*. The flows, processes, lifecycle stages, and system boundary of the LCA are given in Figure 4. The impact assessment method used is CML 2001. It is observed that the production of the solar photovoltaic panel production (CED-3230 MJ/m^2 and Emission- 46 gCO_2/kWh) and the manufacturing of the battery (39-45 MJ/kg and 2.3 gCO_2/kg) have the highest embodied energy and emissions profile. While the disposal stage of these systems presents unforeseen challenges, as recycling the photovoltaic panels is a complicated process. The cumulative energy demand of silicon production and processing is highest (2110 MJ/m^2); followed by the assembly of the photovoltaic panel (243 MJ/m^2), and production of photovoltaic cells (108 MJ/m^2). The most water depleting process is found to be the silicon production and processing, and most particulate matter formation is also exhibited by silicon production. Hence, production and pre-production processes have high embodied energies as compared to other processes. Energy payback time (EPBT) is the time taken for the solar photovoltaic system to payback its embodied energy. The solar insolation for Sonitpur district is 4.29 kWh/m^2/day which translates into 1565.85 kWh/m^2/year. The EPBT of the SPVHS is 0.82 years (assuming 70% as the efficiency of the whole system).

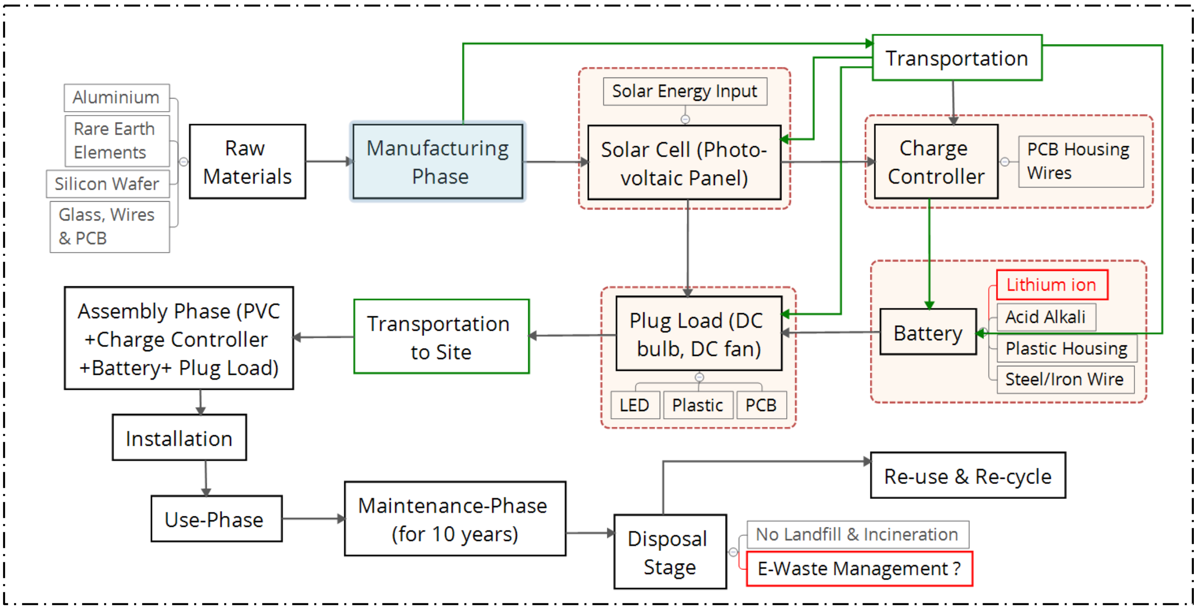

Figure 4. The lifecycle of a small-scale solar photovoltaic system in the rural context

5. Distribution model(s) for solar photovoltaic energy in India

Two decentralized distribution models are proposed to provide solar photovoltaic energy to rural homes in Indian villages. Figure 5 shows the schematic plan of solar photovoltaic home system (SPVHS) distribution model and the decentralized DC microgrid based distribution model. It can be noted that in the microgrid distribution model, community/social spaces have the photovoltaic panel and the battery, from which the electricity is sourced to 3-4 houses with common ownership. Meanwhile, the SPVHS model has photovoltaic (PV) panel power-supply for individual houses with a private ownership model. The system architecture of these models is described in the subsequent section.

5.1. Description of system architecture

System architecture for both SPVHS and decentralized DC microgrid system is shown in Figure 5. The details are described in further subsections.

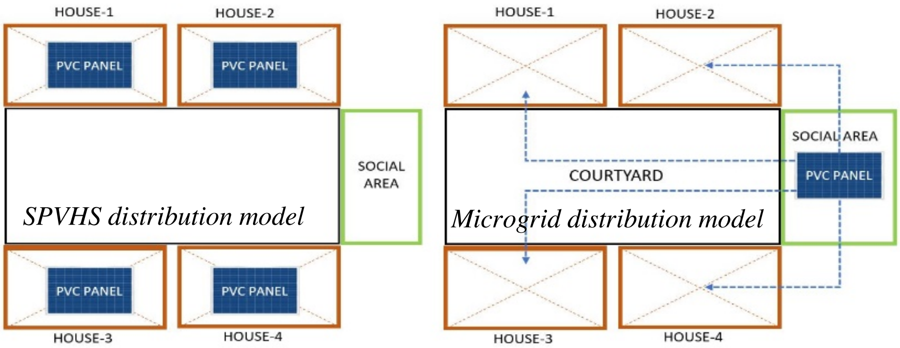

Figure 5. Schematic of SPVHS distribution model and decentralized microgrid distribution model

5.1.1 Solar photovoltaic home system

Basic parts of SPVHS (figure 6a) consist of photovoltaic panels, energy storage system (Batteries), charge controller, and DC loads (lights, fan, mobile charging hub, Television). The charge controller regulates the power flow from the photovoltaic module to the battery bank and from the battery bank to various DC loads.

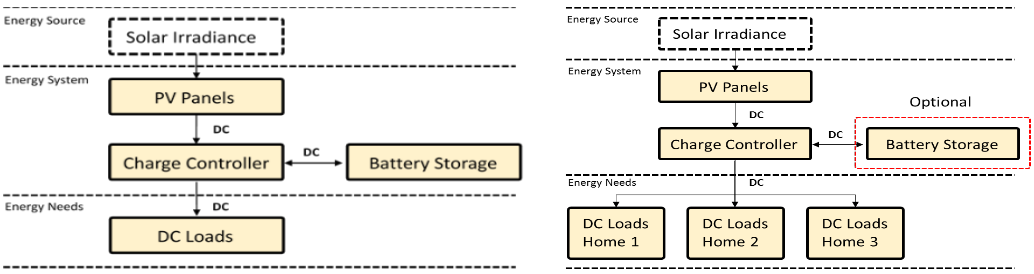

Figure 6. a) Basic architecture of solar photovoltaic home system and b) basic architecture of decentralized DC micro grid system

5.1.2 Decentralized DC microgrid system

The critical parts of a microgrid as seen in figure 6b consist of photovoltaic module/s (and in some cases battery bank) to fulfil load requirement for the cluster of 3-4 rural households. Microgrid, a term coined by Lawrence Berkeley National Laboratory, is “a small electrical domain, connected to the less than 100 kW grid output and is limited to a network of less than 5 kW off-grid loads”.

Ownership of the photovoltaic system plays a pivotal role in the success of such schemes in the rural Indian context. Moreover, the individual ownership model in SPVHS system provides for better maintenance, care, and durability of the system while raising the life-cycle cost and *embodied energy* of the system. On the other hand, the decentralized microgrid distribution model provides increased energy and resource efficiency while exhibiting issues in maintenance and installation. It is observed that in terms of flexibility of use and operational cost, the decentralized DC microgrid system displayed efficiency when compared with SPVHS. On the contrary, it was observed that the sense of ownership is low in the microgrid system due to the sharing of power among households. Nonetheless, installation of such systems will gradually improve the technical capability of the user to maintain the system. It is noteworthy to mention that this could create an opportunity for startups to install and maintain photovoltaic systems creating opportunities for employment in the rural context. Considering the affordability and usefulness of design, the DC microgrid distribution model ensures an optimal design to fulfil the energy need based on the rural user requirements. Hence, such a system could be beneficial to society in addressing their subsistent energy needs. Hence, it can be inferred that a decentralized microgrid system with proper maintenance and ownership structure could go a long way in ensuring the socio-economic success of photovoltaic systems in the rural context.

6. Conclusion

Small-scale photovoltaic applications can serve as an empowering technological solution to energy poverty in rural India. Such multi-dimensional applications facilitate socio-economic benefits like creating job opportunities, an extension of work-hours, better health and education opportunities, and upliftment of overall sustainability of rural society. In addition, the environmental and socio-cultural sustainability of such systems needs to be studied in detail as it is seen that the production and disposal of photovoltaic panels are highly energy consuming and have a high emissions profile. In terms of their embodied energy and emissions profile, the production of battery and photovoltaic panels show maximum footprint. Furthermore, the disposal of these panels could be an area of concern in the near future. This study also opens a design opportunity for photovoltaic energy-based applications at the systemic level. For a developing country like India, the introduction of small-scale photovoltaic applications like SPVHS and DC microgrid can help to improve the self-reliance of the villages.

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