

# **A Study of Design Intervention for Discrete Off-Grid Photovoltaic Home System in Rural Lifestyle Context.**

*Thesis submitted in partial fulfillment for the requirements for the degree of*

***Doctor of Philosophy***

*in Design by*

**Brajesh Dhiman**

(Reg No 156105014)



Department Of Design

**Indian Institute of Technology Guwahati**

Guwahati – 781039, INDIA

April 2020

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Under the supervision of

**Professor Debkumar Chakrabarti**



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## Declaration

I hereby declare that the work contained in this thesis entitled “A Study of Design Intervention for Discrete Off-Grid Photovoltaic Home System in Rural Lifestyle Context” is my work and done under the guidance of Dr. Debkumar Chakrabarti, Professor at the Department of Design, Indian Institute of Technology Guwahati, Assam, India. To the best of my knowledge, it contains no materials previously published or written by another person or substantial properties of the material which has been accepted for the award of any other degree or diploma at Indian Institute of Technology Guwahati or any other educational institution, except where due acknowledgment is made in the thesis. Any contribution made to this research by others, with whom I have worked at Indian Institute of Technology Guwahati or elsewhere, explicitly acknowledge in the thesis. I declare that the intellectual content of this thesis represents my work and words. I have adequately cited and referred to the original work where others’ ideas, work, and words have been included. I also declare that I have adhered to all principals of academic honesty and integrity and not misrepresented or fabricated or falsified any idea/ data/ fact/ source in my submission.

Place: IIT Guwahati  
Date: April 2020



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## Certificate

This is to certify that the work contained in this thesis titled “A Study of Design Intervention for Discrete Off-Grid Photovoltaic Home System in Rural Lifestyle Context” submitted by Mr. Brajesh Dhiman to the Indian Institute of Technology Guwahati for the award of the degree of Doctor of Philosophy has been carried out under my supervision. This work has not been submitted elsewhere for the award of any other degree or diploma.

Place: IIT Guwahati  
Date: April 2020

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## **To Parents, Wife and beloved Sons**

Sh. Bansi Lal  
Smt Swarn Lata

Smt Bandna Dhiman  
Ananmoy Dhiman  
Ojas Dhiman





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## Abstract

For a developing country like India, which currently has more than 239 million people without access to energy, propagation of decentralized energy utility especially solar photovoltaics is of utmost importance, as the country has enormous potential for it. The existing literature emphasized the need for energy research towards energy systems in a broader socio-cultural context. Due to 'top-down' approach for the dissemination of decentralized energy, design and technology aspects never recognized the needs of rural society leading to the failure of most of existing decentralized energy applications and programs in regional context of northeast India. Thus, there exists an opportunity to bridge the gap between rural photovoltaic utility and shaping its social relevance with product design intervention. This doctoral study aimed to build the impetus of research to look into the design and development of a discrete off-grid photovoltaic system considering local imperative needs in the context of the rural background of northeast India.

Study deliberates the scope to facilitate the productive usage of photovoltaic energy through design intervention. To achieve the research objectives we set to explore, design, and develop different aspects of the discrete off-grid solar photovoltaic home system considering inter-household energy exchange, and household enterprise productivity in a localized context to assess the impact of proposed design intervention in the context of a rural lifestyle with specific reference to the northeast region of India.

The methodological approach followed in this research takes inspiration from research through design and ethnography. As part of the methodological approach, an intervention is designed, implemented, and investigated with a mixed-method study, conducted at seven off-grid villages of district Sonitpur and Majuli in rural Assam for approximately one year (1 August 2017 – 31 September 2018). Design criteria and specifications for design intervention were concluded from the field study. Besides, the system architecture and design concepts were shortlisted using fuzzy multi-criteria decision-making method. In the context of the above, Matlab@Simulink based simulations were done for context-specific hardware development. Hardware assembly and testing were done for the fabrication of the

high-fidelity prototype. The design intervention reported assisting energy exchange and rural enterprise productivity in the studied region.

Theory of change framework was applied to formalize design evaluation by providing evidence concerning the anticipated impact of design. In this quasi-experiment study, conventional and proposed design groups were selected as two user groups, and pre-intervention, the post-intervention variance was examined between the groups. The independent sample study was made for the comparison between the conventional and proposed system. It captured the actual field condition that arrived while validating the design intervention. Study witnessed that discrete SPVHS design improved household enterprise work productivity. Besides, the intervention also resulted in mutual energy exchange benefits when compared with a conventional system. The qualitative data reveals three types of mutual energy exchanges: 'mutual energy sharing' (MuES), 'mutual energy trading' (MuET), and 'mutual energy lending (MuEl). The study defines a 'mutual energy sharing' as a social and personal energy exchange where an energy-giver and energy-receiver participate for the sake of social relationship between them. In contrast, 'mutual energy trading' is a social and personal energy exchange where an energy-giver or donor and energy-receiver participate in a calculated exchange for monetary gains. Furthermore, study witnessed that MuES and MuEl encouraged social cohesion between households as the proposed intervention found coherent with rural lifestyle needs.

Overall, the research highlights that to address the array of challenges related to solar photovoltaic energy in the northeast region, it requires a systemic approach for design development. The study indicated that for design development; alone cannot provide an acceptable energy solution if not embraced to societal relevance. In particular, it is crucial to develop design solutions that take into account the localized context. Present research recommends to energy researchers and practitioners that design development of small-scale off-grid system needs to enable diversity in peer-to-peer energy exchange, and is found critical for the dissemination and sustainability of photovoltaic interventions in the regional context.

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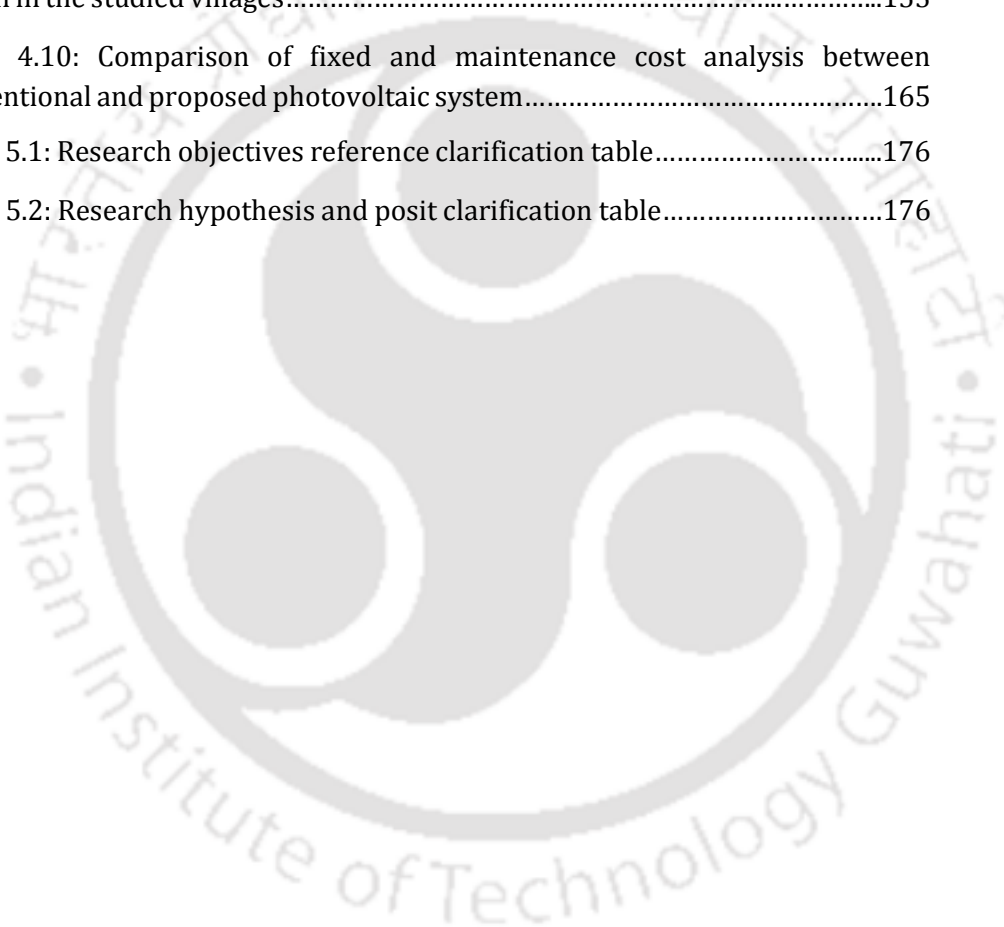
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*“Have you worked out the problem of electricity for every home?  
My remark quoted by you is a poser for the time being  
... Since you believe in it I want you to work it out and  
demonstrate the physical and economic possibility of ‘electrifying  
every home’ of the seven hundred thousand villages of India”...*

**Mahatma Gandhi's letter dated 30 April 1945 to Shri Amiya Nath Bose<sup>1</sup>**

Amiya Nath Bose, returned from Cambridge with an Economics Tripos, worked out a rural electrification plan on Mahatma Gandhi's request, with no access to electricity for 45 million households (REC, 2017). Even to date, household access to energy remained abysmally low and slow. The shifting regimes continued without probing more in-depth into the issues and challenges of electricity access to rural households (Palit & Bandyopadhyay, 2017). Concerning the mentioned above, the design intervention for small-scale decentralized energy applications indicates a promising potential pivotal to the rural setting of India.

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<sup>1</sup> <http://www.dailyo.in/politics/mahatma-gandhi-indian-freedom-struggle-sarat-chandra-bosepartition-congress/story/1/6599.html>; last accessed on 20 November 2017.



# Chapter 1

## Scope of Decentralized Energy-Based Design

**Chapter One** of the thesis describes the study background, motivation, and scope. This section is a research justification that sets out the need to study decentralized energy, especially solar photovoltaics, in the regional context of the rural mode of life. The chapter reviews the existing energy scenario and highlights the importance of a product design-based approach to address the challenges for photovoltaic energy in a regional context. Furthermore, it deals with design intervention for an off-grid photovoltaic home system, context-specific to fulfill local needs, and establishes the critical role of photovoltaic utility for rural development. It defines the current research gaps that lead to the proposed hypothesis to pose particular research questions.

## **1.0 Introduction**

The compatibility of an appropriate design and technology for a decentralized energy-based application like an off-grid photovoltaic system to the beneficiary is usually not considered and promoted with the consideration that the users will modify their lifestyles with the given design and technology (Palit, 2003; Barman et al., 2017). Concerning the reference above, the inadequate understanding of consumer needs, lead to inappropriate solutions (AEDA 2016) to fulfill the user requirement. Attempts to promote solar photovoltaic applications such as solar home system (SHS), solar lamps (SL), etc. must consider the importance of localized design intervention to facilitate its social relevance. The design and technology aspects for photovoltaic products never recognized the regional or local needs of rural society leading to failure for most of the existing applications and programs in the regional context of northeast India (Barman et al., 2017; Dhiman et al., 2017). The regional challenges for the dissemination of decentralized energy led to the failure of many energy applications and development programs adopted by relevant authorities from time to time.

In the context of the above, negligible attention had paid to the issue of adopting design and technology specific to rural lifestyle needs. The present study was an attempt to explore the suitable and socially relevant design for the off-grid photovoltaic home system, considering the poor state of rural electrification in the regional context of north-east India.

### **1.1 State of Rural Electrification in India**

Rural electrification is a valuable program to improve the socio-economic conditions of the villages in India. It facilitates economic development, supports the sustainability of livelihood by providing electricity as input for efficient uses in remote rural areas and contributes to improving the livelihood (Nouni, Mullick, & Kandpal, 2009) in general. Considering that the majority of the Indian population lives in rural villages; therefore lack of access to energy has been a significant challenge, with about 43% of the rural population still awaiting access to electricity (India Census, 2011). According to statistics from the Rural Electrification Corporation, approximately 55% of rural homes in Bihar stay un-electrified, followed by Uttar Pradesh (52%) and Assam (47%) (REC, 2017). It is a significant barrier to

the socio-economic growth of rural India (Cabraal, Barnes & Agarwal, 2005; Cook et al., 2005; Bernard, 2012; Dinkelman, 2014), and that in developing countries, more than a billion people remain without access to household electricity (Dugoua, Liu, & Urpelainen, 2017). Specific efforts are made by the government to ensure coverage of all corners of India, and in this context, decentralized energy, especially solar photovoltaics, is given urgent attention.

The data shows that rural electrification is more costly than urban electrification. It is due to decreased capacity utilization rates and lower load densities, higher installation costs of transmission lines, and regular infrastructure maintenance costs (Liming, 2009). Low load densities, lengthy distribution lines, and significant losses in transmission and distribution make many programs for rural electrification economically unattractive for conventional grid development. Notwithstanding the apparent economic and social objectives, Indian rural electrification programs still need to gain momentum in bringing about the expected advances in rural people's lives. (Bhattacharyya, 2006).

Decentralized energy is a feasible and more effective alternative for rural electrification (Bhattacharyya, 2006; Nouni et al., 2009; Banerjee, 2006). Modern advancements in energy technology have strengthened its potential use in the form of off-grid electricity to fulfill end-user needs (Mahapatra & Dasappa, 2012). Rural electrification is a critical feature in attempting to bring about the underprivileged population's socio-economic development. The Indian experience suggests that a holistic and systemic approach needs to be developed that goes beyond merely providing 'physical access.' Improving access to energy through rural electrification requires engaging the rural communities and social structures rather than merely adopting a technical solution (Barnes, 2007). Admittedly, product design provides the relevant scope to be embraced to improve energy access in the context of the rural parts of the developing countries. In continuation, for electricity supply systems to embed in a specific strategy related to the social and cultural context, product design can play a crucial role. The type and degree of social embeddedness become a significant factor in the electricity supply system's success (Ulsrud, Rohracher, Winther, Muchunku, & Palit, 2018).

The socio-technical design also shapes the type of electricity access. Affluence tends to inequitably distributed, and since electricity has charged in monetary terms, economically weaker groups are at the possibility of being excluded from access (Studies, 2018; Cheruiyot, K. K. 2010; Leach, Stirling, and Scoones, 2010). Therefore, it is essential to understand the requirements of different groups of people and the challenges they face to take advantage of the electric facilities. In this context, the decentralized energy sources have the potential to demonstrate the efficacy of off-grid generation on a small to large scale. Decentralized electrification signifies generating and distributing local power, eliminating the need for a transmission. The ecosystem of renewable power generation includes various technologies like photovoltaic systems, wind turbines, micro-hydro, and biomass gasification. Primarily solar photovoltaics based solutions are found more feasible for the rural Indian context. The current study considers the systemic purview of electrification based on solar photovoltaics from a product design perspective while retaining a focus on the rural household. A prospective future energy scenario, as seen with the electric continuum, indicates the potential for the development of the photovoltaic application.

## **1.2 Electric Continuum depicting Future Scenario**

A continuum of decentralized electricity technologies has evolved over the previous decades (fig. 1.1). It does not involve the same networks of support as conventional power generation and overcomes the limits of facilitating access to energy (Alstone, Gershenson, & Kammen, 2015) — paired with advanced technology, low-cost photovoltaic generation provides scope for scalable energy generation from megawatts to fractions of a watt, when compared to centralized generation facility. Rapid and constant advances in LED lighting reliability (Azevedo, Morgan, & Morgan, 2009) enable decentralized power and appliances to compete for elementary household needs based on energy running costs. These rapid advances in off-grid technology are expected to continue in the future (Azevedo et al., 2009; Feldman et al., 2015; Jeff, 2004).

### 1.3 Decentralized Energy Technologies and Applications

There exist scope for decentralized applications at a small scale that is particularly suitable for providing electricity services in rural areas (Dhiman, Kumar, Rituraj, & Bhalla, 2019). Furthermore, it is suggested that decentralized energy technologies

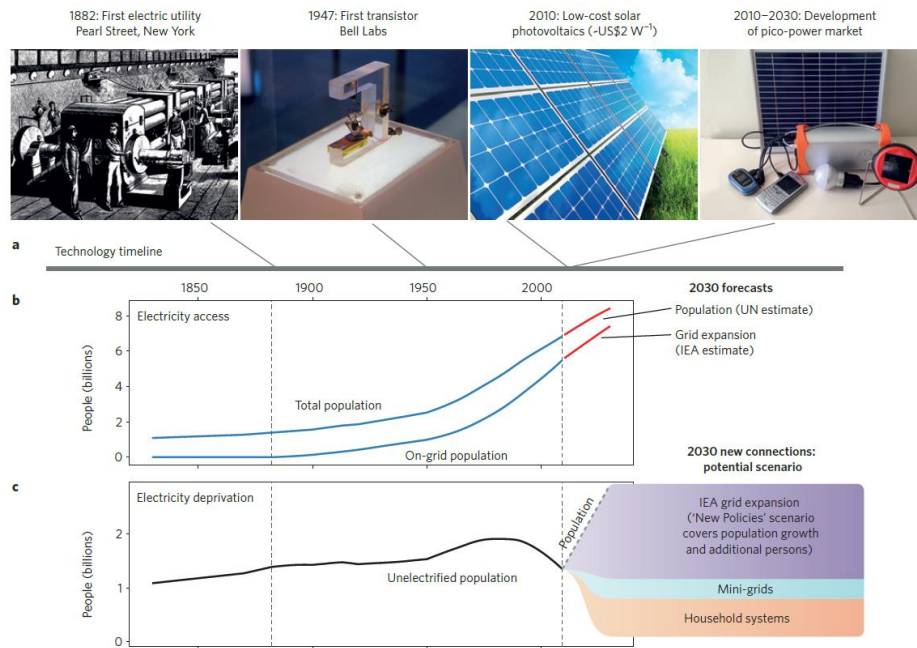


Fig. 1.1: Historical developments and a prospective future scenario for electricity in the context of technology a) timeline of technology displaying significant development times and economic paradigm changes b), c) population with connections to electricity over time, with c) representing prospective future scenarios for the development of decentralized electricity (Source: Kammen, D.M. et al 2015)

and applications (DETA) can provide reliable local power, customized to meet specific user needs (Havet et al., 2009). They also operate on a smaller scale (kWh) suitable for local needs and are accessible in remote generally have low upfront costs and can help avoid grid-related high transmission and distribution costs (Alazraque-Cherni, 2008). The advantage of DETA is that its locations are closer to rural stakeholders. (Kaundinya, Balachandra, & Ravindranath, 2009). Besides, considering the limited scope of conventional grid-based rural electrification programs in developing nations to reach small, scattered rural communities, the prospect of adopting DETA is particularly significant (Goldemberg, 2000; Alazraque-Cherni, 2008). Shifting to decentralized energy can significantly improve poor people's productivity. By 2040, renewables achieve two-thirds of global power plant investment as they become the

least costly source of energy generation for many countries. Concerning the above, government policies throughout the world continue to support renewable-based electricity generation.

### **1.3.1 Scope and Possibilities**

Worldwide, with a growing emphasis on renewable energy technologies due to shortcomings of the conventional grid (Shukla & Bairiganjan, 2011), many scholars have called for enhanced attention to off-grid grid solutions (Kaundinya, Balachandra & Ravindranath, 2009; Alstone, Gershenson & Kammen, 2015). Energy scientists and practitioners have envisioned a systemic transition for electrical energy systems towards decentralized off-grid energy systems (Saad, Glass, Mandayam, & Poor, 2016; Parag & Sovacool, 2016; Ballo, 2015; Ilic, Da Silva, Karnouskos, & Griesemer, 2012a; Van Der Schoor, Van Lente, Scholtens, & Peine, 2016). The main characteristics of this shift are energy to be generated, stored, distributed, and consumed locally, facilitating the productive use of energy. Energy literature predicts that these energy systems will become more social, where local households play an essential part not only in energy production and consumption but also in power distribution (Saad et al., 2016; Parag & Sovacool, 2016; Van Der Schoor et al., 2016; Bellekom, Arentsen & van Gorkum, 2016; Zhou, Yang & Shao, 2016). This aspect is essential to enable rural productive usage of decentralized energy.

The next task for India's ongoing effort in this respect should be increased attention towards off-grid alternatives (Kaundinya et al., 2009; Alstone et al., 2015). Among the various renewables, solar photovoltaic (PV) systems mostly adopted for rural electrification, particularly in areas where the extension of the grid is technoeconomically impossible or in areas where the supply of electricity from the grid is inadequate to meet demand (Palit, 2013). For example, in a small community, a simple off-grid electrical system could deploy solar panels and generate electricity for household needs (Kanase-Patil, Saini, & Sharma, 2010; Urpelainen, 2014). DETA's advantages include no reliance on national planning, low capital investment, and easy access to remote rural communities. The next section discusses the practicability between decentralized energy and convention grid extension for rural electrification.

### 1.3.2 Decentralized Energy vs. Grid Extension

In India's rural context, this local energy generation has numerous benefits, including social and cultural. Off-grid renewable energy application design and development can play a crucial, cost-effective role in delivering electricity to rural regions of developing countries (Chaurey, Ranganathan, & Mohanty, 2004). Concerning above more than 50% of the inhabitants live in rural regions in the developing world, the cost of energy production becomes prohibitive and unaffordable for rural people, resulting in lower living standards and socio-economic inequity (Kaundinya et al., 2009). In India, for instance, a very high population percentage (more than 70%) lives in rural areas (Bhattacharyya, 2006) and about 239 million individuals live without access to energy services equal to approximately a quarter of the global number of the population without access (Vinci et al., 2017). Unlike centralized energy systems, decentralized energy systems are primarily relying on alternative energy sources available locally, operate on lower scales (a few kWh scales), and are easily accessible to remote locations due to the ability of demand-site energy production. It thus appears that by providing environmentally friendly, reliable, and sustainable power availability, DETA can adequately manage the reasoning about rural electrification. The worldwide energy scenario projections have indicated a further rise in the percentage of decentralized power systems, taking into consideration the advantages of decentralized systems considering its advantage in the local context (Alstone et al., 2015).

DETA has several benefits over grid extension. It can be situated nearer to the demand site, thus reducing the cost of production and transmission, hence improving viability. From a socio-economic point of view, applications based on decentralized renewable energy technologies have tremendous scope for creating more jobs, particularly for local people, as the installation, maintenance, and operation of renewable energy technologies usually are of household scale. (Mudziwepasi & Scott, 2014). It is expected, therefore, that rural electrification using renewable energy can provide the benefits of an increase in employment opportunities and strengthen the rural economy through fair and sustainable use of local resources. A developing country such as India provides an ideal setting for experimenting with decentralized energy applications in the context of local productive use.

## **1.4 Solar Potential of India**

India has a significant global horizontal irradiance (GHI). The nation is projected to have approximately 5,000 trillion kWh annually of tremendous solar energy capacity (Kapoor, Pandey, Jain & Nandan, 2014; S. Pandey et al., 2012). The incident solar radiation over India is equivalent to 4–7 kWh per square meter per day (Kumar, Kumar, Kaushik, Sharma, & Mishra, 2010) with annual radiation of 1200–2300 kWh per square meter. It has 250–300 shiny sunny days on average and 2300–3200 hours of annual sunlight (Sharma, Tiwari, & Sood, 2012). Theoretically, India's electricity demands fulfilled in a region of 3000 km<sup>2</sup>, which is equivalent to 0.1 percent of the country's total land. Energy projections have indicated a further rise in the percentage of decentralized energy systems, taking into consideration the advantages of decentralized systems.

Therefore, the scope of solar photovoltaic technologies needs to be explored for rural India concerning the design and development of context-specific photovoltaic applications. Indeed, an Indian energy deficit addressed with the efficient harnessing of solar energy for the rural requirement. The government of India had already recognized the potential of solar energy for the development of context-specific rural applications and programs.

## **1.5 Solar Photovoltaics and Rural Electrification**

Photovoltaic solar applications are one of the most viable alternatives for rural electrification (Nässén, Evertsson & Andersson, 2002). The photovoltaic applications provide scope for energy development in isolated rural regions. Chakrabarti and Chakrabarti, 2002 and Moharil & Kulkarni, 2009 indicate that while conventional grid power is low-priced, the use of solar energy in distant rural regions justifies its perceived social, economic and environmental advantages (Chaurey & Kandpal, 2010; Nouni et al., 2009; Muneer, Asif & Munawwar, 2005). Compared to the grid expansion, solar photovoltaic schemes could be commercially appealing to supply electricity to distant villages, keeping into consideration the rapidly decreasing photovoltaic technology costs. The photovoltaic applications make it much easier to get deployed for multiple rural needs, affecting the rural population. Studies suggest that solar photovoltaic utilities have the potential to provide an appropriate solution for enhancing rural productivity. It is predicted that standalone solutions provide scope

to households for energy benefits such as mobile charging, community television, powering fans, and enabling Internet access. Besides, solar energy can have a multiplier effect by offering rural youth with employment and entrepreneurial possibilities. Adopting decentralized energy has scope to ensure the village's socio-economic development (Ellabban, Abu-Rub, & Blaabjerg, 2014; Chakrabarti & Chakrabarti, 2002).

## 1.6 The Relevance of Off-grid for Rural Electrification

Rural areas are usually dispersed, secluded, economically backward, and lack access to essential amenities, leading to lifestyle opportunities far behind urban regions. Overall, the outcomes of rural electricity production are expensive with a centralized model, so providers have always been unwilling to expand the service to rural zones. This scenario affects rural communities the most. The concern for systems that go beyond the centralized grid model is, therefore, increasing (Mandelli, Barbieri, Mereu, & Colombo, 2016). The International Energy Agency (IEA) forecasts revealed that about 90% of off-grids expected to rely on decentralized energy-based systems and mini-grids (IEA, 2017).

Access to electricity is often limited in developing countries; in such cases, off-grid electrification can become increasingly relevant. Extending the centralized grid to remote and sparsely inhabited rural regions is either economically unfeasible or practically not viable (Sen, 2013). In such cases, off-grid photovoltaic applications can be quite helpful. Significant improvement is required in household access to energy through decentralized electricity using renewable resources available locally (Palit & Chaurey, 2013). Off-grid small-scale generation is now one of the most suitable options to meet the rural electrification target (Bhattacharyya & Palit, 2016). As a result, small-scale energy generation for rural regions needs to connect with off-grid:

- I. **Accessibility:** Small-scale decentralized energy generation, is preferred for remote regions where overall expenditure makes it difficult to expand the conventional grid (Kaundinya et al., 2009; Palit & Chaurey, 2013).
- II. **Load demand:** Rural areas, especially non-electrified regions, have low energy demand and poor load factor; thus it fits small-scale energy generating systems (Chaurey et al., 2004; Narula, Nagai & Pachauri, 2012).

- III. **Upscaling livelihood:** With initiatives such as the Millennium Development Goals, the change towards poverty-based policies by global organizations drew recognition to the relation between contemporary energy options and poverty (i.e., the significance of energy utilities in enhancing living conditions by fulfilling elementary needs). It has resulted in recognition of electricity as a significant element of rural development and small-scale generation programs as a preferred choice for rural electrification (Cook, 2011).

Concerning the relevance of off-grid for rural electrification, it is crucial to look into the off-grid energy delivery model.

### 1.7 Off-Grid Energy Delivery Model

Meeting the elementary energy needs of the rural population is an essential first step for developing countries for the 'modern energy service ladder.' Energy delivery systems often referred to as energy delivery models (Bellanca et al., 2013). The off-grid energy delivery model provides the potential for small-scale off-grid electricity generation as one of the most viable alternatives, in the process of electrification or as a grid development (Mandelli and Mereu 2013; Tenenbaum et al. 2014; Bhattacharyya 2012). According to IEA forecasts reported that the estimated 60% of the generation of electricity is expected to be produced through (below mentioned) off-grid systems to provide access to energy (Mandelli et al., 2016).

Respective off-grid energy models in developing countries context to facilitate access to electrification are as follows:

- I. **Pico-power System** defined as appliances that directly connected to an electricity generation source and delivered 0.001-0.01 kW of electricity. The pico-solar lantern that provides light and power for mobile phone charging is the canonical example. It is referred to as a solar pico-system
- II. **Solar home systems** defined in terms of generating capacity as systems that provide 0.01-1 kW of power for a single home with a combination of solar photovoltaic panels and batteries. The smaller systems in the developing world are generally completely DC (in generation and usage), under 200 W capacity.

III. **Micro-grids** defined as having a generation capacity between 1 - 1,000 kW. Thus, they can typically supply an area from a single school or hospital to a small rural community.<sup>2</sup>

Classification of decentralized energy-based applications suitable for developing countries based on their energy generation capacity and services available (table 1.1) Kammen et al. 2015.

Table 1.1 Basic attributes of electricity access technology options with depictions of the typical spectrum of generation capacity, energy sources, available utilities, and the approximate cost (Source: Kammen et al, 2015)

Technology	Generation capacity (kW)	Energy sources	Services available	Estimated economic cost
Pico-power systems	0.001-0.01	Solar PV	Lighting, radio communication reception, two-way mobile communication	US\$ 10-100
Stand-alone home systems	0.01-1	Solar PV	Same as above plus additional lighting and communication, television, fans, limited motive and heat power	US\$ 75-1,000
Micro/mini-grids	1-1,000	Hydro, wind, solar PV, biomass, diesel, hybrid combinations	Same as above plus enhanced motive and heat power, and ability to power community-based services	Medium-large capital cost, low marginal cost to end-user
Regional grid connection	1,000-1,000,000	Fossil fuel, hydro, wind, solar PV, biomass, geothermal	Assuming high quality of connection, same as above up to a full range of electric power appliances, commercial and industrial applications	Medium-large capital cost, low marginal cost to end-user

Small scale decentralized systems are the most cost-effective entry point for rural applications and provide a broad scope for design customization. In comparison, the other decentralized energy systems, such as Solar Mini-Grids, Wind, Micro-Hydro and

<sup>2</sup> In the 'On-grid' world, the U.S. Department of Energy defines a micro-grid as "...a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A micro-grid may connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode." ([https:// building-microgrid.lbl.gov/microgrid-definitions](https://building-microgrid.lbl.gov/microgrid-definitions)).

Biomass, have a significantly higher cost of installation, maintenance and operating for such systems and have resource-specific limitations in terms of availability, which is a significant advantage in favor of solar photovoltaic energy (Dhiman et al., 2017). It can play a vital role in improving the energy deficit, along with providing productivity benefits for the rural grassroots (Cabraal, Barnes, & Agarwal, 2005). In context to the above productive use of energy is discussed next section.

## **1.8 Access to Energy to Facilitate Rural Productive Usage**

Access to decentralized energy applications provides households, enterprise, and to the rural communities the required flexibility in using energy in the manner they desire in order to enhance their living standard, with reasonable admittance to the spectrum of energy resources and services necessary to support social and economic development (Practical Action 2014; Leopold et al., 2015). Furthermore, the Sustainable Development Goals laid some objectives, among which Goal 7 highlights the importance of affordable and reliable energy in attaining sustainable development of rural regions (Open Sustainable Development Goals Working Group 2014).

Improving availability to energy is acknowledged as a significant prerequisite for overcoming socio-economic challenges in poorer nations, especially in rural regions (Nussbaumer et al. 2012; Sustainable Energy for All 2012 High-Level Group; Modi et al. 2006). It provides an opportunity for researchers to examine productive use of energy through for rural society through appropriate intervention.

## **1.9 Impact of Electrification through Productive Usage**

Electrification interventions are justified based on socio-economic advantages expected from "productive use of energy" (PUE). Exploring this context is essential, not only because it interprets energy access to growth, but also because of its role in ensuring electrification sustainability. Scholars suggest that PUE adds to income, while others have a much more extensive interpretation of the word and comprise welfare benefits through improved livelihood, education, or well-being (Attigah, Rammelt, & Mayer-tasch, 2015). A study of energy programs around the world has shown that through an application-centered approach, productive uses can be encouraged (Hostettler et al., 2015).

### **1.9.1 Application Centred Approach**

As the name suggests, the application-centered approach is used to promote the adoption of PUE applications. The PUE intervention could, therefore, be targeted to a systemic local development-program. The first stage is usually to evaluate the application's technical and economic viability in the local context. It includes introducing and demonstrating the technology from a utilitarian point of view by designing and developing an appropriate application for pilot demonstration in remote and rural parts of the country.

Northeast region of India provides adequate scope for how the approach, as mentioned above for decentralized energy-based design intervention, can address region-specific challenges for renewable utilities. The next section discusses the scope of the off-grid photovoltaic system in the context of PUE.

### **1.10 Off-grid Solar Photovoltaic Home System**

Possibilities and advantages of off-grid DC solar photovoltaic home system with specific reference to northeast India discussed as follows:

#### **1.10.1 Opportunities for Solar Photovoltaic Home System**

The preliminary qualitative inquiry reported that the need for energy consumption is increasing amongst the rural population in northeast India, due to improved access to multiple electronic devices like TV, radio, mobile phone, and fan. Such growing demand cannot meet with Tier 1 PV applications using a solar lantern and Pico-PV systems, which fulfill subsistent energy requirement. While on the other hand, installation and operational costs of large-scale systems like solar-micro-grid are quite high.

Furthermore, there is high resistance from the rural community on issues of land acquisition for installing micro-grids. Improving access to energy based on a solar photovoltaic home system can be a useful alternative for supplying electricity to off-grid remote/rural northeast India. The introduction of design suitable to fulfill local needs for small-scale photovoltaic applications as an off-grid solar photovoltaic home system (SPVHS) have potential to bring multiple advantages in a rural Indian context (Dhiman, B., Kumar, T., Rituraj, G., & Bhalla, K., 2019).

Solar photovoltaic home systems provide adequate scope to be more predominant in non-electrified regions of the country as a reliable solution for electricity access (Komatsu, Kaneko, & Ghosh, 2011). It provides adequate scope for PUE and indicates a pivotal role in mitigating energy dissemination barriers. In this regard, design intervention for an off-grid photovoltaic system shows promising potential to play a vital role as an application for PUE (Dhiman et al., 2017). The next section discusses the fundamentals of such a system.

### 1.10.2 The Architecture of the Solar Photovoltaic Home System

A photovoltaic (PV) home system comprises of PV module, energy storage, power converter, the balance of systems (BOS), and charge controller. Photovoltaic (PV) system design depends mainly on solar radiation (vary according to the location) and the demand for the load (Solanki, 2015). The photovoltaic systems convert solar energy into electrical energy (figure 1.2). The basic building block of a PV module is a PV cell (a semiconductor device) that converts solar energy into DC power. PV cells are typically up to 50 to 200 Watt which is interconnected to make a PV module. Next, to make a PV system, the PV module is combined with inverters, batteries, loads, charge controllers, and mounting systems.

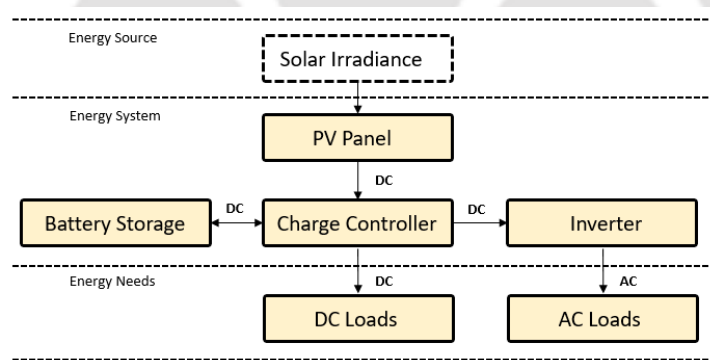


Fig 1.2: Schematic diagram of a solar photovoltaic home system

An off-grid photovoltaic system provides various technical advantages, as discussed.

### 1.10.3 Advantages of Off-grid Photovoltaic System

For power conversion losses, the photovoltaic current is converted from DC to AC and then synchronized with AC power. Besides, AC power converted back to DC for

battery charging, further DC power again converted to AC to be used with loads. All these conversions cause a significant loss of power. These multiple conversions lead to poor economics and inefficiencies. Therefore, the solar-DC system would be of great benefit. Also, compared to their AC counterparts, DC appliances consume about half of the power. Therefore, if the solar-DC system provides DC energy output, it is even better as there are no power conversion losses. (Rajaraman, Jhunjhunwala, Kaur, & Rajesh, 2015).

Concerning the reliability of the system, the conversions between DC-AC and AC-DC not only lead to losses but also affect reliability. Moreover, the electrolytic capacitors (used in most of the converter topologies) are a necessary component but have a limited life span. The Solar DC system does not need electrolytic capacitors and other components that dissipate heat. Power surges, harmonics, voltage fluctuations are also isolated from DC appliances. It results in an overall improvement in the reliability of the system compared to AC or inverter powered system.

In addition to being highly energy-efficient, the advantage of DC loads is that it runs with solar-generated "native" power, and no converters are required. Furthermore, the loads do not get impacted by the harmonics of voltage, surge, and fluctuation in voltage that are a significant concern in India. DC system eliminates transformer, and the losses occur due to poor power factor in addition to eliminating inverter, results in energy savings. Users in developing countries do consider the purchase and operating costs for a given product. In the case of the photovoltaic home system, this means that energy-efficient devices provide more energy from a specified size of solar module and battery to users. In the rural context, the DC system is more economical because, in an inverter-based solar home system, DC power is converted back to AC to power the household appliances. In order to operate such devices, these multiple conversions result in an inefficient system and high maintenance costs in a more prolonged period. For a given DC photovoltaic home system, DC appliances are running on DC power, consuming about 50% lesser power compared to their AC counterparts, resulting in better energy efficiencies and more savings for users.

Keeping in view various advantages of small-scale photovoltaic applications like an off-grid home system in the context of developing countries like India, there is a critical need to embrace energy innovation, as discussed next.

## 1.11 Need for Energy Innovation in Countries like India

The opportunity for developing countries is especially evident for decentralized energy intervention. Developing the country's provision of secure, affordable, and sustainable energy is essential for rural society; access to modern energy is also a critical enabler for development. Using modern energy services beyond fulfilling elementary requirements requires these services to be technically affordable (i.e., at a price that does not limit usage), adequate (i.e., appropriate supply), acceptable (in line with cultural influences), and reliable (usable for the most of the time).

Interventions based on decentralized energy have the potential to assist new enterprise opportunities that can unlock state-of-art economic opportunities (Gates, 2015). "Developing countries context reaffirm the need to accelerate energy innovation," as stated by IEA (ETP, 2015). From figure1.3 it is evident that there exists a correlation between access to energy and the index of human development -

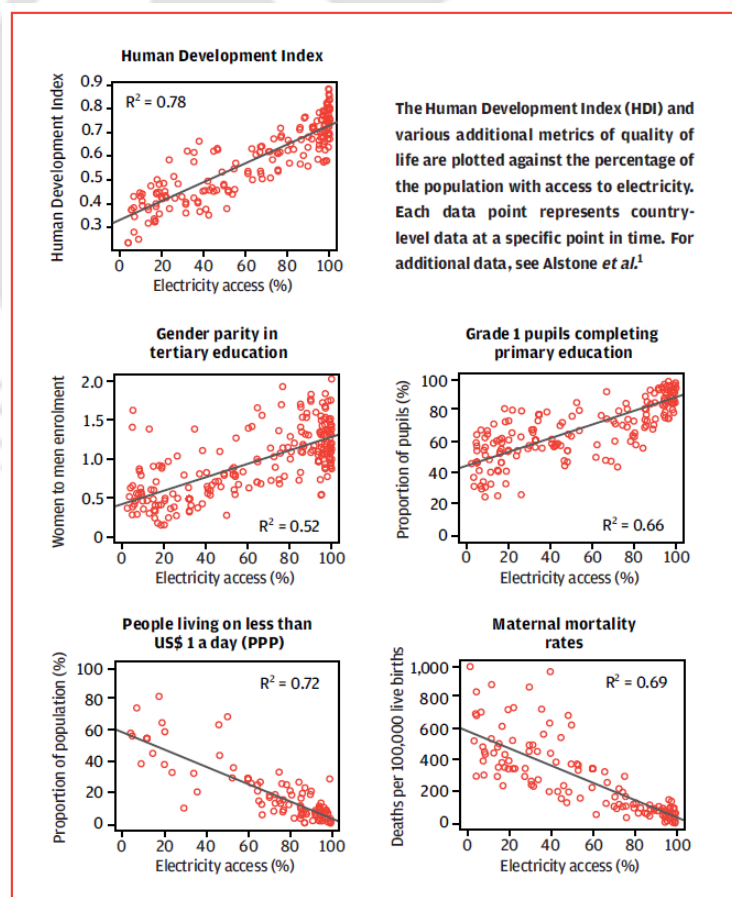


Fig. 1.3: Access to Energy and human development Index (Source: Alstone et al 2015)

which is a measure of human well-being based on gross national income, life expectancy, and educational achievement in equal amounts. With improved access to electricity, all these indices improve significantly and roughly linearly (Alstone et al., 2015; Smart Villages Heap, R.B. 2015).

Approximately 1.4 billion individuals today reported having no access to electricity. Many ostensibly connected individuals in the developing world are experiencing significant power outages, which results in a significant part of the population to stay unproductive (Kammen, 2016). In the context of the above, design intervention has the potential to impact energy innovation, particularly in the context of developing nations such as India, as discussed in the next section.

## **1.12 Photovoltaics driven Product Design**

Decentralized energy, particularly solar photovoltaic energy, is expected to contribute more than 15% of the power mix in large developing nations by 2022, driven by the objective of providing access to energy to millions of rural population who currently do not have access to electricity. (Kammen, 2016). There is an excellent scope for designing and developing decentralized energy applications by directly moving to photovoltaics. Leapfrogging to decentralize technology-based innovation needs to harness for rural productive usage. An interdisciplinary approach to the issue of improving access to energy can provide better solutions than using a mono-disciplinary approach focused solely on improving energy technologies. Decentralized energy applications based on societal needs can help address access to energy for rural grassroots. In this respect, due to the growing complexity, functionality, and user interaction, a systemic approach towards product design and development of decentralized energy applications seems imperative. Considering the challenges faced by people in underdeveloped countries, the potential for energy innovation is enormous and urgent. The product design intervention to modern energy technologies could significantly improve the condition of rural communities (Jannuzzi & Goldemberg, 2012). In developing countries, local renewable electricity production is becoming a viable option (Adib, Coordinator & Webinar, 2015). The adoption of decentralized energy technologies witnessed to remain modest, calling out for intensified initiatives for improvement (IEA and World Bank, 2016).

Design intervention for the off-grid photovoltaic home system indicates the potential for the creation of PUE opportunities encouraging social engagement, human productivity, and employment generation in rural context (B. Dhiman, Chaudhury, Deb, & Chakrabarti, 2017). For a country like India where more than 70% of the population is from a rural background, and about 230 million people do not have access to energy, the context of photovoltaic driven design intervention becomes even more relevant. In regard, one should be exploring potential avenues in the context of solar photovoltaic energy for energy deficient countries like India (Narula et al., 2012; Palit & Sarangi, 2015). Furthermore, access to a well-designed photovoltaic product like an off-grid system provides adequate scope to facilitate rural productivity.

### **1.12.1 Social Construction of Design for Developing Countries**

Societal relevance plays a vital role in the dissemination of decentralized energy products, as it associates economic advantage for livelihood improvement along with social and environmental benefits in rural context (Mondal & Klein, 2011; Wamukonya, 2007). For socially constructed design, it must apprehend and bring positive social change. Such an effort could address dissemination challenges such as lack of local participation and the need for incentive-based opportunities to encourage the dissemination of photovoltaic utilities. Energy solutions based on a participatory strategy involving local stakeholders can play a crucial part in encouraging its social acceptance (Diehl & Verschelling, 2012).

Socially constructed design (SCD) has scope to bring advantages like local resource utilization, assisting rural livelihood, and encouraging the participation of local stakeholders to make energy solutions socially relevant and sustainable (Dhiman, Chaudhury, Mahapatra, & Chakrabarti, 2019). To create a socially benign solar photovoltaic applications, the developing nations with a low socio-economic index need to adopt the strategy as mentioned above. In the context of rural India, it indicates the scope to improve access to energy and deliver design in the broader context of sustainable development. In this context, it is crucial for energy designers to focus on societal needs and to innovate photovoltaic products relevant to society.

### **1.12.2 Influence of Design on Technology Dissemination**

Presently, many sustainable energy technologies have reached levels of maturity that may require product design intervention to push beyond technology in general (Reinders, Diehl, & Brezet, 2012). Incorporating energy technologies into product design requires better insight concerning appropriately developed design to lead to new and relevant products (Diehl, 2013). From a design perspective, many possibilities exist primarily in the context of developing countries for renewable energy technologies based applications. However, how renewable energy solutions offered to end-users will help decide their success and, thus, their capability in providing short-and long-term solutions for energy reliance. Product design could, therefore, play an essential role in encouraging energy innovation and creating sustainable energy solutions that need to incorporate into products appropriate to the requirement of a country. In context with the above, product design has scope to promote the dissemination of decentralized technology to rural grassroots.

Energy innovations have recently appeared as an upcoming field of research to address the challenges for decentralized systems in developing countries, especially since such technologies have better value than centralized alternatives. Rural engagement to energy intervention can help address a range of practical problems at the bottom of the economic pyramid by offering a novel, and innovative energy solutions suitable to the rural mode of life (Radjou et al. 2012). Concerning the above, case studies for photovoltaics driven product design improving PUE in developing countries context discussed next.

## **1.13 Contribution of Product Design in Solar Photovoltaics**

Discussed below case studies are one from Cambodia and another from India, both the context looks comparable. It provides a suitable reference to understand the role played by the product design interventions in the context of off-grid photovoltaic applications.

### **1.13.1 Case Study 1: Kamworks Cambodia**

More than three-quarters of Cambodia's population has no electricity access and depend on unreliable, unsustainable light sources such as kerosene lamps and wicks, candles and vehicle batteries. Kamworks, a solar energy-based company in Cambodia,

identified how lighting could use in rural Cambodia after extensive field research. Solar lighting systems in rural regions have demonstrated the scope as a reliable utility for the low-income segment. Kamworks ' product design-based approach indicates how innovation in user context, technology, and design can result in a social setting for product development. Kamworks designed and developed moonlight, solar lamp for below poverty line user segment. The social significance of design is desired in Kamworks vision to assist young Cambodians with job possibilities and income generation. (Diehl & Verschelling, 2012).

In the field, Kamworks carried out a participatory design approach to familiarize designers with the local context. Observatory research provided useful inputs for the design and development of the solar lighting system. In rural Cambodian background, the environment and use of existing lighting products have investigated. It helped designers create an understanding user in the context of lighting products. Ethnographic studies looked into local household's needs. Participatory methods used to study rural mode of life for shortlisting an appropriate product. For the development of design criteria, focus group discussion, and daily activity mapping used. It was clear from participatory field research that solar energy was needed to support the necessity for rural energy. The determination of suitable design concepts was achieved from the field, applying participatory research. For suggesting valuable design alternatives that were appropriate for rural Cambodia's BoP context, local participants were thoroughly involved from the initial phase of design ideation and development (Fig. 1.4). The participatory design remains advantageous in providing solutions customized to local needs.



Fig. 1.4: Participatory research conducted in rural Cambodia highlighting the strength of product design based approach (Source: Diehl, J. C., & Verschelling, J. 2012)

The socially constructed design resulted in a mutually cohesive, locally-driven approach for design intervention. Direct feedback from the field led to practical, socioeconomically, and culturally driven suggestions for the improvement of the design concepts. The Kamworks have sold Moonlight solar lamps successfully across rural Cambodia to date. A similar approach to design development could further be executed in the given context of rural India.

### **1.13.2 Case Study 2: Rural Spark India**

For a country like India, where access to energy is amongst the poorest, encouraging innovation to energy can be of utmost benefit. Rural Spark is an Indian start-up on rural energy network promoting energy exchange among villagers. According to rural spark, innovative ways of developing products and business models are required to enter the markets at the base of the pyramid. These products and business models cannot be designed outside the context due to the enormous cultural differences.

Rural Spark used agile design and development strategy, involving all stakeholders, at the time of prototype implementation. This strategy facilitated direct participant feedback and enabled sustainable energy solutions to become more adaptive to the rural context. For user research, rural spark did not approach people as participants; instead, they approach them as real customers. It leads to significant real-time feedback from users as they do not provide the answers that one anticipated but rather behaved as the value-conscious customers. Based on the agile design approach, rural spark developed products and services that were wanted and used in the actual context. The disruptive impact of design solutions found significant in this respect.

The above mentioned both the case studies indicate the potential of product design and development based on solar photovoltaics; however, it has observed that the scope of decentralized applications in the rural community is very constrained despite its enormous benefits. Multiple challenges, as discussed in the next section, limit the scope of such benevolent applications and technologies. For energy-chronic countries such as India, context-specific application development, such as for off-grid photovoltaic system, indicates scope to assist rural mode of life. Addressing decentralized energy challenges through photovoltaic driven design approach indicated the potential to provide social, economic, and ecological benefits to rural

communities. Concerning this, it is vital to look into challenges for the dissemination of decentralized energy in the regional context to make design intervention more effective.

## **1.14 Regional Energy Context for North-East India**

Status of rural electrification in the northeastern region (NER) of India is among the poorest (MoP, GOI, 2015). NER provides one of the most challenging situations for the dissemination of decentralized energy, especially solar photovoltaics. The region alone has about 4,169 un-electrified villages comprising about 22% of total un-electrified villages of the country. Northeast region has a second-lowest generation capacity of 3,273 MW as compared to the national installed power generation capacity of 2,58,702 MW (Ministry of Power, 2015, GOI). It provides a prospect to mitigate challenges for decentralized energy interventions for the socio-economically oppressed northeast region of India.

### **1.14.1 Challenges for Dissemination of Decentralized Energy Utilities**

Studies based on literature, expert interviews, and discussions with local stakeholders highlighted critical challenges. In the regional context of north-east India, some of the main findings were, design and technology not adapted as per the local conditions, lack of productive use of decentralized energy suitable to rural context and integration of decentralized energy applications with local relevance (Schäfer, Kebir & Neumann, 2014; Dhiman et al., 2019; Luthra, Kumar, Garg, & Haleem, 2015; Yaqoot, Diwan, & Kandpal, 2016; Barman et al., 2017). Challenges for the dissemination of decentralized energy are discussed in detail as follows;

#### **a. Design and technology not adapted to local conditions and users' needs**

Very little attention has been paid to the issue of adopting design & technology as per the rural needs. The appropriateness of a particular D&T to the beneficiary is usually not considered and promoted with the acknowledgment that the users will modify their lifestyles following the available design and technology (Palit, 2003; Barman et al., 2017).

Design and Technology (D&T) should be reliable, feasible, sustainable, and customized to the local context. It should be managed by local stakeholders to

deliver significant and enduring benefits. The impact of such indigenous developed D&T on society should be a necessary forethought for a local scale. Therefore, it is essential to co-create and collaborate with stakeholders who are more familiar with the local context. Pilot design for decentralized energy needs assessment in direct contact with rural stakeholders experiencing D&T issues (Hostettler, S., Gadgil, A., & Hazboun, E., 2015). Inadequate understanding of consumer needs, lead to inappropriate solutions. As director AEDA mentioned, “Understanding that the charging of mobile phones is an equally urgent need as lighting, and hence developing a solution catering to both these needs, resulted in a far greater subscription [to the system].” Therefore, the need for design valuation not recognized as a one-way flow of information from society to the designer but as an engaging two-way process between the two, considering the societal needs.

**b. To integrate decentralized energy intervention with local development initiatives**

The intervention of decentralized energy utility with the socially relevant development in localized context provides scope for intervention to sustain and get socially accepted. Therefore, instead of confining the energy intervention for solar photovoltaics only to a 'cooking and lighting' paradigm, the regional energy interventions should try to address the dissemination of decentralized energy by providing lifestyle benefits (Dhiman et al., 2017; AEDA 2016). Decentralized energy applications need to work with local development initiatives to encourage rural self-reliance (Terrapon-Pfaff, Gröne, Dienst, & Ortiz, 2018).

**c. Productive use of decentralized energy for development strategies**

Studies have demonstrated that ensuring access to energy does not always result in its use for productive purposes. Till recently, quite little has explored the potential of decentralized energy applications for different types of productive use (Cabraal, Barnes, & Agarwal, 2005). Further research on decentralized energy utilities required to facilitate rural productive usage.

**d. The top-down approach needed for decentralized application development**

A 'top-down' approach adopted by state agencies for the growth of renewable energy, where the goal set at the top, and then transferred to various levels below. Often energy targets are determined independent of the felt needs of the people,

leading to identification errors for user needs (Barman et al., 2017). The rural population, the ultimate beneficiaries of the decentralized energy utility, have little role in deciding the design content failing the majority of the cases, with minimal success for energy development initiatives in NER (AEDA, 2016). Lack of knowledge by project planners about how to adapt energy applications catering to the needs of rural communities and by not involving stakeholders in the early phase of design became a significant barrier in the dissemination of solar photovoltaics in the region. It fails to meet the local needs for which intended, hence impeding the utilization of solar photovoltaics in NER (Palit, 2003). Attempts to encourage small-scale solar photovoltaic applications such as solar home system (SHS), solar lamps (SL), and pico-PV must also consider the scope of local customization for recognition and promotion of relevant design and technologies.

Government and State nodal agencies have presumed that the user's needs were similar to those in other regions or countries; this created a gap for recognition of usefulness for renewable energy (Palit & Hazarika, 2002). Addressing social context can result in a significant impact on its widespread usage and improve acceptance for context-specific photovoltaic applications appropriate to the region.

**e. Lack of Rural Engagement**

Lack of rural engagement critically impedes the long-term success of decentralized energy. Community engagement needs a collaborative design approach to generate a sense of ownership. Limited or unsuccessful attempts to engage the community resulted in a partial or total failure of the application of decentralized energy. The importance of rural engagement is confirmed through discussions with local community members during the study and also literature (Palit, 2003; Attigah et al., 2015). A system that is compatible with localized requirements needs to look in.

**f. Limited ability to Pay**

A significant concern that comes during interaction with stakeholders, and often not cited in the literature is the limited ability of the user to pay for household electricity services. The limited ability to pay reported to be a significant problem for various

decentralized energy interventions (Attigah B., Rammelt M., Mayer-Tasch L., 2015). Concerning above, achieving sustainability for decentralized energy interventions, in the long run, becomes a challenge.

For the above-discussed challenges impeding the growth of decentralized energy utility in the regional context, the literature found some of the promising energy initiatives to facilitate productive use and dissemination of decentralized energy in a localized context.

### 1.15 Promising Initiatives for Decentralized Energy

Globally, with the growing adoption of decentralized energy, a transition towards off-grid energy systems is increasing (Ilic et al., 2012a; Parag & Sovacool, 2016; Van Der Schoor et al., 2016). The significant characteristics of this shift are that households can play a prominent role in the local exchange of energy (Camarinha-Matos, 2016a; Carli & Dotoli, 2015). Energy scholars have envisioned these power systems as a potential enabler for improving the context of rural engagement where households obtain an active role in the distribution of local energy (Bellekom et al., 2016; Parag & Sovacool, 2016; Van Der Schoor et al., 2016; Zhou et al., 2016). Technically, using the electricity network is one of the means by which energy exchange can take place. Vandebrom in The Netherlands, Brooklyn Micro-grid in the USA, and SOLShare in Bangladesh are some promising initiatives that enable such an exchange of energy. Concerning the above, another way of exchanging energy is through the use of power storage devices (Figure 1.5).

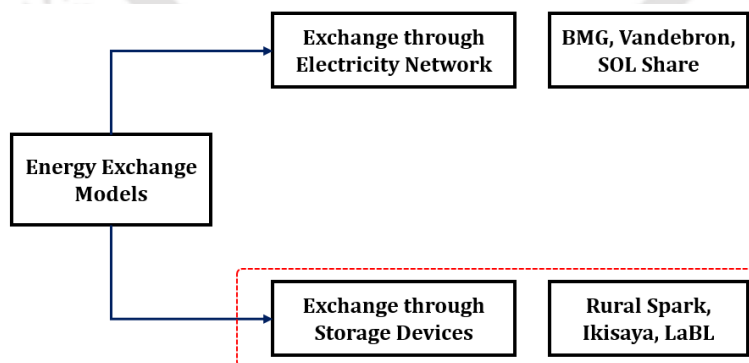


Fig. 1.5: Promising initiatives like prosumption through storage devices for dissemination of decentralized energy in rural context

The Ikisaya Energy Center in Kenya, Lighting a Billion Lives (LaBL) TERI initiative, and Rural Spark in India are just a few off-grid initiatives that structure such energy exchanges. Energy exchange is commonly regarded as an innovative approach in the evolving energy literature to incentivize and actively engage households with energy solutions (Camarinha-Matos, 2016a; Ilic et al., 2012a; Rathnayaka, Potdar, Hussain & Dillon, 2011a; Luo, Itaya, Nakamura & Davis, 2014).

Factors like dispersed population density, low per capita power consumption, economic backwardness in the context of the northeastern region of India, makes storage device based decentralized energy exchange more viable in comparison to exchanging through the electric network. Given the scenario, rural households for storage-based exchange encourage individual independence from the grid. Important to mention that design intervention based on such initiative offers possibilities to explore the scope of rural engagement for productive usage of decentralized energy, as discussed in the next section.

### **1.16 Inter-household Energy Exchange; Enabling Social Relevance of Solar Photovoltaics in Northeast India**

The small-scale off-grid photovoltaic system indicates adequate scope for lifestyle benefits to rural grassroots (Kamalapur & Udaykumar, 2014; Sharma et al., 2012; Reddy & Painuly, 2004). Considering the above, facilitating inter-household energy exchange in the rural northeast shows the potential to fulfill the research gap by bridging rural relevance with design intervention. The present-day energy research is increasingly focused on the study of inter-household energy exchanges (Parag & Sovacool, 2016; Ruotsalainen, Karjalainen, Child & Heinonen, 2017; Singh et al., 2018). This energy exchange model is gaining recognition for improving the adoption of decentralized energy by providing community members a critical position in managing local energy systems for monetary and non-monetary gains (Chaurey, Krithika, Palit, Rakesh, & Sovacool, 2012; Pode, 2010; Singh et al., 2018; Ulsrud, Winther, Palit, & Rohracher, 2015). The aforementioned emphasized the need for energy studies to explore the critical aspect of the social dimension of energy (Cloke, Mohr, & Brown, 2017; A. Singh et al., 2018; Smith & High, 2017; Sovacool, 2014). Concerning the above, the notion of reciprocity found relevant for exploring energy systems for the inter-household energy exchange. Rural NER provides a suitable

scope to explore inter-household energy exchange based design intervention to encourage productive use of energy.

### **1.17 The motivation for the Present Research**

The motivation for the present study resulted in exploring specific issues as follows.

- a. To identify and develop a context-specific off-grid photovoltaic application
- b. To study the effect of compatible design in the context of provincial rural lifestyle
- c. To assess the scope of the social relevance of productive usage of energy to be studied in the context of part of northeast India.
- d. Facilitating Access to Rural Energy, a 10% village electrification scenario needs addressing. 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 of 90%.
- e. To broaden scope of photovoltaics driven product design for a design practitioner and researcher.

### **1.18 Scope and Rationale of the study**

D&T aspects never recognized the needs of rural users leading to failure for the majority of decentralized energy applications and programs in the regional context of northeast India (Barman et al., 2017; Dhiman et al., 2017). In the context of the above, the design and development of small-scale decentralized energy intervention provide scope for off-grid photovoltaic design to explore PUE in the context of rural northeast India.

### **1.19 Research Gap**

In general, the compatibility of a particular design and technology for decentralized energy-based applications to the beneficiary is usually not considered and promoted with the consideration that the users will modify their lifestyles following the available design and technology (Palit, 2003; Barman et al., 2017). Government and State nodal agencies have presumed that the user's needs were similar to those in other regions or countries; this created a gap for recognition of usefulness for utilities like an off-grid photovoltaic system in the context of rural northeast India (Palit & Hazarika, 2002). An important consideration on a localized scale should be the

usefulness of such indigenous developed design and technology (Hostettler, S. & Hazboun, E., Gadgil, A., 2015). Concerning the above, the lack of rural engagement critically impedes the long-term success of decentralized energy resulting in the very-limited success of such energy interventions in NER. The local study and literature references confirmed the lack of rural engagement (Palit, 2003; Attigah et al., 2015). Thus, achieving sustainability for energy interventions, in the long run, becomes a challenge (Attigah B., Rammelt M., Mayer-Tasch L., 2015). Decentralized energy needs to embed with social significance for benefit rural communities (Terrapon-Pfaff et al., 2018).

The research concerns on how design intervention for an off-grid photovoltaic system can integrate decentralized energy with rural lifestyle advantage gives rise to research questions, needs attention.

## **1.20 Research Questions**

From the existing literature, pilot study, and interactions with stakeholders, it establishes a significant research challenge to address the research gap by integrating decentralized energy utility with rural relevance, which builds scope for design intervention. Consequently, the research questions attempt to answer whether such intervention contributes to realizing the impact on the rural lifestyle in the context of northeast India. For this, the following questions raised:

- a. **RQ1:** What would be a suitable approach for the design development of an off-grid photovoltaic application in the context of the rural setting of northeast India?
- b. **RQ2:** How a compatible design for a small-scale off-grid system can address rural user prerequisites and the regional challenges for the dissemination of photovoltaic utility?
- c. **RQ3:** Can the discrete design of an off-grid photovoltaic home system be appropriately used to expedite rural household enterprise productivity, and to support add-on services for a cross-section of rural users towards achieving impact on rural lifestyle in a localized context?

- i. **SubRQ1:** Does discrete design facilitate work efficiency in the context of handloom weaved mekhla chaddar and handmade incense sticks as a typical household enterprise in rural northeast India?
- ii. **SubRQ2:** Does the proposed intervention result in mutual energy trading benefits due to mobile and solar lamp charging in comparison to the conventional off-grid photovoltaic system?
- iii. **SubRQ3:** Does discrete photovoltaic home system results in inter-household energy exchange benefits like mutual energy lending and mutual energy sharing?

The present thesis has looked into the possible explorations towards addressing the above.

### **1.21 Aim and Objectives**

The study aims at looking into assessing the efficacy of the intervention through the design and development of a discrete off-grid solar photovoltaic home system to address imperative localized needs in the context of rural locations of northeast India.

- a. To determine the rural gap and issues related to the existing product for small scale photovoltaic application in terms of energy needs and usage pattern
- b. To determine the feasibility of conceptualization for off-grid SPVHS
- c. To explore, design, and develop different aspects of the discrete off-grid solar photovoltaic home system considering inter-household energy exchange and household enterprise productivity in a localized context.
- d. To determine the effectiveness of the impact of proposed design intervention for an off-grid photovoltaic home system in the context of productive benefits for typical rural household enterprise and local energy exchange with specific reference to the north-east region of India.

### **1.22 Hypothesis and Posit**

An in-depth study and identification of the research gap indicate scope to integrate design development with productive usage of energy in the context of an off-grid

photovoltaic home system. The study attempts to investigate the outcome of intervention through the discrete, off-grid solar photovoltaic home system. Thus, two specific issues concluded to address. At first, the proposed design should bring about benefits of inter-household energy exchange, and secondly, design intervention has a positive effect on household enterprise productivity. Concerning the above, there is the following hypothesis and posit to raise.

**H<sub>1</sub> (a):** Discrete design of the off-grid solar photovoltaic home system improves household enterprise work efficiency when compared to the conventional photovoltaic system.

**H<sub>1</sub> (b):** Discrete Design for the off-grid solar photovoltaic home system has a positive effect on inter-household mutual energy trading for a cross-section of the rural prosumers in the context of rural northeast when compared with a conventional solar photovoltaic system.

**P<sub>1</sub> (a):** Discrete design for off-grid solar photovoltaic home system encourages mutual energy sharing and mutual energy lending between households facilitating social cohesion, and stimulates decentralized energy distribution network in rural background.

Consequently, the research questions attempt to answer are; whether and how design intervention leads to rural productive use; and whether such intervention contributes to achieving impact on rural lifestyle in a localized context.

### **1.23 Methodological Framework**

The research design adopted to accomplish the research goal for the thesis, as shown in fig 1.6 (details of the same are discussed in the last chapter). The study aimed to look into the design and development of a discrete off-grid solar photovoltaic home system addressing imperative localized needs in the context of rural locations of northeast India. The study primarily divided into three phases, as follows.

## Phase 1: Literature Review and Feasibility Study

- ❖ Literature review (after collecting different research papers, journals, conference papers, and books) related to the broad area of research, stated to segregate as; Applications of decentralized photovoltaics in a rural context,

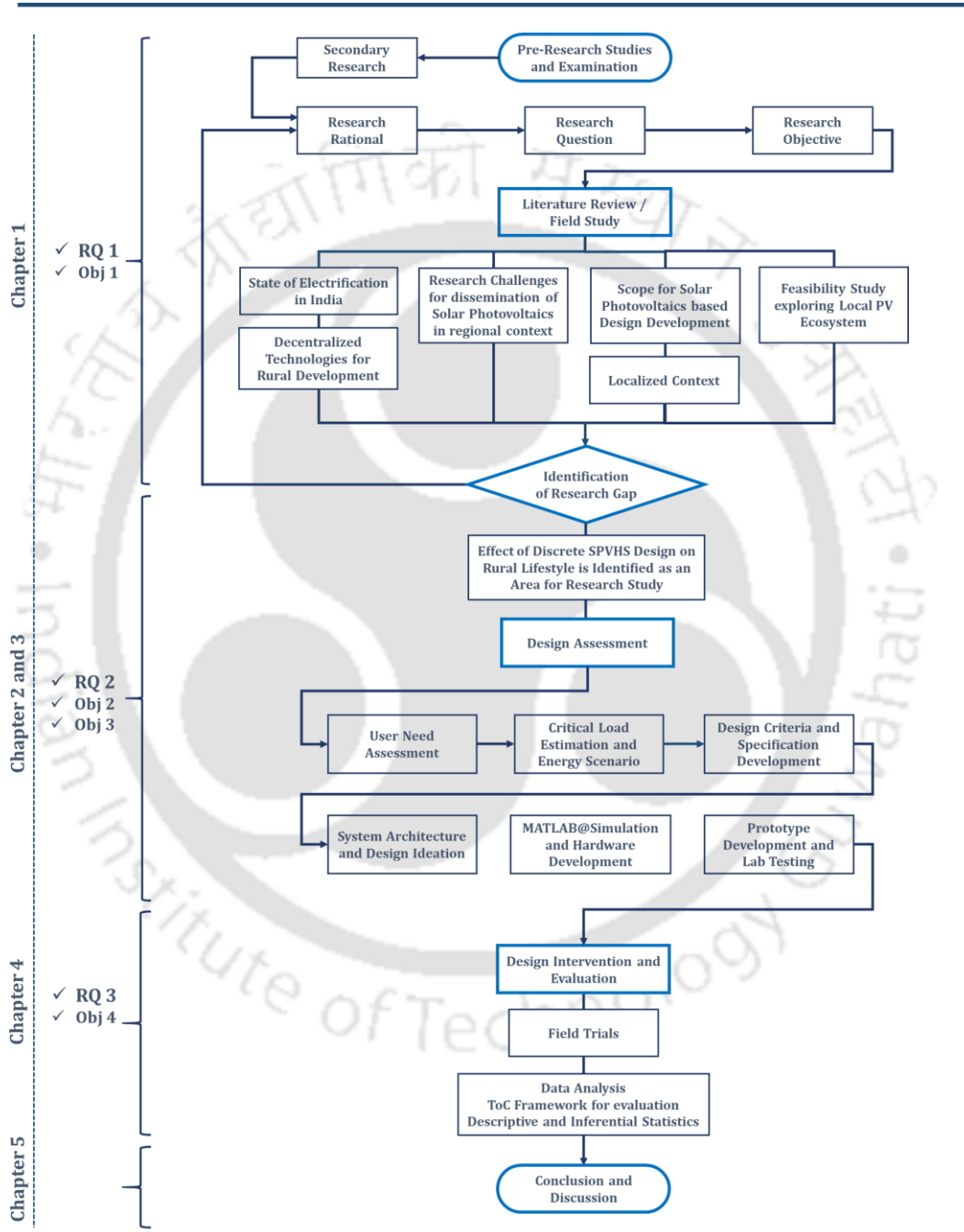


Fig 1.6: Schematic diagram of the study design and plan followed in present thesis work. The work carried out in three phases is presented in five chapters specific research questions and objectives covered there in.

potential barriers related to dissemination of decentralized energy, and the context of design related to decentralized energy.

- ❖ Location and field selected based on electrification status and population demographics for the feasibility study.
- ❖ Study of local photovoltaic ecosystem & rural energy scenario made using direct observation & photo-ethnography for off-grid photovoltaic products like a solar home system.

### **Phase 2: Design Assessment for Off-grid Solar Home System**

- ❖ Data collection for critical load estimation and system sizing done administering questionnaire and semi-structured interviews
- ❖ Design criteria developed mapping used needs, energy scenarios, and user environment. The user and expert opinion considered for conceptualizing system architecture & design concepts for an off-grid photovoltaic home system. The multi-criteria decision-making technique used for concept evaluation.
- ❖ Hardware development is done using MATLAB@Simulink based results. Prototype fabrication realized with hardware integration for both controller and storage unit.

### **Phase 3: Design Intervention and Evaluation**

- ❖ Systematic assessment of the outcome carried out for design intervention of the discrete solar home system. Trial and testing under lab and field conditions carried out to evaluate the efficacy and social relevance of the proposed design.
- ❖ The field trial of the proposed design was validated using a representative sample size of a total of 134 families to attain test significance at 95% for comparison of indicators between conventional and proposed photovoltaic home system design.

- ❖ Thus, research design broadly divided into three phases; Literature review and feasibility study, design assessment, and data collection for a discrete solar home system and evaluation of the proposed intervention.

## 1.24 Thesis Layout

The thesis divided into five chapters according to the content of the work and the chronological order of different activities during the studies. The details of which are as given below;

Chapter -1	Scope of Decentralized Energy-based Design
Chapter -2	Solar Photovoltaic Ecosphere & Home System Design Criteria
Chapter -3	Design and Development of Discrete Photovoltaic Home System
Chapter -4	Design Evaluation of Discrete Photovoltaic System: Results and Analysis
Chapter -5	Discussion and Conclusion

- ❖ **Chapter One** of the thesis outlines the background, motivation, and scope of research. This chapter is the justification of the research, which establishes the need to study decentralized energy in particular solar photovoltaics based applications like SPVHS in a regional rural lifestyle context. It reviews the existing energy scenario for decentralized energy and highlights the importance and opportunities for product design to address dissemination barriers to rural grassroots. Furthermore, it deals with the context of design intervention for a discrete solar photovoltaic home system, imperative to localized needs in the context of rural northeast India. The chapter establishes the critical role of off-grid decentralized energy for social relevance. It describes the present research gaps for posing specific research questions leading to the proposed hypothesis and posit.
- ❖ **Chapter Two** contains a localized study of the photovoltaic ecosystem for establishing design criteria. Feasibility options were statistically analyzed to validate the local context for solar photovoltaic design intervention. Field survey includes user need mapping, critical load estimation for system sizing,

and component fault analysis. The outcome of the study resulted in design parameters and specifications for the photovoltaic system.

- ❖ **Chapter Three** covers details of the core design and development for an off-grid photovoltaic system. Design criteria and specifications were used to conceptualize design architecture and design concepts for the solar home system confirming product design principles. Multi-Criteria decision-making (MCDM) based Fuzzy Topsis technique used for the evaluation of concepts. Technical realization of final design includes hardware development based on Matlab @Simulink based comparative study for smart controller motherboard and battery monitoring PCB. Finally, high fidelity beta prototype of the proposed solar photovoltaic home system fabricated and examined under lab-conditions. The prototype further inquired about human factors and usability evaluations.
- ❖ **Chapter Four** involves the final workout of the experimental field trials to compare the advantages of the proposed photovoltaic home system over the conventional system. The research includes a comparative study of design in the context of rural lifestyle benefits. The theory of change-based framework was used for impact assessment of design intervention. Both qualitative and quantitative analysis has been adopted to interpret the effect of proposed design under given rural conditions.
- ❖ **Chapter Five** consists of discussion abridging complete research work. The conclusion was reported based on the findings of studies in this chapter. Furthermore, this last chapter of the thesis also labels salient findings and key contributions along with how the hypothesis of present research-validated.

## 1.25 Summary

The rationalization for the present study has established. From the perspective of design intervention, regional challenges for the dissemination of photovoltaic utility looked in. The research gap recognized from literature for posing specific research questions resulting in the proposed hypothesis and posit. The next chapter involves a feasibility study for the small-scale off-grid photovoltaic system in the localized context of northeast India.

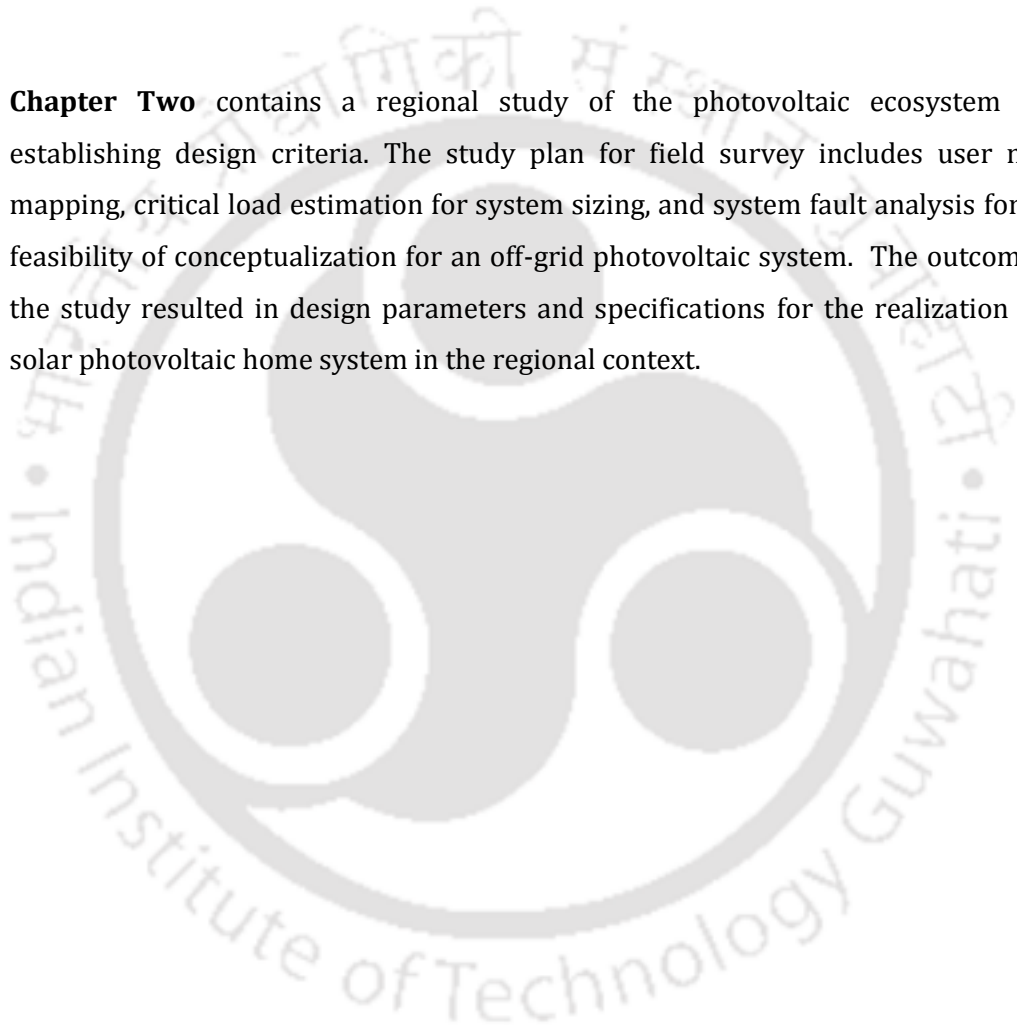




# Chapter 2

## Solar Photovoltaic Ecosphere and Home System Design Criteria

**Chapter Two** contains a regional study of the photovoltaic ecosystem and establishing design criteria. The study plan for field survey includes user need mapping, critical load estimation for system sizing, and system fault analysis for the feasibility of conceptualization for an off-grid photovoltaic system. The outcome of the study resulted in design parameters and specifications for the realization of a solar photovoltaic home system in the regional context.



## **2.0 Introduction**

A feasibility study was conducted in the context of an off-grid photovoltaic system, as it was crucial to recognize issues related to D&T to facilitate it as per localized needs. The literature observed that photovoltaic applications promoted in a regional context with the assumption that users will adapt their lifestyles as per the existing design and technology (Palit, 2003; Barman et al., 2017). It resulted in multiple shortcomings like a poor utility, lack of rural engagement, and low dissemination of off-grid photovoltaic system in rural parts of northeast India (AEDA, 2016).

Therefore, in a regional context, it is essential to investigate the user-need based design requirements to comprehend the usefulness of design intervention in the context of the rural lifestyle.

### **2.1 Study Objectives**

In the above context the objective of this study was 1) to understand the technical features, performance, and issues with an existing photovoltaic home system, 2) to investigate user perception for existing photovoltaic utility, 3) to identify critical load estimation and rural energy scenario, 4) to map user requirement for energy in a rural lifestyle context, and 5) to derive upon the design specification and parameters, based on the feasibility study.

### **2.2 Local PV Ecosystem**

The study observed that the off-grid solar photovoltaic home system (SPVHS) is typically used utility by rural users considering growing energy requirements due to the adoption of different electronic products like mobile phones, CFL, radio, fan, and TV. The requirement above cannot be fulfilled with tier 1 applications like pico-PV or solar lamps. In the state of Assam, Assam Energy Development Agency (AEDA) was the state nodal agency responsible for installing SPVHS in 776 villages in various districts of the state in partnership with various NGOs. While organizations as Assam Power Distribution Company Limited (APDCL), Assam Forest Department, and other private players also have remotely installed similar setups in rural and remote villages, which still do not have access to the conventional grid. Therefore, understanding the impact, limitations, and other shortcomings was necessary to design a context-specific intervention based on field survey assessment.

Ethnographic techniques like field notes, field observation, photo-ethnography, and semi-structured interviews used to recognize user needs while design research. This study identifies lack of add-on benefits, incompatibility between user needs, design and technology limitations, and lack of productive usage of energy as one of the primary shortcomings in the context of the conventional off-grid photovoltaic home system.

### 2.3 Details of the Area Studied

The study area is villages in district Sonitpur and Majuli in the state of Assam (table 2.1); the state has a power deficit of 189 MW as of March 2016 (APDCL, 2016).

Table 2.1 Details of the area of the study

District	District Literacy Rate	Latitude and Longitude	Village Name	Grid Electrification Status at time of Survey	No of Households Surveyed
Sonitpur	67.34%	26.67° N, 92.85° E	Bherveri Pathar	Un-electrified	85
			Mishing Gaon	Un-electrified	
			Nabil	Un-electrified	
			Gohpur	Electrified	76
			Barigaon	Electrified	
			Gopalpur	Electrified	
			Nayaghagra Tea Estate	Electrified	
Bodigaon	Electrified	90			
Changaigaon	Electrified				
Majuli	78.56%	27.00° N, 94.22° E	Sikali Chapari	Un-electrified	90
			Bhagunmari	Un-electrified	
			Raiti Gaon	Un-electrified	
			Kachikata	Un-electrified	
			Ban Fakuwa	Un-electrified	

\* District Literacy Rate as per 2011 Consensus

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The power consumption is 314 kWh per capita, while 1010 kWh is the national average is (CEA, 2015). The state of Assam has a significant 803 number of un-electrified villages of the total (GOI, 2015). For Assam's total number of 6,367,295 households, 38% of households are dependent on electric lighting, while 62% of households rely on kerosene lighting (India Census, 2011). In the studied villages of district Sonitpur and Majuli, in Assam, SPVHS were utilized to fulfill the elementary energy requirement of rural households.

The study reported that other decentralized energy applications based on wind, micro-hydro, and biomass, have not found feasible due to higher installation, operation, and maintenance costs, other than resource-specific constraints. In addition, due to the dispersed and low population density, solar micro-grids (SMG)

experienced significant limitations, making SMG financially unsustainable. It observed that studied villages are remotely located and have very-low household percentages; also, these villages have limited access to the conventional grid. Geographically Sonitpur district is located on the northern bank of Brahmaputra river (figure 2.1), having non-homogeneous demographics as several linguistic, religious, and ethnic communities reside in the district.

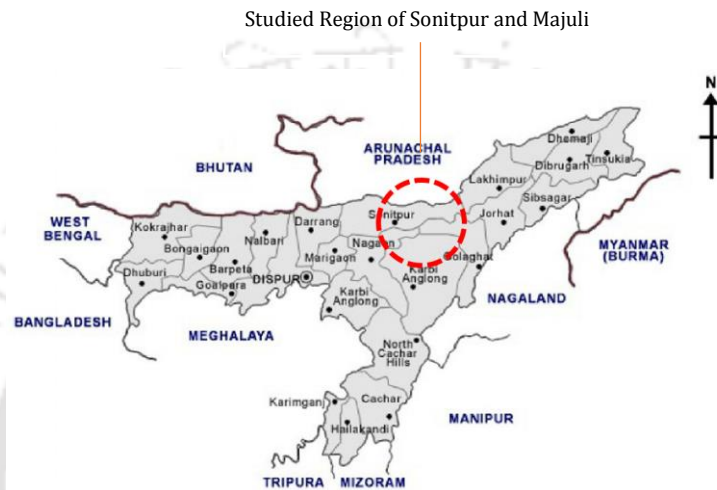


Fig. 2.1 Field map representing study location of solar photovoltaic home system in Assam

Besides, the Majuli district is the world's biggest river island (fig 2.2a), in Assam and is the country's first inland district; the region has poor grid connectivity (fig 2.2b). The study reported that the installed photovoltaic system not designed as per localized needs (fig 2.2c). Despite many limitations, the majority of households in the studied area are dependent on pico-PV (fig 2.3a), off-grid photovoltaic home system (fig 2.3b), and solar lanterns (fig 2.3c) to fulfill daily energy requirement. Remote geography, dispersed population density, techno-financial challenges for central grid extension, and modest energy requirement sets the need for decentralized energy intervention for the studied region.



(a)



(b)



(c)

Fig. 2.2 a) Considering the adverse geography the remote island of Majuli presents rural electrification challenges b) and c) Remote village house in Majuli district of Assam, having issues with conventional solar home system as design and technology not adopted to local conditions and user needs, which sets the need for decentralized energy intervention.



(a)



(b)



(c)

Fig. 2.3 Studied ecosystem of off-grid photovoltaic applications in rural context a) Pico-PV system b) Conventional solar home system for household use was typically used as most common photovoltaic utility and c) Solar lantern used to fulfil basic rural energy requirement

## 2.4 Methodology

The villages in district Sonitpur and Majuli signify varied socio-economic conditions purposively selected for the study, where access to the grid is almost negligible; therefore, the off-grid photovoltaic home system is predominant in these districts. The study was co-investigated and facilitated by AEDA for four months between Jan 2016 till April 2016. A total of 251 (n) number of participants spread across the two districts were selected from villages, as shown in table 2.1. The sample size for the survey (Bartlett et al., 2001)<sup>3</sup> calculated with a confidence level of 90% and  $\pm 5\%$  margin of error. For the survey, a total of fourteen villages having an off-grid photovoltaic home system installed in the majority of households shortlisted using selective random sampling. Besides, the inclusion criteria for the households identified was that the SPVHS installed at least two years before the survey period to ensure that the system is sufficiently old for field assessment. The data for the selection of the study area provided by AEDA (AEDA, 2016).

Field notes, direct observation, and semi-structured interviews used to collect data. A comprehensive questionnaire for data collection related to socio-economic status, education, income, technical features of the photovoltaic home system, directly adopted from Barman et al., 2017, and modified (Appendix 1). In addition, a contextual inquiry conducted in the selected villages.

## 2.5 Contextual Inquiry: Localized Assessment

A contextual inquiry conducted across shortlisted villages in district Sonitpur and Majuli of Assam. The objective of contextual inquiry was to determine the viability of small-scale photovoltaic applications and to assess the scope of design intervention in a localized context. The results of the inquiry interpreted using chi-square  $\{\chi^2\}$ , which found significant for solar photovoltaics to be a feasible option in the regional context of northeast India  $\{\chi^2 = 91.28(2), \text{ and } p \leq 0.01\}$  when compared to wind,

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<sup>3</sup> Sample size (n) is calculated using following formulae;

$$n = \frac{z^2 \times \hat{p}(1-\hat{p})}{\epsilon^2}$$

z is the z score,  $\epsilon$  is the margin of error,  $\hat{p}$  is the population proportion, N is population size  
For finite population corrected sample size( $\hat{n}$ ) becomes;

$$1 + \frac{z^2 \times \hat{p}(1-\hat{p})}{\epsilon^2 N}$$

biomass, and micro-hydro. It indicated that small-scale photovoltaic applications like a solar home system were given preference from the utilitarian point of view for household use  $\{\chi^2= 44.24(2), \text{ and } p \leq 0.01\}$  as compared to large-scale applications like a solar-microgrid. Also, solar photovoltaics based design intervention  $\{\chi^2= 37.21(2), \text{ and } p \leq 0.04\}$  for an off-grid photovoltaic system have promising potential to assist rural mode of life. The household participants suggested an incentive-based photovoltaic home system having add-on benefits  $\{\chi^2= 79.28(2), \text{ and } p \leq 0.01\}$ . Concerning the socio-economically deprived status of the studied population, the inherent desire for add-on benefits found to be one of the key motivations to adopt an off-grid photovoltaic intervention. The details of the results given in Table 2.2.

Table 2.2 Contextual inquiry results as observed for feasibility study

Item	$\chi^2$	df	p
Item a	91.28	2	0.01
item b	44.24	2	0.01
item c	37.21	2	0.04
item d	79.28	2	0.01

\*, \*\*, \*\*\* represents two-tailed significance at  $p \leq 0.05$ ,  $p \leq 0.01$ ,  $p \leq 0.001$ , while NS stands for Non-Significant

Item, a Feasibility of Solar Photovoltaics, compared to Wind, Biomass and Micro-hydro

Item b Utilitarian aspect of Small Scale as compared to Large Scale Photovoltaic Applications in localized context

Item c Potential of Design Intervention for Off-grid Photovoltaic Application in a localized context

Item d Potential of Incentive-based Photovoltaic Home System

Besides, technical aspects also observed to suggest an optimized solution, custom specific to the user requirements.

## 2.6 Technical Features and System Functionality

A typical AEDA-installed photovoltaic home system includes a PV module (37Wp), a battery (12 V, 40 AH), a charge controller (5 A), and two light units (2@5 W CFL). The modules consist of 36 polycrystalline solar cells, and the size of the module is 12x669x35 mm, which may vary slightly based on the manufacturer. The system specification adopted from the Ministry of New and Renewable Energy (MNRE). The prescribed specification was presumed to meet the most basic energy requirement. It involves lighting in an average household size of four persons for a minimum of 4 hours per day with two days battery autonomy (i.e., 8 hours of total run time) (MNRE,

Table 2.3 Details of installed conventional photovoltaic home system as observed during field study

Component	AEDA / APEDA	APDCL	Assam Forest Dept. (Social Forestry)	Private Agencies	N.G.O
					RGVN(Rashtriya Grameen Vikas Nidhi) CRDC(Chaidur Rural Development Centre)
<b>PV Panel</b>	35 Watt, 12V Polycrystalline	40 Watt, 12V Polycrystalline	40 Watt, 12V Polycrystalline	40 Watt, 12 V 60 Watt, 12 V 75 Watt, 12 V Polycrystalline	40 Watt, 12V Polycrystalline
<b>Battery</b>	40 Ah, 12 V Tubular Plate Pb-Acid	40 Ah, 12 V Tubular Plate Pb-Acid	40 Ah, 12 V Tubular Plate Pb-Acid	40 Ah, 12 V 60 Ah, 12 V 75 Ah, 12 V Tubular Plate Pb-Acid	40 Ah, 12 V Tubular Plate Pb-Acid
<b>Charge Controller</b>	6 Amp, 12 V	6 Amp, 12 V	6 Amp, 12 V	10 Amp, 12 V	6 Amp, 12 V
<b>Lumen</b>	2 CFL@9 Watt	2 CFL@9 Watt	2 CFL@5 Watt	2 CFL@5 Watt 3 LED @ 3 Watt	2 CFL@9 Watt
<b>Standby Time</b>	4-5 Hrs	4-5 Hrs	4-5 Hrs	7-8 Hrs	4-5 Hrs

2015). Various state organizations such as Assam Power Distribution Company Limited, Assam Forest Department, Assam Energy Development Agency, Arunachal Pradesh Energy Development Agency, and NGOs such as Rashtriya Grameen Vikas Nidhi, and Chaidur Rural Development Centre were investigated. The details of which are presented in table 2.3.

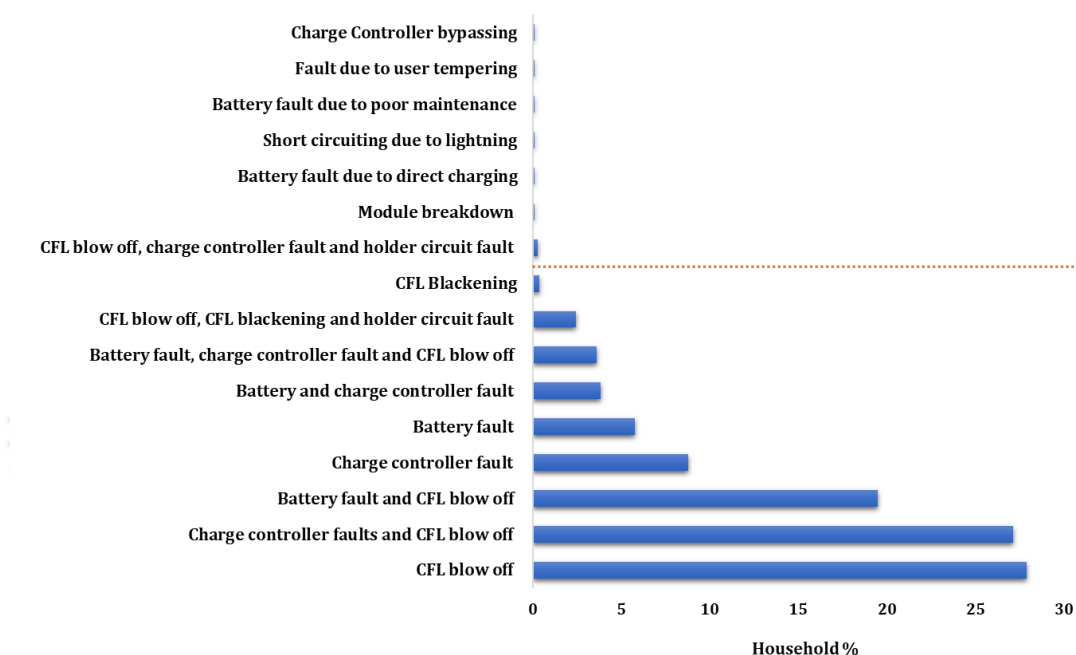
## 2.7 System Performance and Technical Analysis

Analysis of the field survey observed that the hierarchy of the performance of the solar home system was that only 21.9% of the surveyed installations function without any fault. The analysis reported that 64.3% of the SPVHS operates mainly with faults like charge controller damage, partial battery failure, and short-circuit of CFL. While approximately 13.8% of SPVHS observed to be defunct due to complete battery damage and also charging controller. Additional loads like luminaires, mobile charging, and DC Fan, TV (in rare cases) resulted in system overloading, because of which batteries reported damaged. Besides, due to low solar irradiance in the NER, the study observed inadequate charging of the battery. The inputs from the fault assessment considered for the formulation of the design parameters. Although a conventional photovoltaic system has been more economical; however, due to non-optimized design, it leads to repeated malfunctions and higher maintenance cost. The study observed user-tempering for charge controller; the power supplied directly to the luminaire from the battery bypassing controller, which lead to battery damage in the majority of cases (fig 2.4). Also, the short-circuiting of the charge controller observed due to un-regulated voltage.



Fig. 2.4 Component faults as observed during study (a) Bypassing of charge controller (b) Damaged battery due to direct charging

Different types of faults experienced by users	Household Percentage (%)
CFL blow off	27.89
Charge controller faults and CFL blow off	27.12
Battery fault and CFL blow off	19.48
Charge controller fault	8.74
Battery fault	5.76
Battery and charge controller fault	3.83
Battery fault, charge controller fault and CFL blow off	3.6
CFL blow off, CFL blackening and holder circuit fault	2.4
CFL Blackening	0.34
CFL blow off, charge controller fault and holder circuit fault	0.24
Module breakdown	0.1
Battery fault due to direct charging	0.1
Short circuiting due to lightning	0.1
Battery fault due to poor maintenance	0.1
Fault due to user tempering	0.1
Charge Controller bypassing	0.1



\* Combination of faults due to various components in household as observed during study

Figure 2.5 Details of typical faults as experienced by user in case of conventional solar photovoltaic home system as reported during study.

The multiple primary critical faults reported are shown in figure 2.5, were CFL blows off (27.89%), charge controller fault along with CFL blow off (27.12%), battery fault along with CFL (19.48%), charge controller fault (8.74%) and complete battery fault (5.76%). It is depicting the household percentage of different types of faults as experienced by users related to various components of the photovoltaic home system. Field study indicated that the majority of the photovoltaic system installed seemed to have an incompatible design, having the poor configuration of the charge controller, battery, and PV module. It led to higher losses, reduced performance, and frequent

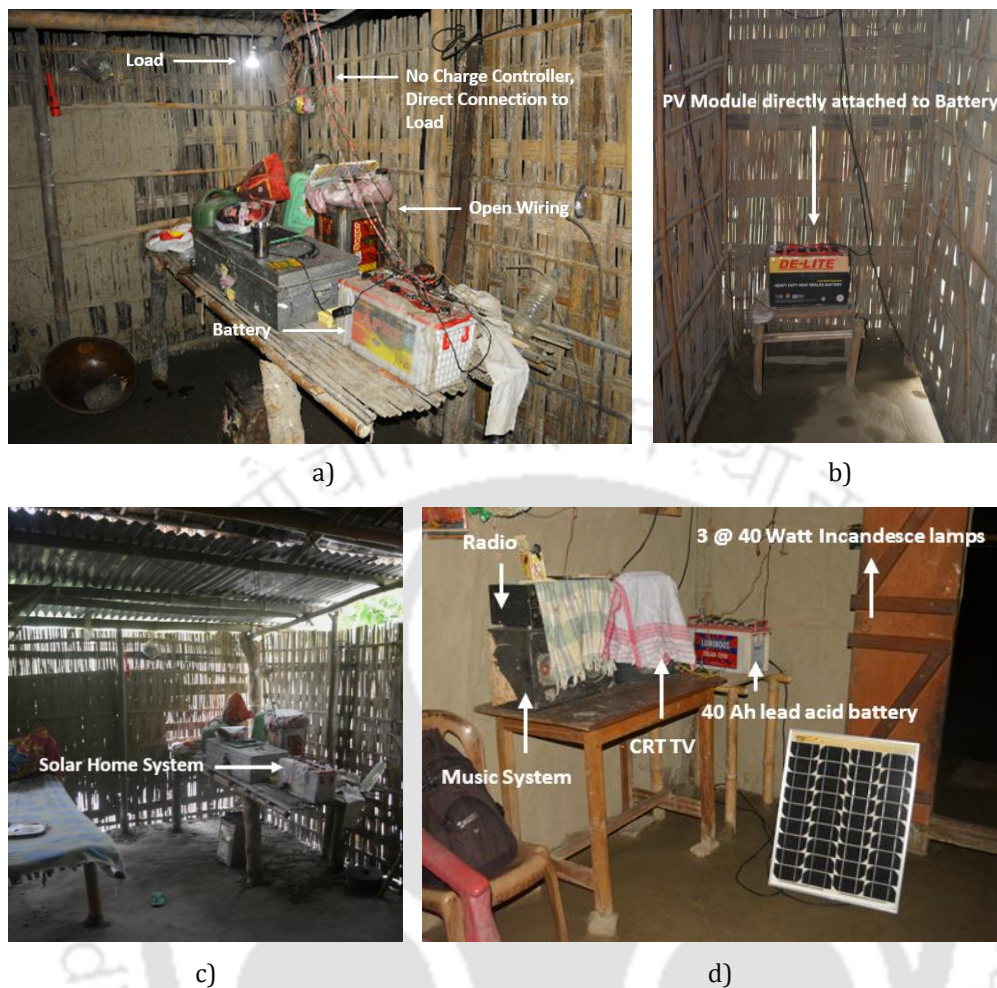


Fig 2.6-Studied conventional solar home system highlighting a) Visible drawbacks of existing system b) Battery directly attached to PV module without charge controller in a rural household c) Typical rural home environment for conventional solar system instigated electrical and chemical hazards and d) System overloading with multiple loads like radio, CRT TV, music system and incandescence lamps.

malfunction of system components. The technical inadequacy of such a system is evident in figure 2.6. It comprised of the open wiring structure, battery directly attached to the PV module (2.6a, and b). Typical rural home environments instigated electrical and chemical hazards making the conventional system more prone to incidents (2.6c). The system was overloaded with multiple loads, as seen in fig 2.6d. The study also observed that for a non-optimized conventional system, owing to its high maintenance costs, it becomes costly for the rural user in the longer term. Also, the use of quality-unverified components is one of the major causes of defunct solar photovoltaic home systems in rural villages. Concerning the above, design optimization issues, like the use of automotive battery fig 2.7a and b, and use of

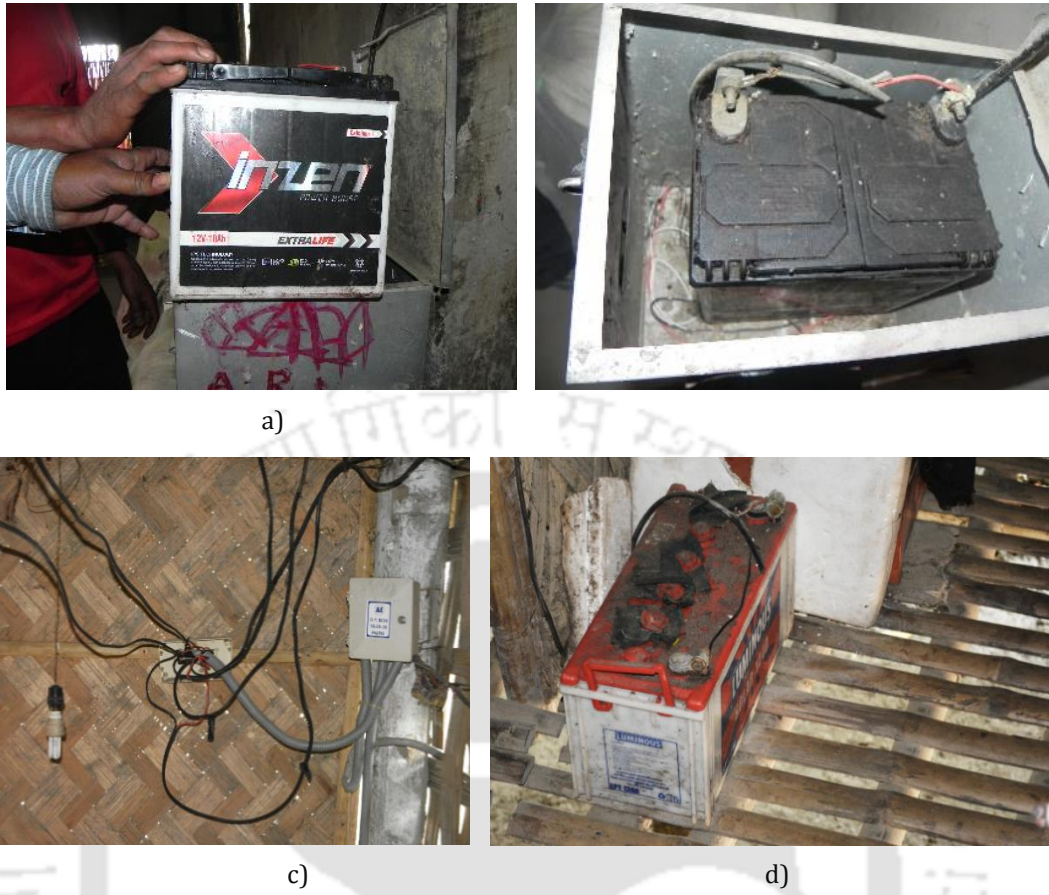


Fig 2.7 Design optimization issues for conventional solar home system. As observed in a) and b) use of automotive batteries in place of solar batteries, for c) , and d ) Non-optimized configuration between battery, charge controller and PV module

quality-unverified components fig 2.7c and d, shown in the figure. The average work hours per day found to be 3.10 hrs lower than its design value of 4.0 hrs per day. It was due to overuse of the battery, and the use of extra loads, as discussed previously. The study reported that 67.72% of users were highly dissatisfied with conventional photovoltaic systems.

Post feasibility study, the need for design development of the photovoltaic home system is realized, with the consideration that installation of a similar type of system for all households has already reached the level of design and technology saturation. Furthermore, rural households not been able to benefit much from conventional solar home system as existing design and technology not been able to address rural needs efficiently. The study indicated that the majority (73.70%) of users felt the need for the context-specific design of the solar home system. Besides, user perception is one of the most critical indicators, as described in the next section, for evaluating the

performance of conventional SPVHS at the field level. Besides, technical assessment and user insights are taken into consideration. The study found it critical that the adaptability of existing designs does not consider rural engagement. Also, the users forced to acclimatize as per the conventional design (Palit, 2003; Barman et al., 2017).

## **2.8 User Perception for Conventional Photovoltaic System**

For the total households surveyed, their mean response for different indicators of subjective user perception along with its standard deviation shown in table 2.4. It was rated on a 5-point Likert scale, taking into account portability, maintenance, affordability, functionality, and user satisfaction, as shown in appendix 1, question number 32. The study witnessed photovoltaic systems installed by AEDA, APDCL, Assam Forest Dept., various private agencies and NGO's like Rashtriya Grameen Vikas Nidhi and Chaidur Rural Development Centre (first NGO in Assam to work primarily in Solar). It was reported that many villages in the studied area being remote and prone to annual floods, so the users have to move to a safer place during a flood. Therefore, the portability of the photovoltaic system becomes a key factor. As indicated by the mean value in table 2.4, the majority of users were dissatisfied (77.68%) with the portability of solar photovoltaic home systems installed by various state agencies, private players, and NGO's. The use of a single bulky lead-acid battery in conventional SPVHS made the portability of the system very poor.

Furthermore, the researcher observed that even in case of minor malfunction, the entire system became defunct and remains in non-working condition for an average of 4-5 months due to lack of maintenance services. Post-purchase users were highly-dissatisfied (70.91%) due to a lack of maintenance services for different government agencies. While in the case of private players and NGO's, users were found dissatisfied as indicated from the mean response for maintenance shown in table 2.4. Conventional SPVHS was found acceptable to the user in terms of affordability due to its initial low purchase cost (comparative cost analysis given in section 4.12). Another critical factor in shortlisting a solar home system over the conventional grid is functionality. The recurrent power-tripping during the evening hours makes the grid unreliable even in electrified villages, while in un-electrified villages, the user was completely reliant on the off-grid photovoltaic home system as the dependent power source. The study indicated that the majority of users (64.54%)

were highly dissatisfied with the functionality of the system due to the poor quality of components used and non-optimized configuration, resulting in electrical losses and frequent system malfunction (Brajesh Dhiman, Rituraj, & Chaudhury, 2019). The study reported that overall user satisfaction was quite low among 67.72% of users for the conventional system, as indicated in mean value.

Table 2.4 User perception of a conventional solar home system for different parameters as reported during study

	AEDA	APDCL	Assam Forest Dept. (Social Forestry)	Private Agencies	NGO Rashtriya Grameen Vikas Nidhi / Chaidur Rural Development Centre
	Mean±SD	Mean±SD	Mean±SD	Mean±SD	Mean±SD
<b>Portability</b>	2.30 ± 0.91	2.37 ± 0.84	1.95 ± 0.98	2.39 ± 0.91	2.27 ± 0.78
<b>Maintenance</b>	1.45 ± 0.81	1.54 ± 0.93	1.30 ± 0.79	2.84 ± 1.01	2.10 ± 0.91
<b>Affordability</b>	3.20 ± 0.98	3.34 ± 0.76	3.16 ± 1.03	2.30 ± 0.83	3.10 ± 1.0
<b>Functionality</b>	1.20 ± 0.74	1.32 ± 0.89	1.16 ± 0.76	2.71 ± 0.96	1.98 ± 0.79
<b>User Satisfaction</b>	1.16 ± 0.92	1.10 ± 0.84	1.03 ± 0.75	2.23 ± 0.67	2.09 ± 0.89

Overall it resulted in poor user perception for the given photovoltaic utility in the studied area. Besides, another observation during interaction with stakeholders was the negligible contribution of photovoltaic systems to support rural livelihood. Concerning the above, the impact of a conventional photovoltaic system on rural livelihood was looked-in and discussed next.

## 2.9 Conventional System's Contribution to Rural Livelihood

The study observed no significant contribution of conventional SPVHS in the context of rural livelihood. Out of the total sample studied, the majority (89.64%) of participants reported a lack of productive use of energy in the case of a conventional photovoltaic system. Considering the poor socioeconomic status of the region, the percentage, as mentioned above of households felt the need for add-on benefits like additional income as intrinsic motivation to adopt SPVHS in the future. It is also evident in literature that, so far, the potential of decentralized energy applications in the context of different types of productive uses of energy explored very little (Cabraal et al., 2005). It provides a potential scope to examine it further. Concerning the above product design based intervention was investigated further with the consideration that an off-grid photovoltaic home system indicates scope to provide add-on benefits in a rural lifestyle context.

Besides, rural lifestyle activities mapped to look into the utilitarian aspect of energy and how design intervention can be made useful for context-specific use. Also, the study reported load quantification along with critical load estimation to formalize design parameters and specifications.

## **2.10 Analyzing User Need Matrix for Design Parameters**

The like-dislike method<sup>4</sup> was adopted to formalize design criteria (Otto, K. N., & Wood, K. L., 2006). The user was asked to describe what they like (Pros) and what they do not like (Cons) about the conventional solar photovoltaic system. Asking about likes ensured what is expected and what must be provided. Asking about dislikes established what could be provided to improve user satisfaction. The details of the user need matrix shown in table 2.5; the fourth column of table records the linguistic expression of priority user has. Typically this includes Must, Good, Should, and Poor. Must rating used when users absolutely must have those features. An essential user need should have a Good rating. Needs that are presumed have Should rating. Off-Grid use and affordability cited as likes for an existing solar home system. Poor repair, maintenance, and repeatedly occurring faults of various components, charge controller, luminaires, and batteries caused user inconvenience and considered as dislikes.

The study reported that the conventional photovoltaic home system found to be bulky and static in use. At the same time, the rural lifestyle in the studied region encouraged active multiple indoor and outdoor use; hence the system, which could concurrently be used in multiple scenarios, is required. The user felt the need for low maintenance design due to the limitation of repair and maintenance services. Many systems became defunct because of frequent user tempering, so the all-enclosed integrated system was a prerequisite. Existing use of single lead-acid battery affected its portability and reliability. Besides, the researcher observed that due to battery malfunction entire system stopped working. In this case, the splitting of storage recommended as a discrete module. Discrete architecture gives scope to improve the portability of the system and makes it more reliable in case of battery malfunction.

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<sup>4</sup> Kevin Otto and Kristin Wood suggested like-dislike method for effectively understanding customer needs in their book, Product Design: Techniques in reverse engineering and new product development. Pg 120

Table 2.5: User need matrix adopted to formulate design parameters for an off-grid photovoltaic system.

Indicator	Existing	Proposed	Priority
<b>Pros</b>	<ul style="list-style-type: none"> <li>▪ Off-Grid</li> <li>▪ Affordable</li> </ul>	<ul style="list-style-type: none"> <li>▪ Product should meet basic criteria of existing design</li> </ul>	Should
<b>Cons</b>	<ul style="list-style-type: none"> <li>▪ Poor Repair &amp; Servicing for Malfunctioned Solar Products</li> <li>▪ Lack of Ability to do Basic Repair</li> <li>▪ Frequent Luminaire Blow-off &amp; Blackening</li> <li>▪ Battery Malfunction like Leakage of Electrolyte-Fast Discharge-Sulfation-Carbon accumulation on electrodes-etc., Low Short circuiting of PCB and CFL's, Not enough Power / Storage for running wider range of loads for longer duration</li> <li>▪ Bypassing Charge Controller, System Overloading</li> </ul>	<ul style="list-style-type: none"> <li>▪ Need for better Servicing to address Malfunction</li> <li>▪ Need for Low Maintenance Design</li> <li>▪ Need for Integrated Design Solution to Minimize User Tempering like Bypassing Charge Controller, Battery Overloading, Wrong Wire Connections etc.</li> </ul>	Must
<b>Suggested Improvements</b>	<ul style="list-style-type: none"> <li>▪ Existing Lead Acid Battery is quite Heavy to carry for Repair</li> <li>▪ Due to Single Battery Malfunction entire System stops Working</li> <li>▪ Poor Performance due to Environmental Factors like Shading, Sub-Tropical Monsoon Climate</li> <li>▪ Productive Usage of System Suggested</li> </ul>	<ul style="list-style-type: none"> <li>▪ Portability of System Needs Improvement</li> <li>▪ <b>Splitting of Storage Required</b></li> <li>▪ Need for Hybrid Charging Solutions</li> <li>▪ <b>Incentive based System Design for Household Productivity</b></li> </ul>	Must
<b>Typical Uses</b>	<ul style="list-style-type: none"> <li>▪ Indoor Activities Studying Charging Mobile/ Running TV, Radio, etc. Cooking / Other Indoor Activities Household Micro Enterprise like Pickle Making, Weaving etc</li> <li>▪ Outdoor Activities Going to Fields, For Fishing, Dish Washing, Toilets Namghar Pooja, Neighbourhood Visits</li> <li>▪ Existing System is Bulky and Static in Use.</li> </ul>	<ul style="list-style-type: none"> <li>▪ <b>To be Concurrently used in Multiple Rural Scenarios for both Indoor and Outdoor Activities.</b></li> </ul>	Good

Sub-tropical monsoon climate and low solar irradiance in the region reduced the performance of the conventional solar home system, so provision for hybrid-charging was suggested to work under challenging climatic conditions of north-east (Akikur, Saidur, Ping, & Ullah, 2013). Also, different types of daily energy usage were observed and visually represented concerning the rural mode of life. The study observed the use of energy in rural lifestyle contexts for both indoor and outdoor settings. A visual map of reported energy activities shown in figure 2.8.

Primary indoor activities mapped related to energy usage were studying, cooking, TV, and radio-based entertainment, indoor-socializing, mobile charging, and household enterprise activities. Also, the primary outdoor post-dark activities reported during the study were, going to rural shops and vegetable vendors, visiting the neighbourhood, using outdoor toilets, attending community functions, visiting Naam-Ghar, playing outdoor games like carom, and visiting local fields. Observing such activities helped understanding energy usage in the context of a rural lifestyle, and how design intervention for the photovoltaic home system can assist lifestyle activities.

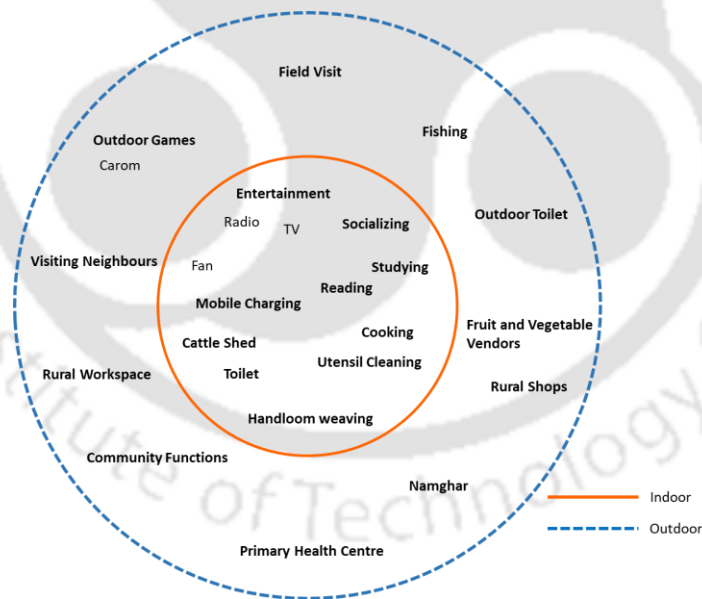


Fig 2.8 Indoor and outdoor rural lifestyle activities based mapping related to the use of energy as observed during field study.

Besides, the critical load was estimated as it helped to design an optimized photovoltaic system as per the prerequisites discussed in previous sections — concerning details of the critical load discussed next.

## **2.11 Critical Load Estimation and Possible Energy Scenarios**

The development of the photovoltaic home system involves the assessment of the amount of electricity required by different loads. The load estimation includes determining the capacity and size of various parts (such as SPV modules, battery, and charging controllers) to use in a photovoltaic home system (Labouret, A., Viloz, M., 2010). Solar photovoltaic system design needs information including number and type of load to be connected, solar irradiance data of the location, and total hours of use for each load. Off-grid DC-SPVHS needs to operate load during non-sunshine hours and also during sunlight hours regardless of variability in solar irradiance. It requires a battery to use in off-grid SPVHS. Whenever a battery used, the charging controller is also used to control the supply of voltage to ensure the battery's longevity. Critical load estimation results in establishing an optimized design configuration, customized to rural requirements.

### **2.11.1 Energy Flow and Design Diagram**

In an off-grid photovoltaic system, critical load estimation was done based on energy flows from the battery towards connected loads. Therefore the flow of electricity is from the photovoltaic module to battery. In this regard, the system design works in the direction opposite of the energy flux (Solanki, 2015). Thus, first loads and their specifications (power, operating hours, and energy requirement) identified, and then the system-sizing has done. It followed the battery sizing, charge controller, and PV panel sizing calculated as per load<sup>5</sup> requirement. In the system design flowchart, the design proceeds in the reverse direction of the flow of energy.

### **2.11.2 Solar Photovoltaic System Design Methodology**

Concerning the system design flow-chart, the design proceeds in the reverse direction of the flow of energy, as shown in fig 2.9. The study used the following methodology for system configuration and development of energy scenarios.

- a. Determine connected loads and estimate their energy requirement (in watts)

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<sup>5</sup> The load refers to any connected device that solar photovoltaic system needs to power.

- b. Determine the size and choice of electronic components (their power rating, voltage and current input and output of the electronics)
- c. Determine the battery size (number, capacity, voltage and Ah ratings)
- d. Determine PV module size (number, power rating, voltage, and current ratings)

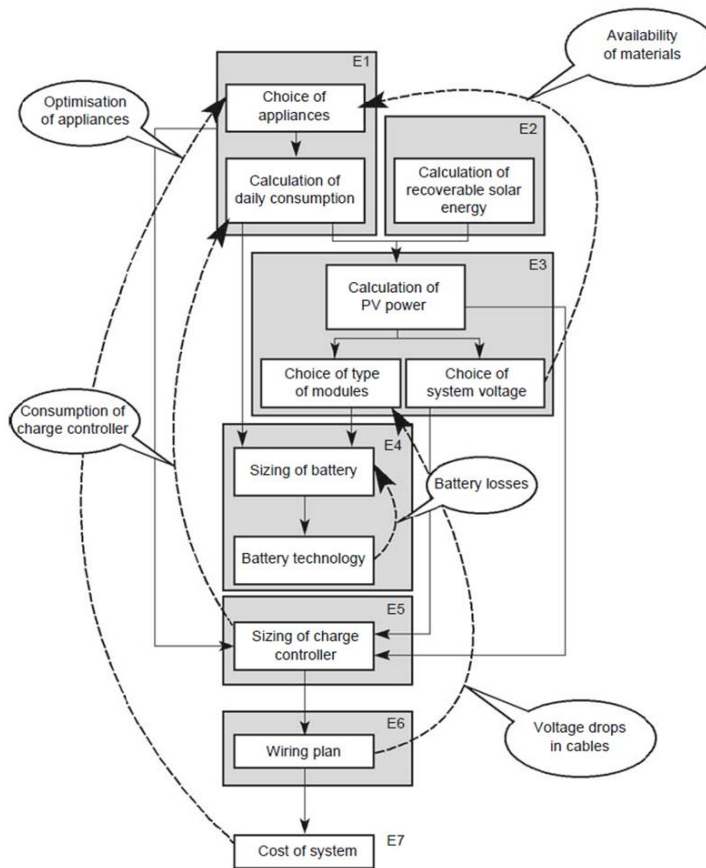


Fig 2.9: Simplified diagram for sizing of stand-alone PV System  
(Source: Labouret, A., & Viloz, M. (2010))

### 2.11.3 Load Quantification and Types

The study reported that 53.80% of the household of the total surveyed population were using an average of four CFL luminaires, while 49.01% of the population were using a single fan. A TV is primarily used for entertainment and watching the local news. The study reported that around 73.30% of respondents were using a single TV. Besides, 58.58% of households owned two mobile phones. Noteworthy to mention that household's dependency on other electronic gadgets like radio, music system & personal computer drastically reduced due to the arrival of similar features in low-cost smartphones supported with drastically falling prices of high-speed internet. It

Table 2.6 Frequency chart of the number and types of load reported during study

No of Luminaire	1	2	3	4	5 and Above	Total
F	0	34	56	135	26	251
P	0%	13.54%	22.31%	53.80%	10.35%	100%
No of Fan	1	2	3	4	5 and Above	Total
F	123	86	25	17	0	251
P	49.01%	34.26%	9.96%	6.77%	0%	100%
No of TV	1	2	3	4	5 and Above	Total
F	184	67	0	0	0	251
P	73.30%	26.70%	0%	0%	0%	100%
No of Mobile	1	2	3	4	5 and Above	Total
F	89	147	15	0	0	251
P	35.45%	58.58%	5.97%	0%	0%	100%
Total Backup/Day	0-3 Hrs	4-7 Hrs	8-11 Hrs	12-15 Hrs	Total	
F	40	98	79	34	251	
P	15.93%	39.06%	31.47%	13.54%	100	

\* Dependency of other Electronic Gadgets like Radio, Music System & Personal Computer is drastically reduced due to arrival of same features in Low Cost Smart Phones supported with drastically falling prices of High Speed Internet

\* Average back-up of 8 hrs. is required / day.  
F-Frequency, P-Percentage

Derived Load	
Load Type	Value
Luminaire	4
Fan	1
TV	1
Mob	2
Autonomy	8 hours

has dramatically affected dependency on types and the number of loads in a rural context. Regarding average back-up time, 39.06% of respondents recognized the minimum back-up time for SPVHS of 4-7 hours per day. While, 31.47% of households acknowledged the 8-11 hours as a minimum back-up time for SPVHS. The Derived load for an average household required support for a minimum of four luminaires, one Fan, one TV, and two Mobiles. Average back-up time of eight hours required per day. Design development of the photovoltaic system should support load criteria, as shown in table 2.6.

#### 2.11.4 Possible Energy Scenarios for Photovoltaic System Development

One estimated how much energy is needed to function the derived loads in this step. Energy consumed on a given day by the load attained by multiplying the power rating of a load to the sum of its operating hours. Thus, in wathour, the total energy

calculated. If there are additional loads of a similar type, then total energy consumed by each load is attained by multiplying watt consumed (column 3) by the total loads (column 4), for example, as shown in table 2.7. Concerning the above, two different types of energy scenarios concluded after critical load estimation. The derived energy scenario 1 is 700 Watt-hour for moderate energy requirement, and energy scenario 2 is 300 Watt-hour for elementary energy requirement. The following are the details of the same.

**Energy Scenario 1:** Here, the critical load estimation of 700-watt-hour concluded in Table 2.7. It comprises of 2 LED (12 v) luminaire of 5 watts with 10 hrs of running time. 2 LED (12 v) luminaire of 10 watts with 8 hrs of running time. 1 DC Fan (12 v) of 30 watts with 8 hrs of running time. 1 DC TV (12 v) of 30 watts with 3 hrs of running time and 2x5 watt for Mobile with 2 hrs of running time. PV module of 200 Wp should have appx 21° of inclination angle facing south direction (calculated as per study area longitude and latitude; this may differ as per region).

Table 2.7 Critical load estimation for energy scenario 1

Critical Load Estimation						
	1	2	3	4=2x3	5	6=4x5
S.No	Appliance	Watts / Appliance (W)	No #	Total Watts=W x No (W)	No of Hrs	Energy=Total Watts x No of Hrs (Wh)
1	DC LED Lumen (9-12 V)	5	2	10	10	100
2	DC LED Lumen (9-12 V)	10	2	20	8	160
3	DC Fan ( 12 V)	30	1	30	8	240
4	DC LED TV ( 12V)	30	1	30	3	90
5	Mobile Charging	10	2	20	2	40
<b>Total</b>				90		630
Future Need+Misc Losses				20%		20%
				<b>108</b>		<b>756</b>
<b>Total</b>				<b>110 Watt</b>		<b>750 Watt Hour</b>

Details of SPVHS calculations for energy scenario-1 for the battery bank, PV module, and charge controller presented in appendix 2a. The schematic diagram for scenario-1 is shown in fig 2.10, along with design specification, as shown in table 2.8. The 120 Ah of required capacity split into two batteries of 60 Ah considering rural lifestyle advantage for remote, rural geographies as discussed previously. Related calculations performed using solar photovoltaic technology and systems book, Chapter 10 (Solanki, 2015).

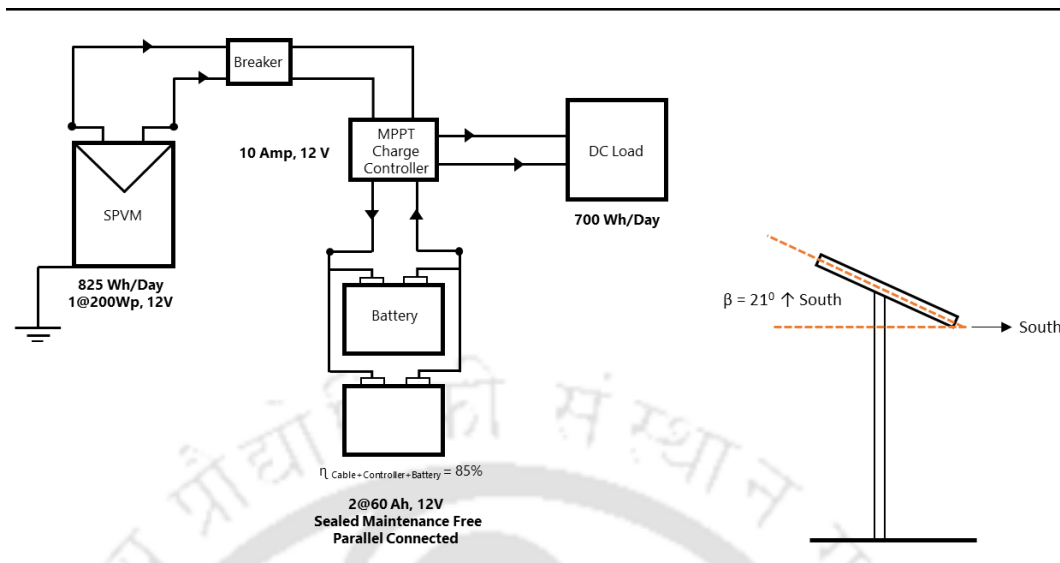


Fig 2.10 Schematic diagram of energy scenario 1 based photovoltaic system

Table 2.8 Design specification for energy scenario 1 based photovoltaic system

Component Specification				
Component	Specification	Number	Type	Direction
PV Module	12V,200Wp	1	Polycrystalline	21 Deg South
Battery	12V,60Ah	2	VRLA	NA
Charge Controller	12V,10Amp	1	MPPT	NA

**Energy Scenario-2:** Critical load estimation of 300-watt-hour derived in table 2.9 It comprises of 2 LED (12 v) luminaire of 5 watts with 10 hrs of running time, 2 LED (12 v) luminaire of 10 watts with 8 hrs of running time and 1x5 watt for Mobile Charging with 1 hrs of running time. PV module of 80 Wp should have appx 21° of inclination angle facing south direction (calculated as per study area longitude and latitude; this may differ as per region). Details of calculations for energy scenario-2 for the battery bank, PV module, and charge controller presented in appendix 2b. The schematic diagram for scenario-2 is shown in fig 2.11, along with design specification, as shown in table 2.9.

Table 2.9 Critical load estimation for energy scenario 2

Critical Load Estimation						
	1	2	3	4=2x3	5	6=4x5
S.No	Appliance	Watts / Appliance (W)	No #	Total Watts=W x No (W)	No of Hrs	Energy=Total Watts x No of Hrs (Wh)
1	DC LED Lumen (9-12 V)	5	2	10	10	80
2	DC LED Lumen (9-12 V)	8	2	16	8	128
3	Mobile Charging	10	2	20	2	40
<b>Total</b>				90		248
Future Need+Misc Losses				20%		20%
				<b>108</b>		<b>296</b>
<b>Total</b>				<b>110 Watt</b>		<b>300 Watt Hour</b>

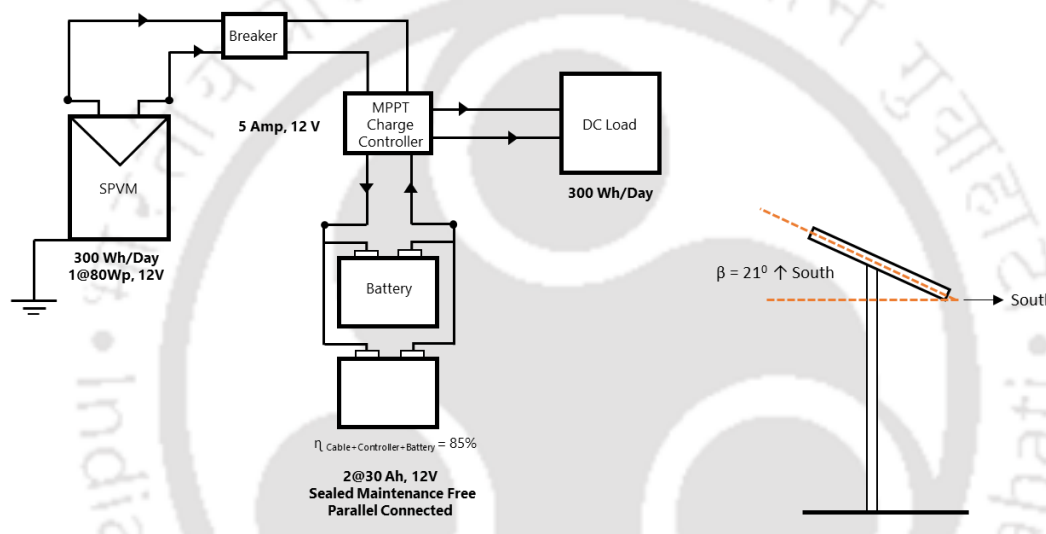


Fig 2.11 Schematic diagram of energy scenario 2 based photovoltaic system

The 60 Ah of required capacity split into two batteries of 30 Ah considering rural-lifestyle advantage for remote geographies. The respective design specification is shown in table 2.10.

Table 2.10 Design specification for energy scenario 2 based photovoltaic system

Component Specification					
Component	Specification	Number	Type	Direction	
PV Module	12V,80Wp	1	Polycrystalline	21 Deg South	
Battery	12V,30Ah	2	VRLA	NA	
Charge Controller	12V,5Amp	1	MPPT	NA	

## 2.12 Design Specification and Parameters Formulation

Design parameters and specifications formulated by integrating inputs from technical and user assessment, as shown in fig. 2.12. These parameters and specifications were used as a reference for design ideation by a team of senior designers and solar technologists to ideate design concepts for an off-grid photovoltaic system. The entire study divided into two parts; 1) technical assessment in which technology-related issues were studied, and 2) opinion and user lifestyle based study to assess user compatibility, as discussed next.

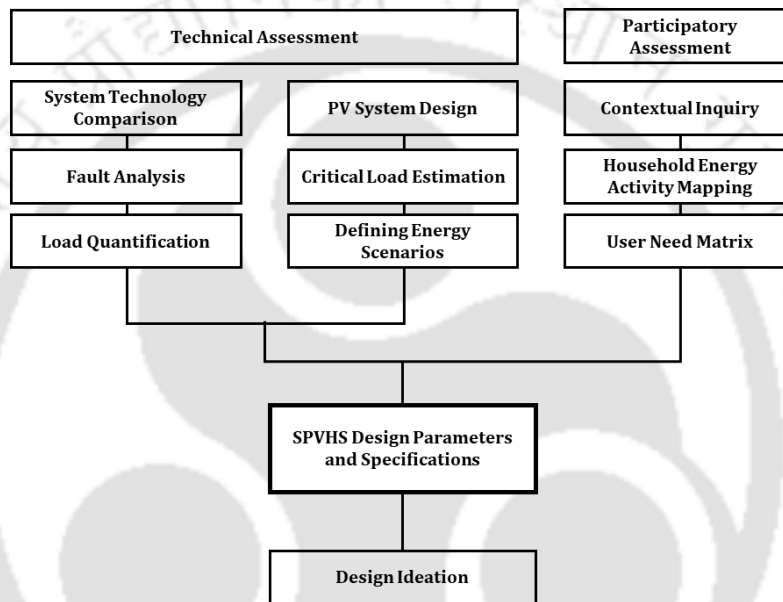


Fig 2.12 Methodology adopted for formulation of design parameters and specification

### 2.12.1 Technical Assessment

Customization of technical aspects found necessary to address regional household needs. The study includes investigation of typical 12V, 40 Ah battery capacity photovoltaic system installed by different state agencies like AEDA, APDCL, various private agencies, and NGO's. The use of a single, bulky lead-acid battery in a conventional solar home system restricted its use in the rural scenario. Besides, the entire system stopped working in case of even a minor battery malfunction, as the studied system has only one battery. The study indicated that, due to sub-tropical monsoon climate and low solar irradiance, in the northeast region, hybrid charging was proposed to improve system performance. It was observed that portability was one of the significant issues for a conventional off-grid home system considering

remote geography use. Hence, the splitting of storage proposed the details of which are discussed in the chapter ahead. Fault analysis of the conventional photovoltaic system indicated that the maximum numbers of cases reported CFL blown-off as it was prone to temperature fluctuations in rural outdoor spaces. Frequently CFL malfunction added to the cumulative cost. Also, low-intensity CFL resulted in visual stress to rural users due to which they used more luminaires, leading to system overloading. So an optimum intensity LED luminaire proposed for the system. As LED is more durable and consumes less energy, this saved the running cost for the user. It was observed that for a conventional system, in the majority of cases for maintenance of tubular batteries, users were not able to top-up regularly with distilled water. This study witnessed the local evidence and observation that householders replaced distilled water with sulphuric acid, which entire spoiled battery and the entire system stopped functioning, it reported being a key reason for the malfunctioning of batteries. Concerning this, maintenance-free VRLA batteries proposed to ease routine maintenance issues.

Furthermore, critical load estimation resulted in the development of two rural energy scenarios as 300 watts and 750 watts, resulting in the formulation of the design specification.

### **2.12.2 Participatory Assessment**

Contextual inquiry indicated that photovoltaics based design intervention for the solar home system had promising potential to assist rural lifestyle, in-addition rural population suggested productive usage, through the incentive-based solar photovoltaic home system. Energy activities mapped for both indoor and outdoor use. Limitation of conventional SPVHS design observed to address the need for concurrent multiple location use in a rural lifestyle context. In this regard, discrete design architecture shown scope to address lifestyle needs by splitting storage into smaller modules of equivalent capacity. Plug-n-Play system proposed for ease of operation and installation of the solar home system. Table 2.11 represents a comprehensive list of the design parameters and specifications for the solar photovoltaic home system.

Table 2.1.1 Design parameters and specification resulted due to feasibility study in context of solar photovoltaic home system

<p style="text-align: center;"><b>Design Parameters</b></p>	<p>Design Intervention should address following:</p> <ul style="list-style-type: none"> <li>▪ Design should be able to address need for Energy Scenario 1 &amp; 2</li> <li>▪ Poor Efficiency due to Sub-Tropical Monsoon Climate, Needs Hybrid Charging based Solution</li> <li>▪ Split Storage to be explored to improve technical and usability concerns</li> <li>▪ Portability of System to be considered due to use in Remote Geography &amp; Natural Calamities</li> <li>▪ Consideration for Efficient Solar and Storage Technologies</li> <li>▪ LED based lighting for better Efficiency &amp; Durability</li> <li>▪ Low Maintenance Solution</li> <li>▪ Plug n Play System for Ease of Usage</li> <li>▪ Integrated Design to avoid User Abuse / Tempering</li> <li>▪ Discrete Design Architecture Suitable to Rural Needs</li> <li>▪ Incentive based System Design for Rural Productive Use</li> </ul>		
<p style="text-align: center;"><b>Design Specification</b></p>	<table style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 50%; vertical-align: top;"> <p>SPVM 1@80Wp, 12V SPVM Fixed Mount Tilt Angle <math>\beta = 21^\circ \uparrow</math> South</p> <p>Battery 2@30 Ah, 12V, Valve Regulated Lead Acid, Parallel Connected</p> <p>MPPT Charge Controller 5 A, 12 V</p> </td> <td style="width: 50%; vertical-align: top;"> <p>SPVM 1@200Wp, 12V SPVM Fixed Mount Tilt Angle <math>\beta = 21^\circ \uparrow</math> South</p> <p>Battery 2@60 Ah, 12V, Valve Regulated Lead Acid, Parallel Connected</p> <p>MPPT Charge Controller 10 A, 12 V</p> </td> </tr> </table>	<p>SPVM 1@80Wp, 12V SPVM Fixed Mount Tilt Angle <math>\beta = 21^\circ \uparrow</math> South</p> <p>Battery 2@30 Ah, 12V, Valve Regulated Lead Acid, Parallel Connected</p> <p>MPPT Charge Controller 5 A, 12 V</p>	<p>SPVM 1@200Wp, 12V SPVM Fixed Mount Tilt Angle <math>\beta = 21^\circ \uparrow</math> South</p> <p>Battery 2@60 Ah, 12V, Valve Regulated Lead Acid, Parallel Connected</p> <p>MPPT Charge Controller 10 A, 12 V</p>
<p>SPVM 1@80Wp, 12V SPVM Fixed Mount Tilt Angle <math>\beta = 21^\circ \uparrow</math> South</p> <p>Battery 2@30 Ah, 12V, Valve Regulated Lead Acid, Parallel Connected</p> <p>MPPT Charge Controller 5 A, 12 V</p>	<p>SPVM 1@200Wp, 12V SPVM Fixed Mount Tilt Angle <math>\beta = 21^\circ \uparrow</math> South</p> <p>Battery 2@60 Ah, 12V, Valve Regulated Lead Acid, Parallel Connected</p> <p>MPPT Charge Controller 10 A, 12 V</p>		

### 2.13 Summary

The compatibility of design and technology to the beneficiary studied in a localized context. Field analysis resulted that about 67.72% of users were highly dissatisfied with their existing solar home system. It was worthy of mentioning that during study majority (73.70%) of households felt the need for the context-specific design of the solar home system in the rural perspective of northeast India. Out of the total sample (n=251) of households studied, about 89.64% of householders reported that they did not perceive any significant benefits for livelihood improvement due to the adoption of the conventional system. The study confirmed that very little attention paid for context-specific design in a localized context. User need assessment (section 2.11) resulted in findings that (a) splitting of storage was required (b) Incentive-based design was reported in the study as motivation to adopt a photovoltaic home system in a localized context. (c) It should be used for concurrent multiple rural lifestyle needs. It fulfilled research objective one and two; to understand rural prerequisites for energy needs, usage patterns, and existing concerns for design intervention to study the feasibility of conceptualization for off-grid SPVHS.

Furthermore, the researcher observed that rural households considered peer-to-peer energy transactions as intrinsic lifestyle benefits to made available to the user to facilitate their poor socio-economic status. Such an energy exchange has potential to facilitate dissemination of photovoltaic applications to rural grass-roots as is lauded for improving rural participation, by providing local stakeholders a vital role to facilitate interhousehold energy exchange (Chaurey, Krithika, Palit, Rakesh, & Sovacool, 2012; Emili, Ceschin, & Harrison, 2016; Zerriffi, 2011). Design development for the intervention was explored (as discussed in the next chapter) based on the reported design parameters and specifications for an off-grid photovoltaic system.

# Chapter 3

## Design and Development of Discrete Photovoltaic Home System

**Chapter Three** covers the details of design and development for an off-grid photovoltaic system. It involves ideation for system architecture and design concepts based on parameters concluded from the feasibility study — multi-criteria decision-making technique used for design evaluation, which led to the proposal of an optimal solution. Hardware compatible with design parameters was realized based on the Matlab@simulink models for both conventional and proposed system. Furthermore, the prototype development of the proposed design implemented conforming to product design principles, considering usability and human factors evaluation.

### **3.0 Introduction**

The background of the rural lifestyle in northeastern India is such that it necessitated the productive use of energy, to design, and develop an off-grid photovoltaic home system in a localized context. Therefore, the study focuses on a systematic approach to accomplish the development of the proposed design for an off-grid photovoltaic home system. Design assessment has shown an advantage in the case of the discrete off-grid photovoltaic system both from a technical and user perspective.

#### **3.1 Off-grid Photovoltaic Home System Possible Architectures**

An expert group comprising of three core professionals teamed for conceptualization and evaluation of possible system architecture; having one senior-level manager associated with the solar sector industry, the second person was the director of state nodal agency responsible for the development of decentralized energy in Assam, while third-person in the group was energy consultant cum researcher. Besides, there were two non-core professionals. The selection criteria for the experts include industrial, research, or consultancy experience (a minimum of ten years), competent in decision-making, and expertise in the domain of solar energy application development. Besides, non-core professionals have relevant experience of three to five years.

After the finalization of the expert panel, the next task was conceptualization sessions to explore the possibilities of design intervention. For this, the brainstorming session conducted with a group of experts, as mentioned above, about possible system architectures for an off-grid photovoltaic system in the regional context. Concept ideation utilized expert-opinion based indicators like affordability, usability, the novelty of system architecture, and feasibility for rural demonstration and context-specific use. Five concepts for system architectures recognized useful during the brainstorming session, as shown in table 3.1. Details of system architecture concepts discussed as follows;

- ❖ The advantage of conventional system architecture 1, is its low cost but had multiple disadvantages like incompatible design and technology of conventional system not fulfilling existing user needs. Malfunction of single lead-acid battery made system defunct in the majority of cases; also, it severely affected the system

portability. The architecture of the conventional system found contrary to regional needs. Since the conventional system has an open architecture, it subjected to user-tempering like charge controller bypassing, use of automotive batteries instead of solar, and was prone to overloading.

- ❖ In system architecture 2, battery and charge controller housed inside the casing, keeping in view the issues related to user tempering. The solar PV module suggested being independent of the controller unit.
- ❖ While in system architecture 3, the luminaire integrated with the casing, so the concept to use as portable luminaire aid cum charging unit. The casing also contains a battery and charge controller. The advantage of such a system is that the casing box can be disconnected from the solar panel and use as a mobile light source along with a mobile charging point.
- ❖ For system architecture 4, the idea of a discrete system architecture conceptualized considering its multiple benefits in a regional context. Each storage module can be docked along with another module to the controller unit to reciprocate to the demand-driven use. The beneficiary can buy a storage module in increment considering affordability. Discrete architecture indicated scope to address rural requirements, as add-on benefits like peer-to-peer energy exchange in rural settings.
- ❖ System architecture 5 proposes PV-Grid based hybrid-charging solution, considering sub-tropical monsoon climate with heavy rains in the north-east region. While System architecture 6 proposes, micro-hydel based charging of solar home system along with PV-Grid. Architecture can support higher loads but could be more expensive in the longer run.

Post conceptualization of system architecture, it was subjected to expert assessment using multi-criteria decision-making based method called Fuzzy-Topsis, details of which are discussed in the next section.

Table 3.1 Possible architectures for solar photovoltaic home system ideated during expert brainstorming, to be found appropriate in the regional context.

Type	Figure	Features
System Architecture 1		<ul style="list-style-type: none"> <li>All the units are independent of each other.</li> <li>External solar panel, separate battery, charge controller and luminaire. Solar photovoltaic module can be placed outside or on roof as Independent Unit.</li> <li>Advantage of such architecture is affordability.</li> <li>Disadvantage however is open architecture subjected to component malfunction due to repeated user abuse</li> </ul>
System Architecture 2		<ul style="list-style-type: none"> <li>Battery &amp; Charge Controller integrated into a single casing.</li> <li>Solar photovoltaic module can be placed outside or on roof as Independent Unit.</li> <li>Advantage of such architecture is less prone to user abuse as battery and charge controller placed inside casing. It have support for basic phone charging and luminaire.</li> <li>More cost compared to conventional architecture</li> </ul>
System Architecture 3		<ul style="list-style-type: none"> <li>Battery, Charge Controller &amp; Luminaire are integrated into single casing.</li> <li>The casing can be used as portable luminaire aid cum charging unit, which also contain battery and charge controller.</li> <li>The advantage of such type of system is that external solar photovoltaic module can be placed on the roof, independent of controller box. Also controller box which house luminaire, can be disconnected from the solar panel and can be used as a mobile light.</li> <li>No independent use of luminaires</li> </ul>
System Architecture 4		<ul style="list-style-type: none"> <li>To give more possibilities for users, the system architecture aims at a discrete design which can be integrated or used independently with other modules to increase or decrease capacity (and user possibilities) of the system.</li> <li>User can buy discrete storage units in increments considering their affordability.</li> <li>The advantage is that it serves the purpose of fulfilling demand driven customized energy requirement in coherence with rural lifestyle requirement. Other than luminaire and mobile charging, architecture provide support to run DC fan and TV</li> </ul>
System Architecture 5		<ul style="list-style-type: none"> <li>It proposes PV-Grid based hybrid charging solution. Solar photovoltaic module is independent of controller unit.</li> <li>The advantage of architecture is that hybrid charging is quite useful considering climatic and geographic conditions of northeast along with quite unreliable grid in rural areas.</li> <li>Supports luminaire and mobile charging.</li> <li>Hybrid charging depends on grid availability</li> </ul>
System Architecture 6		<ul style="list-style-type: none"> <li>PV-Micro Hydro-Grid based Hybrid charging solution.</li> <li>Multi-input hybrid charging is quite useful considering challenging geo-climatic conditions of northeast India.</li> <li>Architecture supports more loads. Provision for Mobile/SL charging. It supports DC Fan, TV and Multiple Luminaires.</li> <li>Installation and maintenance needs consideration.</li> <li>More cost compared to other architectures.</li> </ul>

### **3.1.1 Home System Architecture Concept Evaluation**

Multi-criteria decision-making (MCDM) used for photovoltaic home system architecture evaluation. Expert-based criteria for evaluation of multiple-concepts for system architecture were functionality, usability, affordability, novelty, and feasibility. Fuzzy Multi-criteria decision-making (MCDM) used to evaluate architecture concepts. In fuzzy MCDM lower, middle, and upper value associated with the triangular membership function assigned to the preference value, which mitigates the uncertainty associated with decision-maker's preferences, and to encourage decision-makers to shortlist the best option from a wide range of available alternatives. (Nadaban, Dzitac, & Dzitac, 2016; Rodrigues, Junior, Osiro, Cesar, & Carpinetti, 2014). The method used qualitative assessment criteria expressed by the use of linguistic variables described qualitatively in linguistic terms and quantitatively by a fuzzy set of numbers.

#### **3.1.1.1 Fuzzy TOPSIS Method**

Hwang and Yoon (Hwang, C. L. & Yoon, K., 2012) introduced multi-criteria decision-making (MCDM) method named order performance by similarity to ideal solution (TOPSIS). This method based on selecting an option that should have the minimum distance from Positive Ideal Solution (the solution that minimizes cost criteria and maximizes benefit criteria) and the farthest distance from Negative Ideal Solution. TOPSIS used considering qualitative linguistic criteria used by experts for decision-making. Experts rated on a five-point fuzzy scale, which converted linguistic rating into fuzzy numbers. The expert weighted criteria based on the level of importance to each criterion. Assigned fuzzy weights were; Functionality (3.0,5.0,7.0), Reliability (5.0,7.0,9.0), Affordability (5.0,7.0,9.0), Novelty (5.0,7.0,9.0) and Feasibility (5.0,7.0,9.0).

First, a decision matrix of alternatives and criteria formulated. The normalized decision matrix and construction of the weighted decision matrix then implemented, followed by the positive-ideal and negative-ideal solutions. The experts, as decision-makers, expect to have a minimum value for cost criteria and maximum value for benefit criteria. It then followed by separation measure and calculating relative closeness coefficient to the ideal solution. The best alternative is one that has the the

shortest distance to the ideal solution and the longest distance to a negative ideal solution. (Buyukozkan & Ifi, 2012; Pohekar & Ramachandran, 2004).

### 3.1.1.2 Methodology

**Step 1.** Assignment rating to the criteria and the alternatives.

We assume that we have a decision group with K members. The fuzzy rating of the k<sup>th</sup> decision-maker about alternative SA<sub>i</sub> w.r.t. criterion C<sub>j</sub> is denoted  $\tilde{x}^{k_{ij}} = (a^{k_{ij}}, b^{k_{ij}}, c^{k_{ij}})$ . System architectures, as discussed in table 13, are considered as alternatives (SA<sub>i</sub>), while criteria for evaluation were Functionality (C1), Reliability (C2), Affordability (C3), Novelty (C4) and Feasibility (C5). The fuzzy preference scale (table 3.2) used to assign a rating to criteria and alternatives.

Table 3.2. Fuzzy preference scale with linguistic terms for alternatives

Linguistic Terms	Triangulation FN
Very Good	(7,9,9)
Good	(5,7,9)
Medium	(3,5,7)
Poor	(1,3,5)
Very Poor	(1,1,3)

**Step 2.** Compute the aggregated fuzzy ratings for alternatives and the aggregated fuzzy weights for criteria

The aggregated fuzzy rating  $\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij})$  of *i*<sup>th</sup> alternative w.r.t., *j*<sup>th</sup> criterion obtained as follows:

$$a_{ij} = \min_k \{a_{ij}^k\}, b_{ij} = \frac{1}{K} \sum_{k=1}^K b_{ij}^k, c_{ij} = \max_k \{c_{ij}^k\} \quad (1)$$

The aggregated fuzzy weight  $\tilde{w}_j = (w_{j1}, w_{j2}, w_{j3})$  for the criterion, C<sub>j</sub> calculated by formulas:

$$w_{j1} = \min_k \{w_{j1}^k\}, w_{j2} = \frac{1}{K} \sum_{k=1}^K w_{j2}^k, w_{j3} = \max_k \{w_{j3}^k\} \quad (2)$$

**Step 3.** Construct the normalized fuzzy decision matrix.

The normalized fuzzy decision matrix is  $\tilde{R} = [\tilde{r}_{ij}]$ , where;

$$\tilde{r}_{ij} = \left( \frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*} \right) \text{ and } c_j^* = \max_i \{c_{ij}\} \text{ (benefit criteria)} \quad (3)$$

$$\tilde{r}_{ij} = \left( \frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}} \right) \text{ and } c_j^- = \min_i \{a_{ij}\} \text{ (cost criteria)} . \quad (4)$$

**Step 4.** Construct the weighted normalized fuzzy decision matrix.

The weighted normalized fuzzy decision matrix is  $\tilde{V} = (\tilde{v}_{ij})$ , where

$$\tilde{v}_{ij} = \tilde{r}_{ij} \times w_j. \quad (5)$$

**Step 5.** Determine the Fuzzy Positive Ideal Solution (FPIS) and Fuzzy Negative Ideal Solution (FNIS).

The FPIS and FNIS are calculated as follows:

$$A^* = (\tilde{v}_1^*, \tilde{v}_2^*, \dots, \tilde{v}_n^*), \text{ where } \tilde{v}_j^* = \max_i \{v_{ij}\} ; \quad (6)$$

$$A^- = (\tilde{v}_1^-, \tilde{v}_2^-, \dots, \tilde{v}_n^-), \text{ where } \tilde{v}_j^- = \min_i \{v_{ij}\} . \quad (7)$$

**Step 6.** Calculate the distance from each alternative to the FPIS and the FNIS.

Chen introduced a vertex method to calculate the distance between two triangular fuzzy numbers. If  $\tilde{x} = (a_1, b_1, c_1)$ ,  $\tilde{y} = (a_2, b_2, c_2)$  are two triangular FNs then for triangular fuzzy numbers (FN), this is expressed as;

$$d(\tilde{x}, \tilde{y}) := \sqrt{\frac{1}{3} [(a_1 - a_2)^2 + (b_1 - b_2)^2 + (c_1 - c_2)^2]} \quad (8)$$

Let  $d_i^*$  and  $d_i^-$  be the distance from each alternative  $A_i$  to the FPIS and to the FNIS, respectively.

$$d_i^* = \sum_{j=1}^n d(\tilde{v}_{ij}, \tilde{v}_j^*), \quad d_i^- = \sum_{j=1}^n d(\tilde{v}_{ij}, \tilde{v}_j^-) \quad (9)$$

**Step 7.** Calculate the closeness coefficient  $CC_i$  for each alternative.

For each alternative  $A_i$  we calculate the closeness coefficient  $CC_i$  as follows:

$$CC_i = \frac{d_i^-}{d_i^- + d_i^*} . \quad (10)$$

**Step 8.** Rank the preference order.

The alternative with the highest closeness coefficient represents the best alternative

### 3.1.1.3 Results and Discussion

The decision-makers made evaluations of the weight of the criteria and the ratings of the alternatives according to the linguistic values shown in Table 3.3. Based on Chen (Chen, 2000), the linguistic values of these variables were specified using triangular fuzzy numbers (TFN). Table 3.3 presents the linguistic judgment of criteria weights and alternatives ratings for the three decision-makers (k=3) engaged in the selection process. Linguistic variables, as shown in Table 3.2, converted into triangular fuzzy numbers.

Table 3.3. Comparative judgements of the weight of the criteria made by decision makers

	C1	C2	C3	C4	C5
<b>DM1</b>					
SA1	(1.0,3.0,5.0)	(1.0,3.0,5.0)	(7.0,9.0,9.0)	(1.0,3.0,5.0)	(5.0,7.0,9.0)
SA2	(5.0,7.0,9.0)	(3.0,5.0,7.0)	(3.0,5.0,7.0)	(3.0,5.0,7.0)	(3.0,5.0,7.0)
SA3	(5.0,7.0,9.0)	(5.0,7.0,9.0)	(3.0,5.0,7.0)	(3.0,5.0,7.0)	(3.0,5.0,7.0)
SA4	(7.0,9.0,9.0)	(5.0,7.0,9.0)	(5.0,7.0,9.0)	(7.0,9.0,9.0)	(3.0,5.0,7.0)
SA5	(5.0,7.0,9.0)	(3.0,5.0,7.0)	(5.0,7.0,9.0)	(5.0,7.0,9.0)	(5.0,7.0,9.0)
SA6	(3.0,5.0,7.0)	(5.0,7.0,9.0)	(1.0,3.0,5.0)	(3.0,5.0,7.0)	(1.0,3.0,5.0)
<b>DM2</b>					
SA1	(3.0,5.0,7.0)	(1.0,3.0,5.0)	(7.0,9.0,9.0)	(1.0,3.0,5.0)	(5.0,7.0,9.0)
SA2	(5.0,7.0,9.0)	(3.0,5.0,7.0)	(3.0,5.0,7.0)	(3.0,5.0,7.0)	(5.0,7.0,9.0)
SA3	(5.0,7.0,9.0)	(5.0,7.0,9.0)	(3.0,5.0,7.0)	(3.0,5.0,7.0)	(3.0,5.0,7.0)
SA4	(7.0,9.0,9.0)	(7.0,9.0,9.0)	(5.0,7.0,9.0)	(7.0,9.0,9.0)	(5.0,7.0,9.0)
SA5	(3.0,5.0,7.0)	(3.0,5.0,7.0)	(5.0,7.0,9.0)	(3.0,5.0,7.0)	(5.0,7.0,9.0)
SA6	(1.0,3.0,5.0)	(5.0,7.0,9.0)	(1.0,3.0,5.0)	(3.0,5.0,7.0)	(3.0,5.0,7.0)
<b>DM3</b>					
SA1	(3.0,5.0,7.0)	(1.0,3.0,5.0)	(5.0,7.0,9.0)	(1.0,3.0,5.0)	(5.0,7.0,9.0)
SA2	(5.0,7.0,9.0)	(3.0,5.0,7.0)	(5.0,7.0,9.0)	(1.0,3.0,5.0)	(5.0,7.0,9.0)
SA3	(5.0,7.0,9.0)	(5.0,7.0,9.0)	(3.0,5.0,7.0)	(3.0,5.0,7.0)	(3.0,5.0,7.0)
SA4	(5.0,7.0,9.0)	(7.0,9.0,9.0)	(5.0,7.0,9.0)	(7.0,9.0,9.0)	(3.0,5.0,7.0)
SA5	(3.0,5.0,7.0)	(3.0,5.0,7.0)	(5.0,7.0,9.0)	(3.0,5.0,7.0)	(5.0,7.0,9.0)
SA6	(1.0,3.0,5.0)	(5.0,7.0,9.0)	(1.0,3.0,5.0)	(1.0,3.0,5.0)	(3.0,5.0,7.0)

The aggregated judgment, presented in the form of the combined fuzzy decision matrix, as seen in table 3.4 using equation 1.

Table 3.4. Combined decision matrix of the alternative system architecture concepts

	C1	C2	C3	C4	C5
SA1	(1.0,4.33333,7.0)	(1.0,3.0,5.0)	(5.0,8.33333,9.0)	(1.0,3.0,5.0)	(5.0,7.0,9.0)
SA2	(5.0,7.0,9.0)	(3.0,5.0,7.0)	(3.0,5.66667,9.0)	(1.0,4.33333,7.0)	(3.0,6.33333,9.0)
SA3	(5.0,7.66667,9.0)	(5.0,7.0,9.0)	(3.0,5.0,7.0)	(3.0,5.0,7.0)	(3.0,5.0,7.0)
SA4	(5.0,8.33333,9.0)	(5.0,8.33333,9.0)	(5.0,7.0,9.0)	(7.0,9.0,9.0)	(3.0,5.66667,9.0)
SA5	(3.0,5.66667,9.0)	(3.0,5.0,7.0)	(5.0,7.0,9.0)	(3.0,5.66667,9.0)	(5.0,7.0,9.0)
SA6	(1.0,3.66667,7.0)	(5.0,7.0,9.0)	(1.0,3.0,5.0)	(1.0,4.33333,7.0)	(1.0,4.33333,7.0)

The normalized fuzzy decision matrix and the weighted normalized fuzzy decision matrix represented respectively in table 3.5 and 3.6 using equations 3, 4, and 5.

Table 3.5. Normalized Fuzzy Decision Matrix

	C1	C2	C3	C4	C5
SA1	(0.111,0.481,0.777)	(0.111,0.333,0.555)	(0.111,0.120,0.20)	(0.111,0.333,0.555)	(0.555,0.777,1.0)
SA2	(0.555,0.777,1.0)	(0.333,0.555,0.777)	(0.111,0.176,0.333)	(0.111,0.481,0.777)	(0.333,0.703,1.0)
SA3	(0.555,0.851,1.0)	(0.555,0.777,1.0)	(0.142,0.200,0.333)	(0.333,0.555,0.777)	(0.333,0.555,0.777)
SA4	(0.555,0.925,1.0)	(0.555,0.925,1.0)	(0.111,0.142,0.2)	(0.777,1.0,1.0)	(0.333,0.629,1.0)
SA5	(0.333,0.629,1.0)	(0.333,0.555,0.777)	(0.111,0.142,0.2)	(0.333,0.629,1.0)	(0.555,0.777,1.0)
SA6	(0.111,0.407,0.777)	(0.555,0.777,1.0)	(0.2,0.333,1.0)	(0.111,0.484,0.777)	(0.111,0.482,0.777)

Table 3.6. Weighted Normalized Fuzzy Decision Matrix along with distance of ratings of alternatives from A+ and A- with respect to each criterion.

	C1	C2	C3	C4	C5
Weights	(3.0,5.0,7.0)	(5.0,7.0,9.0)	(5.0,7.0,9.0)	(5.0,7.0,9.0)	(5.0,7.0,9.0)
SA1	(0.333,2.407,5.444)	(0.556,2.333,5.0)	(0.556,0.840,1.80)	(0.778,3.0,5.0)	(2.778,5.444,9.0)
SA2	(1.667,3.889,7.0)	(1.667,3.889,7.0)	(0.556,1.235,3.0)	(0.778,4.333,7.0)	(1.667,4.926,9.0)
SA3	(1.667,4.259,7.0)	(2.778,5.444,9.0)	(0.714,1.40,3.0)	(2.333,5.0,7.0)	(1.667,3.889,7.0)
SA4	(1.667,4.630,7.0)	(2.778,6.481,9.0)	(0.556,1.0,1.80)	(5.444,9.0,9.0)	(1.667,4.0,9.0)
SA5	(1.0,3.148,7.0)	(1.667,3.889,9.0)	(0.556,1.0,1.80)	(2.333,5.667,9.0)	(2.778,5.444,9.0)
SA6	(0.333,2.037,5.444)	(2.778,5.444,9.0)	(1.0,2.333,9.0)	(0.778,4.333,7.0)	(0.556,3.370,7.0)
A+	(1.667,4.630,7.0)	(2.778,6.481,9.0)	(1.0,2.333,9.0)	(5.444,9.0,9.0)	(2.778,5.444,9.0)
A-	(0.333,2.037,5.444)	(0.556,2.333,5.0)	(0.556,0.840,1.80)	(0.778,3.0,5.0)	(0.556,3.370,7.0)

Fuzzy Positive Ideal Solution (A+/ A\*) and Fuzzy Negative Ideal Solution (A-) were computed using equations 6 and 7 (Table 18). The distances  $d^+_i$  and  $d^-_i$  of the ratings of each alternative (SA) from FPIS (A+) and FNIS (A-), calculated according to equations 8 and 9, are presented in Table 3.7 and 3.8 respectively.

Table 3.7. Distances of the ratings of each alternative from A+ with respect to each criterion

	C1	C2	C3	C4	C5	Di+
D(SA1,A+)	1.74506948	3.56582878	4.253139049	4.959091912	0	14.52312922
D(SA2,A+)	0.427666866	1.99633867	3.530968752	3.981438415	0.707914627	10.64432733
D(SA3,A+)	0.213833433	0.598733612	3.509641186	3.145314629	1.597322863	9.064845724
D(SA4,A+)	0	0	4.235379111	0	0.877499044	5.112878155
D(SA5,A+)	0.937946662	1.99633867	4.235379111	2.632497132	0	9.802161576
D(SA6,A+)	1.907796916	0.598733612	0	3.981438415	2.100797854	8.588766797

The rating of each system architecture alternative is given by the closeness coefficient (CC<sub>i</sub>) calculated using equation 10. Finally, this calculation led to the outranking

presented in Table 3.9, meaning that system architecture SA4 is the best alternative, followed by SA3, SA2, SA6, SA5, and SA1 in this order.

Table 3.8 Distances of the ratings of each alternative from A- with respect to each criterion

	C1	C2	C3	C4	C5	Di-
D(SA1,A-)	0.213833433	0	0	0	2.100797854	2.314631287
D(SA2,A-)	1.594457708	1.597322863	1.462845752	1.387777333	1.597322863	7.63972652
D(SA3,A-)	1.74506948	3.194645726	2.927126441	1.863666019	0.707914627	10.43842229
D(SA4,A-)	1.907796916	3.56582878	3.327017336	4.959091912	1.450288904	15.21002385
D(SA5,A-)	1.168869173	1.597322863	1.462845752	2.917239803	2.100797854	9.247075445
D(SA6,A-)	0	3.194645726	2.936922608	1.387777333	0	7.519345667

Table 3.9. Ranking of each alternative

Di+	Di-	Cci	Concept	Rank
14.52312922	2.314631287	0.137466695	SA1	6
10.64432733	7.63972652	0.417835486	SA2	3
9.064845724	10.43842229	0.53521401	SA3	2
5.112878155	15.21002385	0.74841791	SA4	1
9.802161576	9.247075445	0.485430227	SA5	5
8.588766797	7.519345667	0.46680489	SA6	4

Photovoltaic system architecture 4, and 3 were further shortlisted to support the design concept ideation for an off-grid photovoltaic home system.

### 3.2 Solar Photovoltaic Home System Design Ideation

The design ideation for an off-grid photovoltaic home system used Pahl and Beitz model (Pahl and Beitz, 1998), for the design ideation, as shown in Fig 3.1. Each of the recommended stages in the model comprises of a list of work steps that are considered the most helpful strategic design guidelines for design ideation. The Model provides a systematic way for a rational design process; following prescribed steps will ensure that nothing essential omitted. Task clarification for solar photovoltaic home systems executed based on design parameters and specifications concluded from a wide range of potential solutions as design concepts. The implied assumption at the ideation stage is that all ideas have equivalent values. Besides, concept generation is done with a team of experienced designers, and experts with relevant industrial experience — design ideation aimed at developing design concepts that were rigorously evaluated using fuzzy TOPSIS. A set of tasks includes design calculations, 3D CAD models of concepts, and dimensional specification realized for

high-fidelity prototype fabrication. The prototype then technically assessed under lab conditions.

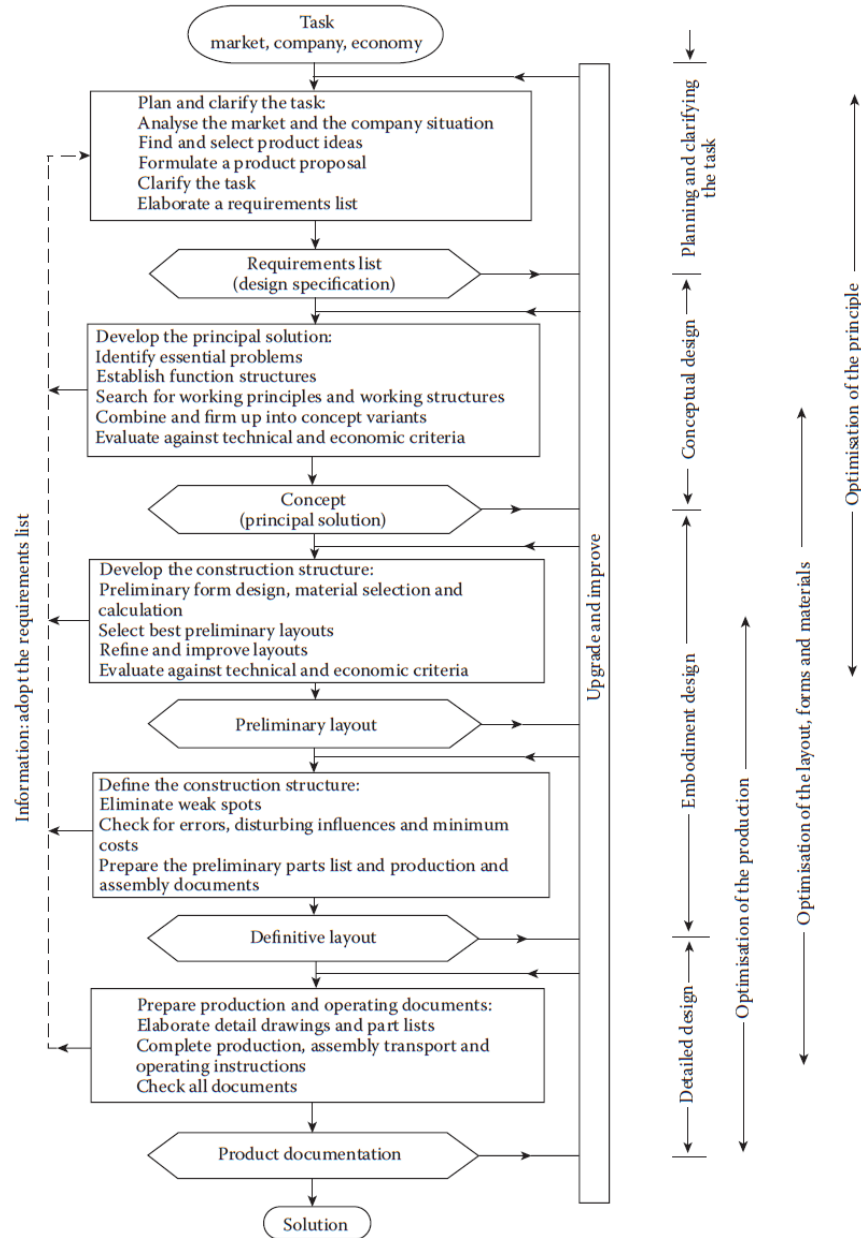


Fig 3.1 Steps of planning and design process (from Pahl, G., Beitz, W. [1998]. Engineering Design: A Systematic Approach. New York: Springer-Verlag.). The model was adopted for design development of SPVHS.

### 3.2.1 Design Ideation Methodology

The experience of AEDA put to use for design concept ideation, as the firm had sufficient experience of installing off-grid photovoltaic systems and solar microgrid in the state; also has vast experience with on-field issues of the photovoltaic system and the needs of the respective users. Design parameters, specification (refer chapter 2), and shortlisted system architecture, as discussed previously, taken as reference for design ideation. Flowchart of design concept ideation shown in fig 3.2.

Furthermore, the team of senior industrial designers ideated for various design concepts, as shown in fig 3.3, while technical inputs from solar experts incorporated for the proposed intervention. In-total, ten design concepts ideated, which were taken forward for design evaluation. Further, a total of ten design concepts for the proposed intervention discussed under section 3.2.2.

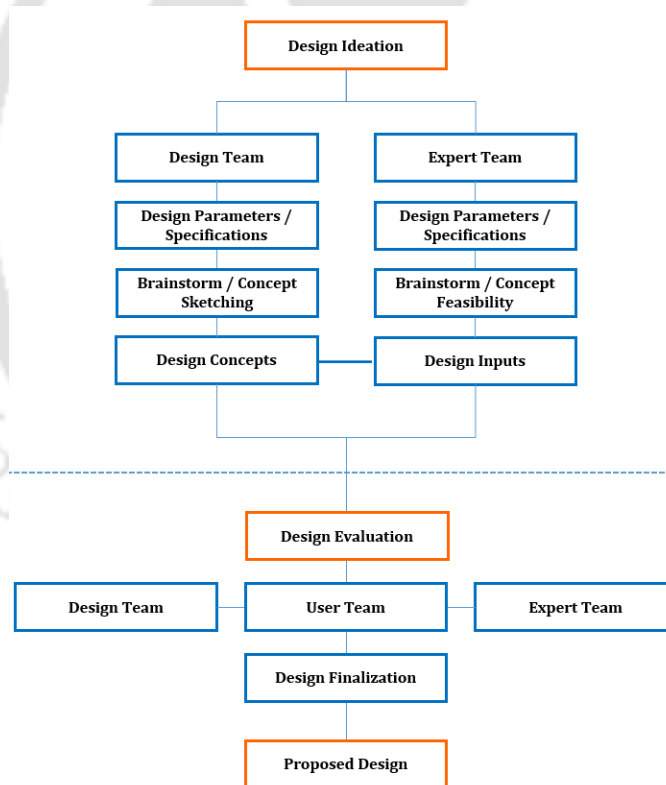


Fig 3.2 Design concept ideation flow chart for proposed design intervention

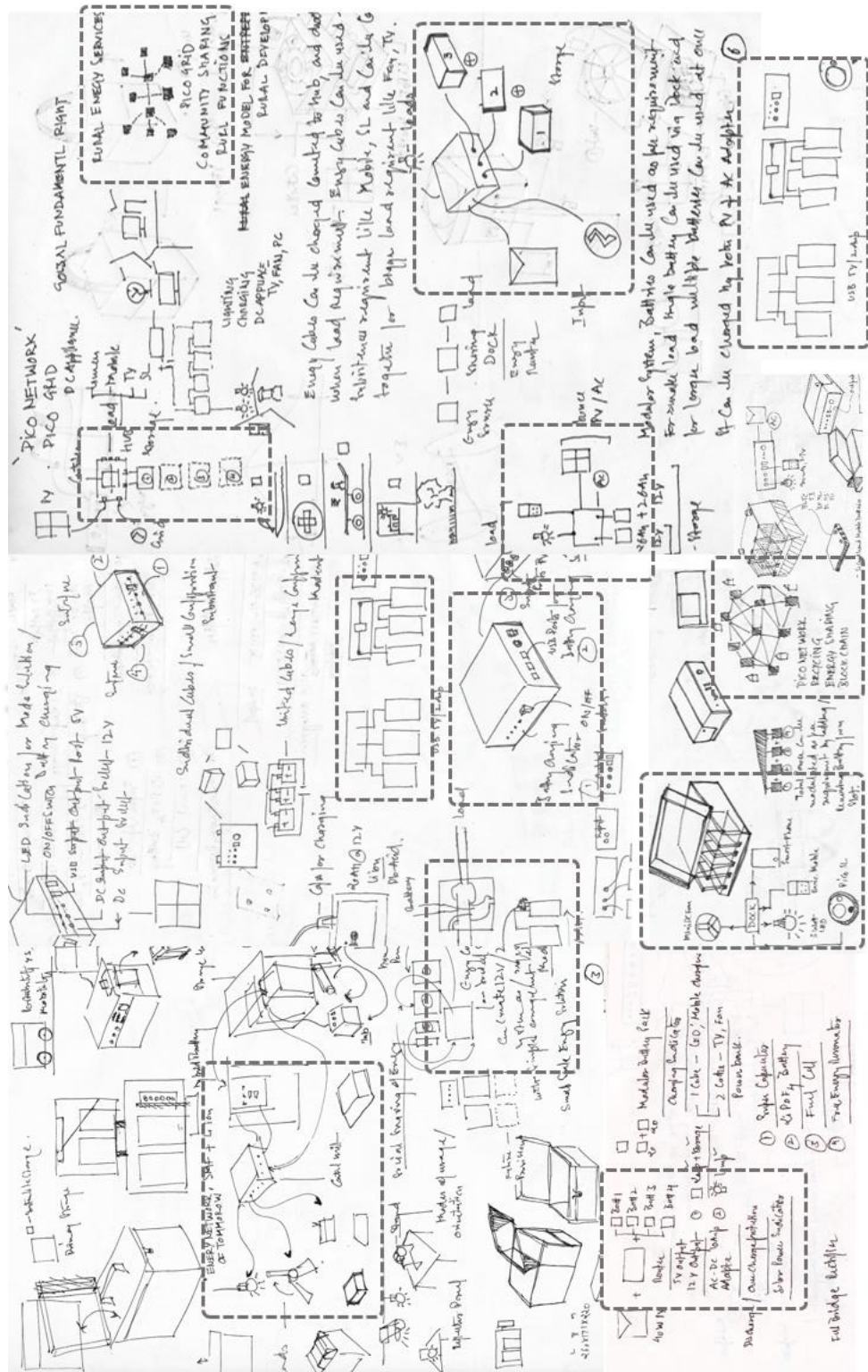


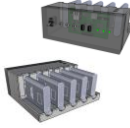

Fig 3.3 Concept generation for solar photovoltaic home system

### 3.2.2 Design Concepts for Proposed System

Details of design concepts as summarized in table 3.10, and are discussed below.

- i. Concept One- the advantage is that storage is segregated based on its usage. The primary module serves for moderate energy requirements like 5 watts LED bulb, charging of the basic phone, and a solar lamp. At the same time, two secondary units fulfill very-low energy requirements like lighting 0.5-watt LED bulb. The concept provides an option for hybrid charging considering sub-tropical monsoon climatic conditions of NER.
- ii. Concept Two- contains a set of two lead-acid batteries & charge controller integrated into a single casing, which can be used as a portable charging unit and can easily be moved to local distances. Provide load support for the higher-energy requirement.
- iii. In Concept Three- discrete storage modules can be used together or independently with other modules as per the customized energy requirement. The storage modules can concurrently be used for varied rural requirements, which goes in coherence with regional lifestyle requirement. This design concept provides ample scope to facilitate the productive use of energy, like localized peer-to-peer energy exchange. Besides, users can buy discrete storage units in increments depending on household energy needs, making it cost-effective in a rural context. Besides, the pay-back time for such a concept would be less.
- iv. Concept Four- makes use of second-hand lithium-ion batteries like BL-4C used in basic mobile phones. The concept can be used in two alternative ways 1 as a low wattage utility 2. To charge villager's phones to result in micro-enterprise benefits.
- v. Concept Five- integrates PV panel with storage unit. The portable module can easily be carried to neighbouring distances; also, the entire unit can be placed directly under the sun for instant charging as required.
- vi. Concept Six- support loads, depending on the number of modules attached. There is a secondary storage unit to be used for outdoor applications like after dark local traveling and fishing in a remote area. Since the north-east region is prone to natural disasters, the concept can be used effectively during flood and earthquake. It proposes the use of lightweight li-on batteries for the rural context.

Table 3.10 Concept matrix for proposed design of solar photovoltaic home system

Type	Design Concept Figure	Features
Design Concept 1		<ul style="list-style-type: none"> <li>▪ Concept have one primary and two secondary lithium ion battery banks.</li> <li>▪ Option of hybrid-charging with both PV &amp; Grid .</li> <li>▪ Advantage of concept is that storage is segregated based on its usage. primary module serves for moderately low energy requirement like charging basic phone, while two secondary units are for very low energy requirement like lighting 0.5 watt LED.</li> <li>▪ Disadvantage however is cost of lithium ion batteries is high</li> </ul>
Design Concept 2		<ul style="list-style-type: none"> <li>▪ The concept can be used as portable charging unit.</li> <li>▪ Can be easily carried at local distances considering a remote location and proximity to service centre</li> <li>▪ Integrated SPVHS concept</li> <li>▪ Suitable to address moderate energy requirement for household energy needs.</li> <li>▪ Expensive compared to conventional solar home system</li> </ul>
Design Concept 3		<ul style="list-style-type: none"> <li>▪ Battery modules which can be integrated or used independently along with other modules to increase or decrease capacity of the system.</li> <li>▪ Discrete system architecture</li> <li>▪ Battery modules can be used to charge mobile phones, solar lanterns and provides ample scope for rural energy trading or peer-to-peer energy exchange.</li> <li>▪ Adaptive design can be used discretely to fulfill different daily requirements like small-shops, vegetable vendors, fishing etc.</li> <li>▪ Design concept goes in coherence with local lifestyle.</li> <li>▪ User can buy storage modules in increments considering their affordability.</li> <li>▪ Option of hybrid-charging with both PV &amp; Grid .</li> </ul>
Design Concept 4		<ul style="list-style-type: none"> <li>▪ Concept make use of second hand lithium-ion batteries used in basic mobile phones like BL-4C. Such batteries are readily available and cheap.</li> <li>▪ Design concept can be used in two alternate ways 1. as low wattage application 2. to charge village phones and have additional income benefit.</li> <li>▪ Portable and easy to use. Plug-n-Play</li> <li>▪ Provide scope as rural energy trading kit</li> </ul>
Design Concept 5		<ul style="list-style-type: none"> <li>▪ Concept integrates PV panel with storage unit</li> <li>▪ Portable module can be easily carried to local distances, also module can be placed directly under the sun for instant charging</li> <li>▪ Hybrid charging based solution considering climatic and geographic conditions of northeast along with quite unreliable grid in rural areas.</li> <li>▪ Fulfill subsistent energy requirement.</li> </ul>
Design Concept 6		<ul style="list-style-type: none"> <li>▪ Adaptive load suport depending on energy requirement</li> <li>▪ Discrete storage modules can be used independently or in conjunction with each other</li> <li>▪ Concept can be used discretely to fulfill rural energy needs</li> <li>▪ Hybrid charging based solution is quite useful considering climatic and geographic conditions of northeast India.</li> <li>▪ Smart system</li> </ul>
Design Concept 7		<ul style="list-style-type: none"> <li>▪ Concept supports larger loads for Pico-networking</li> <li>▪ Design concept can fulfil need of around 8-10 households</li> <li>▪ Centralized system</li> <li>▪ Demand driven storage modules</li> <li>▪ Concept provides scope for easy dissembly and portability to local distances considering a remote location</li> <li>▪ Expensive design when compared with conventional system</li> </ul>
Design Concept 8		<ul style="list-style-type: none"> <li>▪ Control box can be used with different range of battery capacities</li> <li>▪ Demand driven storage modules can be used in conjunction or independent to each other.</li> <li>▪ Plug-n-play system, easy to assemble</li> <li>▪ Digital indication for different charging controls</li> </ul>
Design Concept 9		<ul style="list-style-type: none"> <li>▪ Integrated SPVHS design</li> <li>▪ Provide load support for mobile charging, LED luminaire, DC fan and TV</li> <li>▪ Independent PV module</li> <li>▪ Modular units can be docked with each other as required or demanded</li> </ul>
Design Concept 10		<ul style="list-style-type: none"> <li>▪ High capacity system to support multiple loads for 2-3 households.</li> <li>▪ Centralized system</li> <li>▪ Provision for PV-Micro-hydro charging considering regional potential</li> <li>▪ Parts can be dissembled and assembled easiley</li> <li>▪ More cost due to high capacity</li> </ul>

- vii. Concept Seven- supports larger loads like the Pico grid network; a single product can fulfill the need of around 8-10 households in a village as a centralized design solution, making it economical for users. The concept supports PV-Grid based hybrid-charging feature.
- viii. In Concept Eight- the smart control box can be used with a range of battery capacities from high to low. The concept makes use of lead-acid and lithium-ion storage modules. Digital indication for charging status improve product handling. Discrete storage modules can be used together or independent of each other as demand-driven design.
- ix. Concept Nine had a battery and charge controller housed inside the casing to reduce user tempering. The concept provides substantial load support for mobile charging, luminaire, DC fan, and TV.
- x. Concept Ten supported hybrid-charging based solution on PV-Micro hydro. Fulfill moderate energy needs in a rural context like charging mobile, lighting support, and run DC-TV, fan.

Post design ideation, all the alternate concepts were evaluated using Fuzzy TOPSIS a multi-criteria decision-making technique, as discussed in the previous section.

### 3.2.3 Solar Photovoltaic Home System Concept Design Evaluation

CAD models of design concepts formulated based on experts and designer's input to realize the concepts near-to actual. Criteria selected for the evaluation by the expert team were Portability (C1), Reliability (C2), Affordability (C3), Novelty (C4), and Utility (C5). The weighing for different criteria based on the level of importance to each criterion. One of the most critical decision-making stages in product development was the concept evaluation for the proposed intervention. It concerns that the final impact of product development for poor evaluation cannot be compensated at the later phases of design development (Pohekar & Ramachandran, 2004). It led to the use of rigorous concept evaluation, based on the fuzzy technique for order preference by similarity to ideal solution (Fuzzy-TOPSIS).

The decision-makers assessed the weight of the criteria and the ratings of the alternatives according to the linguistic terms, as seen in table 3.2. Based on Chen (Chen, 2000), the linguistic values of these variables were specified using triangular

fuzzy numbers. Assigned fuzzy weights were Acceptability (3.0,5.0,7.0), Reliability (5.0,7.0,9.0), Affordability (5.0,7.0,9.0), Novelty (5.0,7.0,9.0) and Utility (5.0,7.0,9.0). Table 3.11 presents the linguistic ratings of the alternatives for the three decision-makers ( $k=3$ ) involved in the selection process. The linguistic ratings, as shown in Table 3.2, were converted into fuzzy triangular numbers in table 3.11.

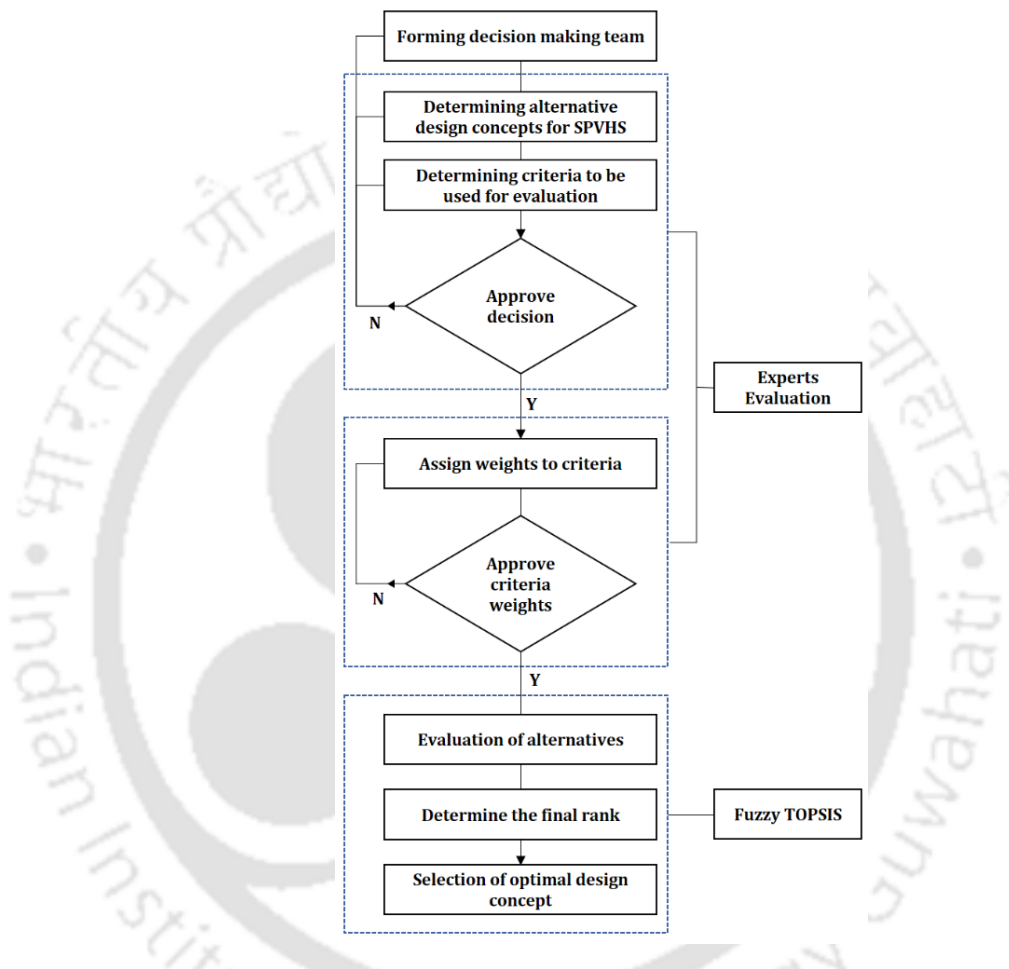


Fig 3.4 Schematic methodology used for Fuzzy TOPSIS based concept evaluation

The decision-making team's expertise used to determine the criteria for concept selection to be used. Post criteria determination, concept development, is explored, and ten possible design concepts for proposed intervention were evaluated. In due consultation with experts, weights were allocated to each criterion. Furthermore, design concepts evaluated using Fuzzy TOPSIS (figure 3.4). The final rank was determined, and an optimal design concept shortlisted based on the closeness coefficient score.

Table 3.11 Fuzzy numbers of the aggregated ratings of the alternative design concepts

	C1	C2	C3	C4	C5
<b>DM1</b>					
<b>DC1</b>	(3.0,5.0,7.0)	(3.0,5.0,7.0)	(3.0,5.0,7.0)	(3.0,5.0,7.0)	(5.0,7.0,9.0)
<b>DC2</b>	(1.0,3.0,5.0)	(5.0,7.0,9.0)	(1.0,1.0,3.0)	(3.0,5.0,7.0)	(3.0,5.0,7.0)
<b>DC3</b>	(7.0,9.0,9.0)	(7.0,9.0,9.0)	(5.0,7.0,9.0)	(7.0,9.0,9.0)	(5.0,7.0,9.0)
<b>DC4</b>	(5.0,7.0,9.0)	(5.0,7.0,9.0)	(5.0,7.0,9.0)	(5.0,7.0,9.0)	(1.0,3.0,5.0)
<b>DC5</b>	(5.0,7.0,9.0)	(3.0,5.0,7.0)	(5.0,7.0,9.0)	(5.0,7.0,9.0)	(5.0,7.0,9.0)
<b>DC6</b>	(5.0,7.0,9.0)	(5.0,7.0,9.0)	(3.0,5.0,7.0)	(3.0,5.0,7.0)	(3.0,5.0,7.0)
<b>DC7</b>	(1.0,1.0,3.0)	(1.0,3.0,5.0)	(1.0,1.0,3.0)	(1.0,3.0,5.0)	(3.0,5.0,7.0)
<b>DC8</b>	(3.0,5.0,7.0)	(1.0,3.0,5.0)	(3.0,5.0,7.0)	(1.0,3.0,5.0)	(1.0,3.0,5.0)
<b>DC9</b>	(3.0,5.0,7.0)	(3.0,5.0,7.0)	(1.0,1.0,3.0)	(3.0,5.0,7.0)	(1.0,3.0,5.0)
<b>DC10</b>	(1.0,1.0,3.0)	(3.0,5.0,7.0)	(1.0,1.0,3.0)	(1.0,3.0,5.0)	(3.0,5.0,7.0)
<b>DM2</b>					
<b>DC1</b>	(5.0,7.0,9.0)	(3.0,5.0,7.0)	(3.0,5.0,7.0)	(3.0,5.0,7.0)	(3.0,5.0,7.0)
<b>DC2</b>	(1.0,3.0,5.0)	(5.0,7.0,9.0)	(1.0,1.0,3.0)	(3.0,5.0,7.0)	(3.0,5.0,7.0)
<b>DC3</b>	(7.0,9.0,9.0)	(7.0,9.0,9.0)	(5.0,7.0,9.0)	(7.0,9.0,9.0)	(5.0,7.0,9.0)
<b>DC4</b>	(7.0,9.0,9.0)	(5.0,7.0,9.0)	(5.0,7.0,9.0)	(5.0,7.0,9.0)	(1.0,3.0,5.0)
<b>DC5</b>	(5.0,7.0,9.0)	(3.0,5.0,7.0)	(7.0,9.0,9.0)	(3.0,5.0,7.0)	(3.0,5.0,7.0)
<b>DC6</b>	(5.0,7.0,9.0)	(3.0,5.0,7.0)	(3.0,5.0,7.0)	(3.0,5.0,7.0)	(1.0,1.0,3.0)
<b>DC7</b>	(1.0,1.0,3.0)	(3.0,5.0,7.0)	(1.0,1.0,3.0)	(3.0,5.0,7.0)	(3.0,5.0,7.0)
<b>DC8</b>	(3.0,5.0,7.0)	(1.0,3.0,5.0)	(3.0,5.0,7.0)	(1.0,3.0,5.0)	(1.0,3.0,5.0)
<b>DC9</b>	(1.0,3.0,5.0)	(3.0,5.0,7.0)	(1.0,1.0,3.0)	(3.0,5.0,7.0)	(3.0,5.0,7.0)
<b>DC10</b>	(1.0,1.0,3.0)	(3.0,5.0,7.0)	(1.0,1.0,3.0)	(1.0,3.0,5.0)	(3.0,5.0,7.0)
<b>DM3</b>					
<b>DC1</b>	(3.0,5.0,7.0)	(3.0,5.0,7.0)	(3.0,5.0,7.0)	(3.0,5.0,7.0)	(5.0,7.0,9.0)
<b>DC2</b>	(1.0,3.0,5.0)	(5.0,7.0,9.0)	(1.0,1.0,3.0)	(3.0,5.0,7.0)	(3.0,5.0,7.0)
<b>DC3</b>	(5.0,7.0,9.0)	(7.0,9.0,9.0)	(5.0,7.0,9.0)	(7.0,9.0,9.0)	(5.0,7.0,9.0)
<b>DC4</b>	(7.0,9.0,9.0)	(5.0,7.0,9.0)	(5.0,7.0,9.0)	(5.0,7.0,9.0)	(1.0,3.0,5.0)
<b>DC5</b>	(5.0,7.0,9.0)	(3.0,5.0,7.0)	(5.0,7.0,9.0)	(5.0,7.0,9.0)	(7.0,9.0,9.0)
<b>DC6</b>	(3.0,5.0,7.0)	(5.0,7.0,9.0)	(3.0,5.0,7.0)	(3.0,5.0,7.0)	(3.0,5.0,7.0)
<b>DC7</b>	(1.0,1.0,3.0)	(1.0,3.0,5.0)	(1.0,1.0,3.0)	(1.0,3.0,5.0)	(3.0,5.0,7.0)
<b>DC8</b>	(3.0,5.0,7.0)	(1.0,3.0,5.0)	(3.0,5.0,7.0)	(1.0,3.0,5.0)	(1.0,3.0,5.0)
<b>DC9</b>	(3.0,5.0,7.0)	(3.0,5.0,7.0)	(1.0,1.0,3.0)	(3.0,5.0,7.0)	(1.0,3.0,5.0)
<b>DC10</b>	(1.0,1.0,3.0)	(3.0,5.0,7.0)	(1.0,1.0,3.0)	(1.0,3.0,5.0)	(3.0,5.0,7.0)

The aggregated judgment presented in the form of the combined fuzzy decision matrix, as seen in table 3.12 using equation 1.

Table 3.12. Combined Fuzzy Decision Matrix

	C1	C2	C3	C4	C5
<b>DC1</b>	(3.0,5.66667,9.0)	(3.0,5.0,7.0)	(3.0,5.0,7.0)	(3.0,5.0,7.0)	(3.0,6.33333,9.0)
<b>DC2</b>	(1.0,3.0,5.0)	(5.0,7.0,9.0)	(1.0,1.0,3.0)	(3.0,5.0,7.0)	(3.0,5.0,7.0)
<b>DC3</b>	(5.0,8.33333,9.0)	(7.0,9.0,9.0)	(5.0,7.0,9.0)	(7.0,9.0,9.0)	(5.0,7.0,9.0)
<b>DC4</b>	(5.0,8.33333,9.0)	(5.0,7.0,9.0)	(5.0,7.0,9.0)	(5.0,7.0,9.0)	(1.0,3.0,5.0)
<b>DC5</b>	(5.0,7.0,9.0)	(3.0,5.0,7.0)	(5.0,7.66667,9.0)	(3.0,6.33333,9.0)	(3.0,7.0,9.0)
<b>DC6</b>	(3.0,6.33333,9.0)	(3.0,6.33333,9.0)	(3.0,5.0,7.0)	(3.0,5.0,7.0)	(1.0,3.66667,7.0)
<b>DC7</b>	(1.0,1.0,3.0)	(1.0,3.66667,7.0)	(1.0,1.0,3.0)	(1.0,3.66667,7.0)	(3.0,5.0,7.0)
<b>DC8</b>	(3.0,5.0,7.0)	(1.0,3.0,5.0)	(3.0,5.0,7.0)	(1.0,3.0,5.0)	(1.0,3.0,5.0)
<b>DC9</b>	(1.0,4.33333,7.0)	(3.0,5.0,7.0)	(1.0,1.0,3.0)	(3.0,5.0,7.0)	(1.0,3.66667,7.0)
<b>DC10</b>	(1.0,1.0,3.0)	(3.0,5.0,7.0)	(1.0,1.0,3.0)	(1.0,3.0,5.0)	(3.0,5.0,7.0)

The normalized fuzzy decision matrix and the weighted normalized fuzzy decision matrix represented respectively in table 3.13 and 3.14 using equation 3, 4, and 5.

Table 3.13. Normalized Fuzzy Decision Matrix

	C1	C2	C3	C4	C5
<b>DC1</b>	(0.333,0.629,1.0)	(0.333,0.555,0.777)	(0.1428,0.20,0.333)	(0.333,0.555,0.777)	(0.333,0.7037,1.0)
<b>DC2</b>	(0.111,0.333,0.555)	(0.555,0.777,1.0)	(0.333,1.0,1.0)	(0.333,0.555,0.777)	(0.333,0.555,0.777)
<b>DC3</b>	(0.555, 0.925,1.0)	(0.777,1.0,1.0)	(0.111,0.1428,0.2)	(0.777,1.0,1.0)	(0.555,0.777,1.0)
<b>DC4</b>	(0.555, 0.925,1.0)	(0.555,0.777,1.0)	(0.111,0.1428,0.2)	(0.555,0.777,1.0)	(0.111,0.333,0.555)
<b>DC5</b>	(0.555, 0.777,1.0)	(0.333,0.555,0.777)	(0.111,0.1304,0.2)	(0.333,0.703,1.0)	(0.333,0.777,1.0)
<b>DC6</b>	(0.333,0.703,1.0)	(0.333,0.703,1.0)	(0.1428,0.2,0.333)	(0.333,0.555,0.777)	(0.111,0.4074,0.777)
<b>DC7</b>	(0.111,0.111,0.333)	(0.111,0.407,0.777)	(0.333,1.0,1.0)	(0.111,0.4074,0.777)	(0.333,0.555,0.777)
<b>DC8</b>	(0.333,0.555,0.777)	(0.111,0.333,0.555)	(0.1428,0.2,0.333)	(0.111,0.333,0.555)	(0.111,0.333,0.555)
<b>DC9</b>	(0.111,0.481,0.777)	(0.333,0.555,0.777)	(0.333,1.0,1.0)	(0.333,0.555,0.777)	(0.111,0.4074,0.777)
<b>DC10</b>	(0.111,0.111,0.333)	(0.333,0.555,0.777)	(0.333,1.0,1.0)	(0.111,0.333,0.555)	(0.333,0.555,0.777)

Table 3.14. Weighted Normalized Fuzzy Decision Matrix along with distance of ratings of alternatives from A+ and A- with respect to each criterion.

	C1	C2	C3	C4	C5
<b>Weights</b>	(3.0,5.0,7.0)	(5.0,7.0,9.0)	(5.0,7.0,9.0)	(5.0,7.0,9.0)	(5.0,7.0,9.0)
<b>DC1</b>	(1.0,3.148,7.0)	(1.667,3.889,7.0)	(0.714,1.40,3.0)	(2.333,5.0,7.0)	(1.667,4.926,9.0)
<b>DC2</b>	(0.333,1.667,3.888)	(2.778,5.444,9.0)	(1.667,7.0,9.0)	(2.333,5.0,7.0)	(1.667,3.889,7.0)
<b>DC3</b>	(1.667,4.630,7.0)	(3.889,7.0,9.0)	(0.556,1.0,2.0)	(5.444,9.0,9.0)	(2.778,5.444,9.0)
<b>DC4</b>	(1.667,4.630,7.0)	(2.778,5.444,9.0)	(0.556,1.0,2.0)	(3.889,7.0,9.0)	(0.556,2.0,5.0)
<b>DC5</b>	(1.667,3.889,7.0)	(1.667,3.889,7.0)	(0.556,0.913,1.80)	(2.333,6.333,9.0)	(1.667,5.444,9.0)
<b>DC6</b>	(1.0,3.519,7.0)	(1.667,4.926,9.0)	(0.714,1.40,3.0)	(2.333,5.0,7.0)	(0.556,2.852,7.0)
<b>DC7</b>	(0.333,0.556,2.333)	(0.556,2.852,7.0)	(1.667,7.0,9.0)	(0.778,3.667,7.0)	(1.667,3.889,7.0)
<b>DC8</b>	(1.0,2.778,5.4444)	(0.556,2.333,5.0)	(0.714,1.0,3.0)	(0.778,3.0,5.0)	(0.556,2.333,5.0)
<b>DC9</b>	(0.333,2.407,5.4444)	(1.667,3.889,7.0)	(1.667,7.0,9.0)	(2.333,5.0,7.0)	(0.556,3.0,7.0)
<b>DC10</b>	(0.333,0.556,2.333)	(1.667,3.889,7.0)	(1.667,7.0,9.0)	(0.778,3.0,5.0)	(1.667,3.889,7.0)
<b>A+</b>	(1.667,4.630,7.0)	(3.889,7.0,9.0)	(1.667,7.0,9.0)	(5.444,9.0,9.0)	(2.778,5.444,9.0)
<b>A-</b>	(0.333,0.556,2.333)	(0.556,2.333,5.0)	(0.556,0.913,1.80)	(0.778,3.0,5.0)	(0.556,2.333,5.0)

Fuzzy Positive Ideal Solution (A+ / A\*) and Fuzzy Negative Ideal Solution (A-) were computed using equation 6 and 7 (Table 3.14). The distances  $D_{i+}$  and  $D_{i-}$  of the ratings of each alternative (SA) from FPIS (A+) and FNIS (A-), calculated according to equation 8 and 9, are presented in Table 3.15 and 3.16 respectively.

Table 3.15. Distances of the ratings of each alternative from A+ with respect to each criterion

	C1	C2	C3	C4	C5	Di+
D(DC1,A+)	0.938	2.491	4.77	3.145	0.707	12.053
D(DC2,A+)	2.597	1.104	0	3.145	1.597	8.443
D(DC3,A+)	0	0	5.449	0	0	5.449
D(DC4,A+)	0	1.104	5.449	1.462	3.194	11.21
D(DC5,A+)	0.428	2.491	5.481	2.365	0.641	11.407
D(DC6,A+)	0.748	1.755	4.77	3.145	2.284	12.703
D(DC7,A+)	3.658	3.282	0	4.251	1.597	12.789
D(DC8,A+)	1.448	4.037	4.77	4.959	3.194	18.409
D(DC9,A+)	1.745	2.491	0	3.145	2.285	9.666
D(DC10,A+)	3.658	2.491	0	4.959	1.597	12.706

The rating of each design concept alternative given by the closeness coefficient (CCi) calculated using equation 10. Finally, this calculation led to the outranking presented in Table 3.17, meaning that design concept three is the best alternative, followed by concept two, concept four and concept five in this order.

Table 3.16. Distances of the ratings of each alternative from A- with respect to each criterion

	C1	C2	C3	C4	C5	Di-
D(DC1,A-)	3.106	1.597	1.466	1.864	2.826	10.859
D(DC2,A-)	1.104	3.195	2.995	1.864	1.597	10.755
D(DC3,A-)	3.658	4.037	3.549	4.959	3.195	19.398
D(DC4,A-)	3.658	3.195	2.926	3.727	0	13.506
D(DC5,A-)	3.399	1.597	1.463	3.137	2.995	12.592
D(DC6,A-)	3.215	2.826	2.754	1.864	1.193	11.851
D(DC7,A-)	0	1.193	1.354	1.217	1.597	5.362
D(DC8,A-)	2.241	0	0.092	0	0	2.332
D(DC9,A-)	2.09	1.597	1.597	1.864	1.193	8.342
D(DC10,A-)	0	1.597	1.597	0	1.597	4.792

Table 3.17. Ranking of each alternative concept

Di+	Di-	Cci	Concept	Rank
12.053	10.859	0.473943992	DC1	6
8.443	10.755	0.560189036	DC2	2
5.449	19.398	0.780695436	DC3	1
11.21	13.506	0.546446951	DC4	3
11.407	12.592	0.524689903	DC5	4
12.703	11.851	0.482633342	DC6	5
12.789	5.362	0.295396662	DC7	8
18.409	2.332	0.112445869	DC8	10
9.666	8.342	0.463217888	DC9	7
12.706	4.792	0.273857928	DC10	9

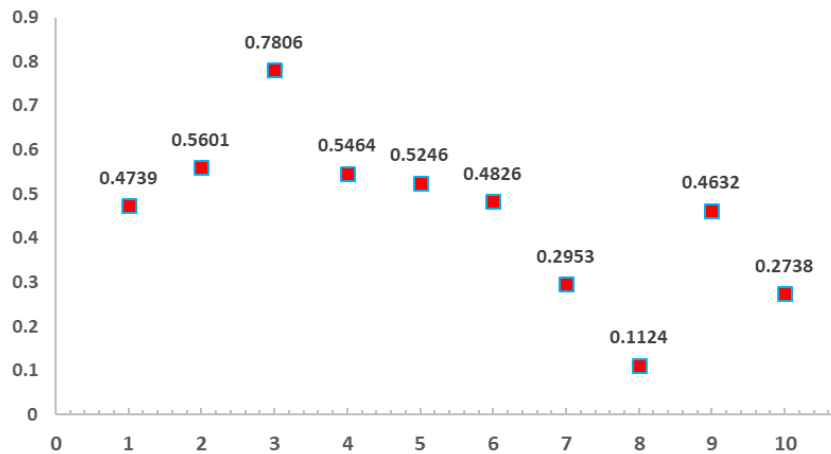


Fig 3.5 Closeness coefficient score of design concepts for proposed intervention

The design concept-3 found to have the highest closeness coefficient score (fig 3.5) and was finalized. The concept provides ample scope for rural productive use in the regional context — the design details of the finalized off-grid photovoltaic home system discussed in the next section.

### 3.3 Proposed Discrete Off-Grid Photovoltaic System

The schematic diagram of the proposed discrete<sup>6</sup> off-grid photovoltaic system given in Fig. 3.6, along with its necessary features (fig. 3.7). For proposed intervention, storage split into multiple individual smart power modules; hence, one derived on name discrete. The discrete design has multiple advantages in a rural lifestyle context, discussed as follows;

- i. From a usability point of view, it will be more convenient to move and carry this discrete storage form one place to another place compared to the one big battery, which used in the conventional scheme.
- ii. From a utility point of view, considering an active rural lifestyle in the studied area, the discrete design potentially is used for both indoor and outdoor activities. The storage modules used simultaneously at different places for concurrent use as per requirement.

<sup>6</sup> Definition of discrete as per Merriam Webster dictionary is 'Individually recognizable, distinct and separate from the similar items. A discrete unit characterized as an individual, independent unit of a larger system.'

- iii. From the maintenance or servicing point of view, generally, in the remote place, the nearest service centers are located very far from the user's houses. Hence, it is challenging to take one big battery to the nearest service centers. Thus, discretization of the battery will help to address the above said.
- iv. From the electrical point of view, if there occurs any fault in the battery used in the conventional scheme, the total system shut down, and the user has to face the problem of power failure. However, with the discretization of power modules, if any fault occurs to the battery, then also the whole system will work simultaneously with less power capacity (running hours will decrease).
- v. From the charging point of view, if we can charge one battery at a time (cyclic charging of four battery), then the charging current requirement will be less compared to the continuous charging current of a big battery (used in the conventional scheme) which reduces the size and cost of photovoltaic modules, making system economical to user.
- vi. From the system architecture point of view, Smart battery tells the controller how much it depleted, so the controller gives more power to the battery with the lowest voltage on priority. During poor weather conditions battery with the lowest voltage get charged first. It will facilitate to fulfill the load requirement of the user even during rainy or winter days.
- vii. From the economics of design point of view, since the discrete architecture provides flexibility in the use of (two plus two) smart storage modules. Therefore, the user can buy only two modules initially; this will save the initial purchase cost. Rest two modules can be upgraded later depending upon user requirement. Besides, since the system uses MPPT pulse charging, so PV modules of half the capacity are required. There is direct cost-cutting by 50% when compared with the PV panel of the conventional system. Furthermore, since the proposed system uses maintenance-free VRLA and Li-Ion batteries so it can endure more abuse compared to conventional liquid vented batteries, this makes the system economical and sustainable in the longer run.

- viii. Hybrid charging support is given to improve the efficiency of the solar home system in climatically and geographically challenged parts of the northeast.
- ix. 'Hot-Swapping'<sup>7</sup> of modular storage proposed for simultaneously used to multiple rural needs. Unlike in conventional solar home system, charging has to be stopped before taking the battery out, which is very time consuming and inconvenient.
- x. From a PUE point of view, discrete smart power modules for the proposed intervention indicated the potential to enable productive usage benefits among rural households.

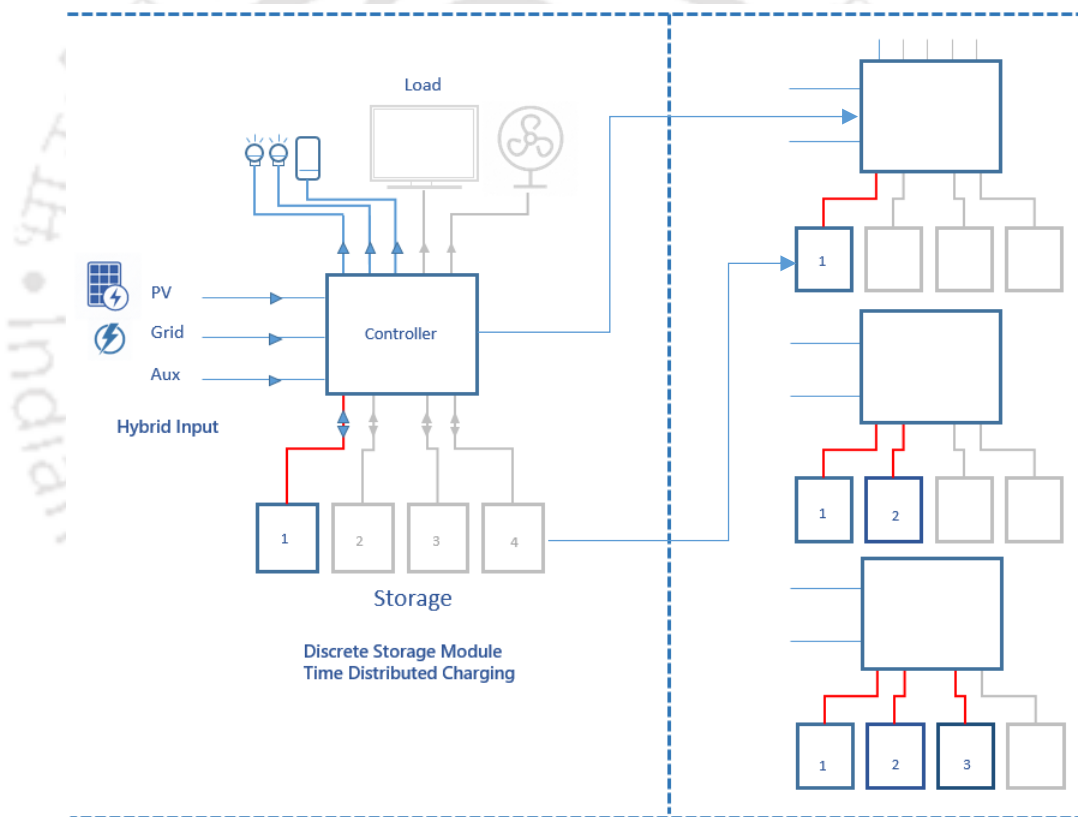


Fig. 3.6 Schematic representation of the proposed off-grid photovoltaic system.

<sup>7</sup> Hot swapping explicitly defines the insertion or removal of parts into the system without disruption. The Universal Serial Bus (USB) is a well-known instance of hot-swap feature that enables users to attach or remove external components to decrease downtime.

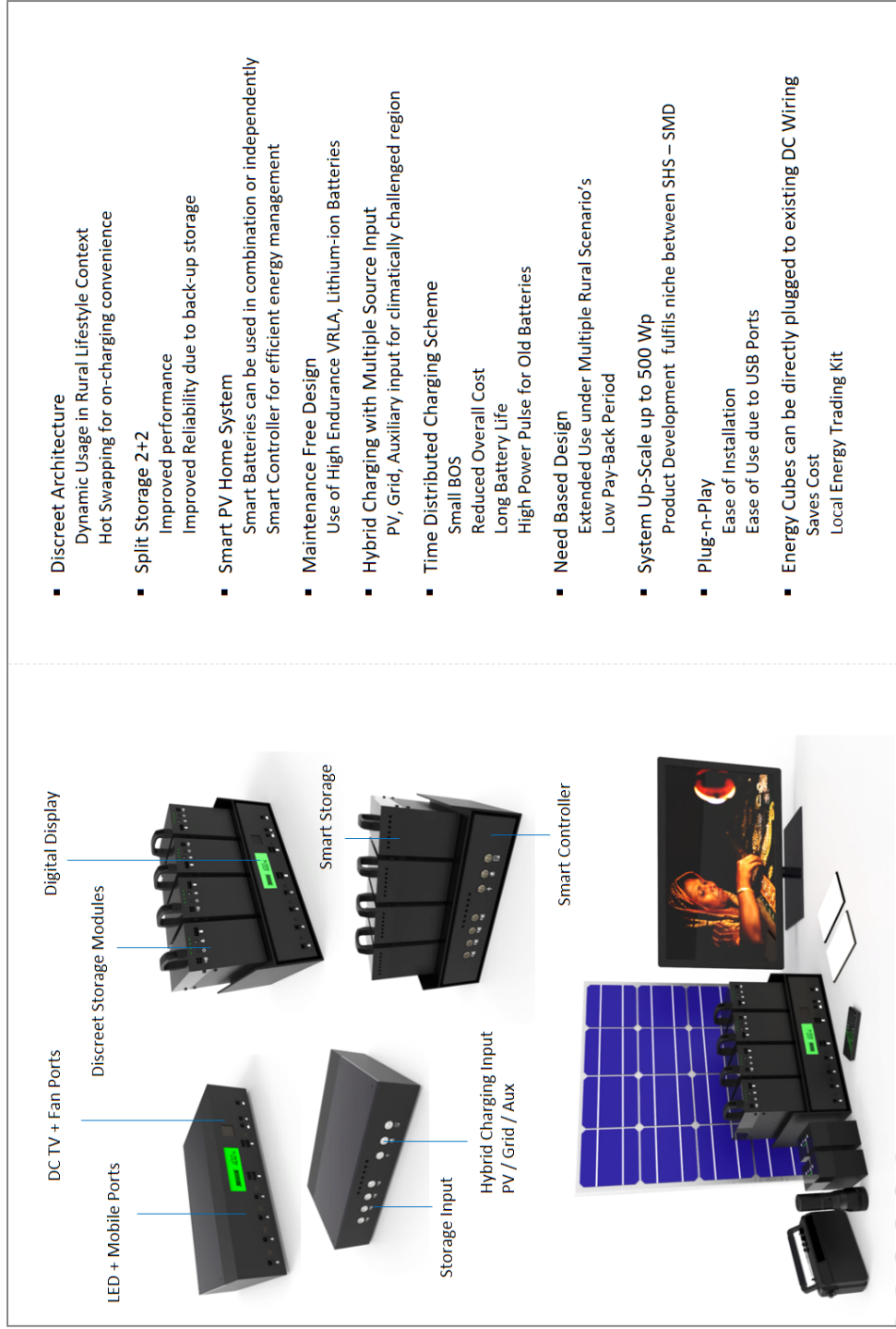


Fig 3.7 Details of Proposed Design for Solar Photovoltaic Home System

The alpha prototype of the proposed intervention was tested to examine its efficacy in comparison to the conventional system, as discussed in the next section.

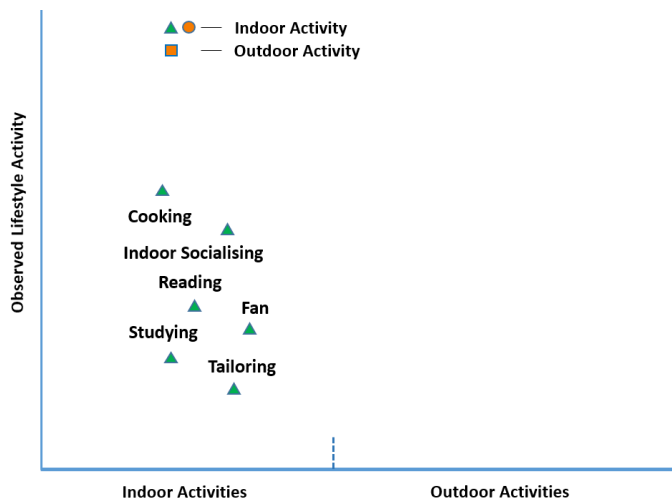
### 3.4 Comparative Study of the Alpha Prototype

For the preliminary study, a purposive sample size of twenty-nine families (N=29) used to verify the efficacy of the proposed design alpha prototype. The field trial was done in remote villages of Bhagunmari and Sikalichhapari in Majuli district, Assam. The field activities were documented through direct observation and field notes for about a month in April 2017. Inclusion criteria were testing the alpha prototype with rural households who had previous experience of using and maintaining SPVHS for a minimum of two years.

The study undertook field investigation of an alpha prototype comprises of four 12 V, 15 Ah VRLA batteries, along with the single 12 V, 40 Ah lead-acid battery, supported with a set of wires, and two 5 watts LED bulbs, setup was representative of proposed and conventional design architecture (fig 3.8) respectively. The local evidence observed primary indoor activities related to rural energy use were cooking, reading, listening to the radio, watching TV, charging mobile, washing utensils, and local bamboo craft like basketry. Besides, primary outdoor activities are going to cattle-yard, outdoor toilets, visiting neighbours, visiting local shops, post-dark fishing, and going to fields. It witnessed that in the case of conventional design, the use of prototype was restricted only to indoor activities, while for outdoor activities it was

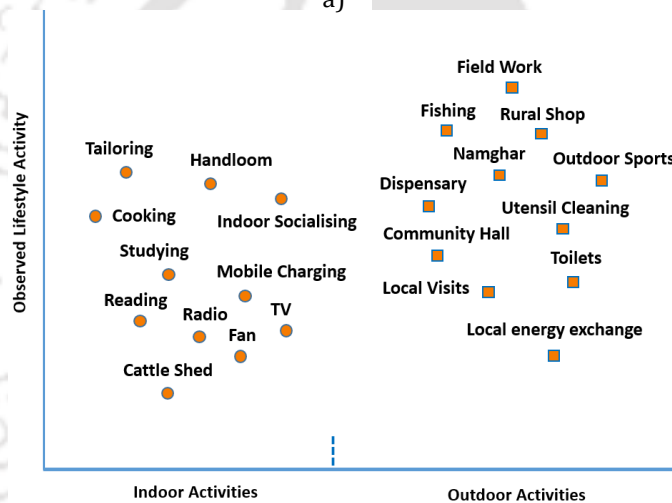


Fig 3.8. Design architecture of a) conventional system using single battery, and b) proposed discrete system using multiple small batteries of an equivalent capacity to conventional system.



Conventional Design

a)



Proposed Design

b)

Fig 3.9 Indoor and outdoor user activities as observed in case of conventional and proposed SPVHS design a) for conventional system no outdoor activities reported, while b) for proposed system frequency of both indoor and outdoor activities reported significantly higher.

found negligible due to the static nature of the system architecture (fig 3.9). In comparison, an increase in energy-related activities observed in the case of a proposed design. Frequency analysis of energy-related activities indicated that the proposed design facilitated indoor and outdoor activities like visiting neighbours in the dark, going to local shops and vegetable vendors, post-dark fieldwork, and local fishing. The mean value for the frequency of energy-dependent indoor activities for

the proposed design prototype ( $\mu$  31.79) is found higher than the mean value for conventional design ( $\mu$  24.45). Also, the mean value for the frequency of outdoor activities due to the proposed design prototype reported much higher ( $\mu$  16.83). In contrast, no energy-related activities reported for outdoor use, in the case of the convention prototype. The frequency of both indoor and outdoor activities was recorded for studied households for one month to derive upon the mean values.

For the proposed intervention, local evidence reported that three respondent families in Bhagunmari village leased power modules on a rental basis to small rural shops and vegetable vendors other than fulfilling their household energy requirement, demonstrating the scope for the local energy exchange. Besides, the proposed design fulfilled requisite in a better manner for indoor and outdoor energy activities when compared to the conventional system. Since the alpha prototype trial demonstrated the scope for productive use of energy considering the widespread energy poverty and economic backwardness in the studied area, there felt the need to test the high-fidelity beta prototype with relevant inputs from the alpha trail. In order to achieve it, hardware realization becomes critical to test a full-scale prototype and to assess its impact on the rural lifestyle. The next section explains the details of realized hardware in the context of the proposed intervention.

### 3.5 Hardware Realization for Proposed Design

To implement the design criteria for the proposed system, as discussed in section 2.13 and 3.3, a simulation model (based on MATLAB@Simulink) for energy scenario 1 (given in chapter two, under section 2.12), is developed and compared with a conventional system, in this section. Furthermore, based on the proposed intervention, demand-driven hardware is realized in further sub-section. The functional features of the prototype are first tested in the lab to validate the proposed concept design. Further, the prototype is intervened in the rural population to investigate its benefits and limitations for the intended use (discussed in the next chapter).

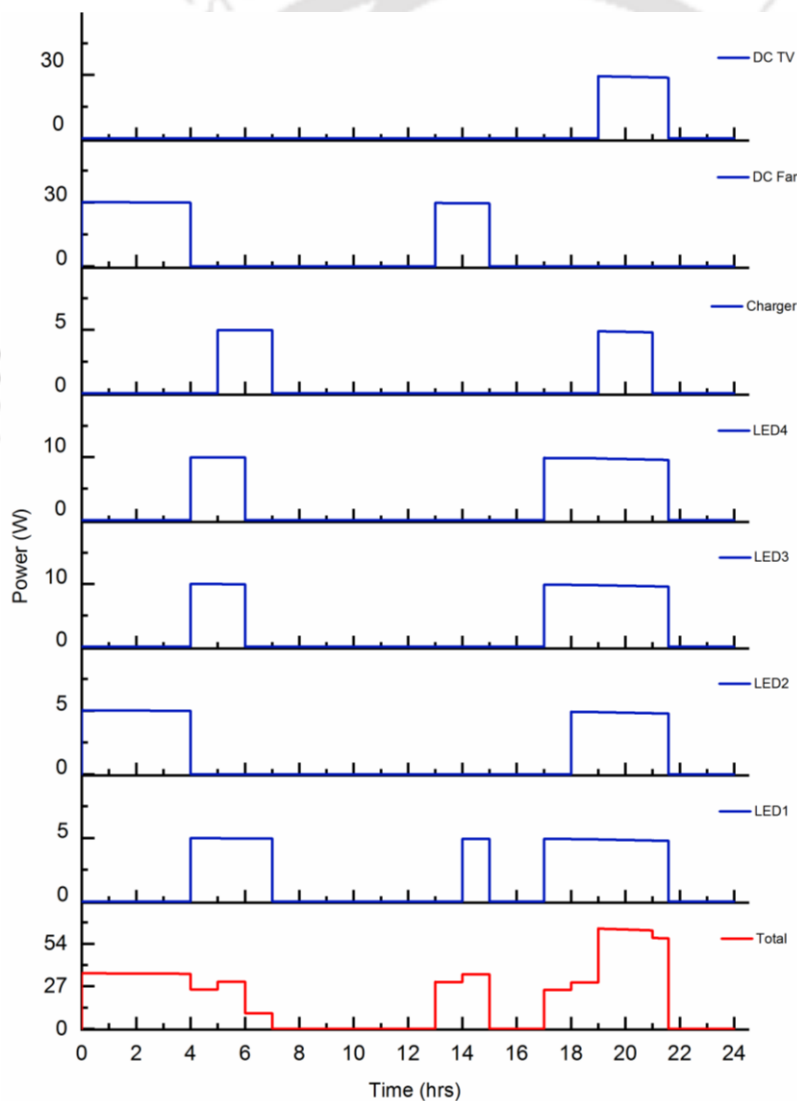


Fig 3.10 Load profile for energy scenario 1 for different types of loads, such as DC TV, DC Fan, Mobile charger and LED luminaire keeping into consideration autonomy of 24 hrs

### 3.5.1 Simulation Models

Before building the simulation models for the conventional and proposed scheme, one-day load profile of a home, as discussed in scenario 1 (mention the section 2.12), is used in both the simulations, as shown in fig 3.10. In this figure, the blue curves show the usages profile for various types of loads during 24 hrs, i.e., one day of autonomy. Moreover, the red curve shows the total power consumption for 24 hrs, for all loads. It helps in determining the peak power demand of the user, which is used to design the proposed SPVHS system. Similar simulation can be performed for both energy scenarios; only power rating in the simulation model will change.

#### 3.5.1.1 Simulation Model of Conventional System

The simulation model of conventional off-grid photovoltaic home system scheme with the load profile mentioned above is shown in Fig. 3.11. The model is having one Lead-acid battery, one solar panel, a direct charging scheme, and the loads mentioned above. Here, the rating of battery and PV panel are taken as 12 V, 100Ah and 150 W, respectively. The battery capacity (100Ah) is chosen by considering the case of energy scenario 1 for the backup time of 24 hours (i.e., if fully charged, can run the aforementioned load profile 24 hours with safe discharged limit (discussed later)), which was found to be the user requirement during the survey. However, the different capacity of the battery, such as 40Ah to 60Ah can be used (as this was the average used capacity in rural areas). It can only impact on the backup time for the same

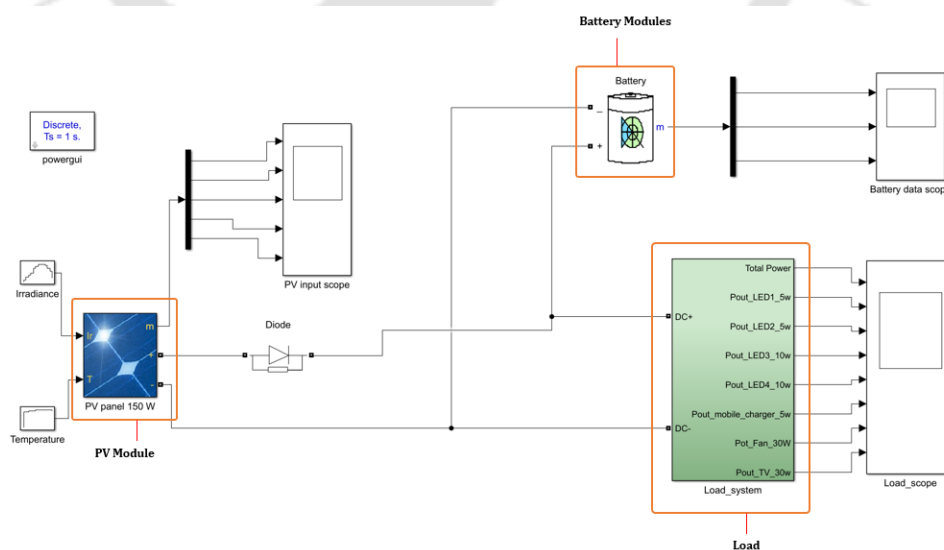


Fig 3.11 MATLAB Simulation model of conventional SPVHS

load profile. The various curves related to system operation such as charging and discharging of a battery for 24 hours are given and compared in the next section.

### 3.5.1.2 Simulation Model of Proposed System

The simulation with the load, as mentioned above profile is based on discrete architecture for SPVHS, as shown in fig. 3.12. The model is having four Lead-acid batteries and maximum power point tracking<sup>8</sup> (MPPT) with pulse charging scheme.

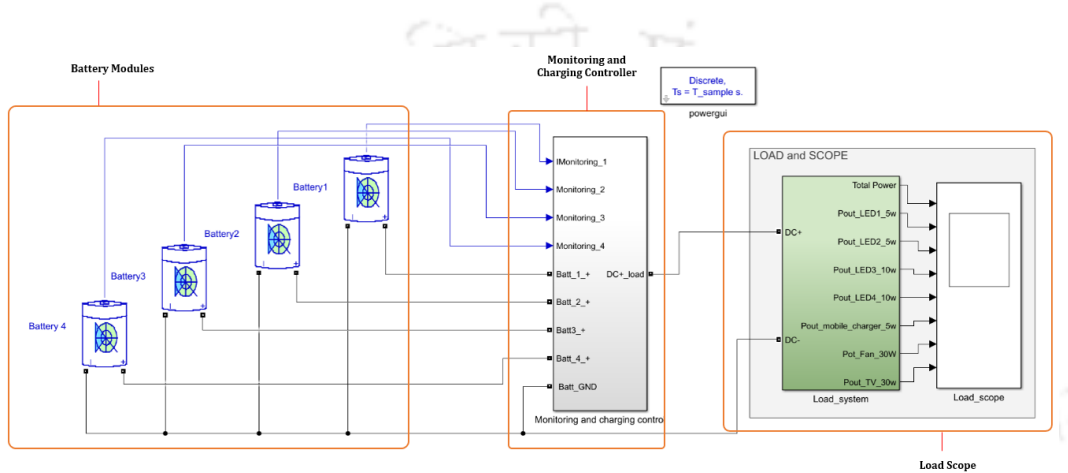


Fig 3.12 MATLAB Simulation model of load profile based on discrete architecture

Four batteries of 25 Ah equivalent to 100Ah capacity are chosen considering the same capacity as discussed in the conventional system. Since the small capacity (25Ah) battery needs lower charging current compared with 100 Ah, two PV panels of 50W are used to meet the requirement. Note that in pulse charging, only one battery is charged at one time with maximum power. The reason for splitting the PV panel into two is- it can be placed in such a way, which increases the time of received solar irradiance and facilitates the logistics. Detail description of the proposed design is shown in fig 3.13. Here, the proposed model has sub-systems and technologies used, as mentioned in subsequent sub-headings a) battery bank b) charging technology.

<sup>8</sup> Maximum Power Point Tracking is electronic monitoring, where the charge controller provides the peak power accessible from the photovoltaic module. It identifies the highest power the photovoltaic module can put out for charging the battery by converting available irradiance to the maximum voltage. This increases batteries charging efficiency. One usually gets 20 to 45% power gain with MPPT in winter and 10-15% in autumn based on the climate.

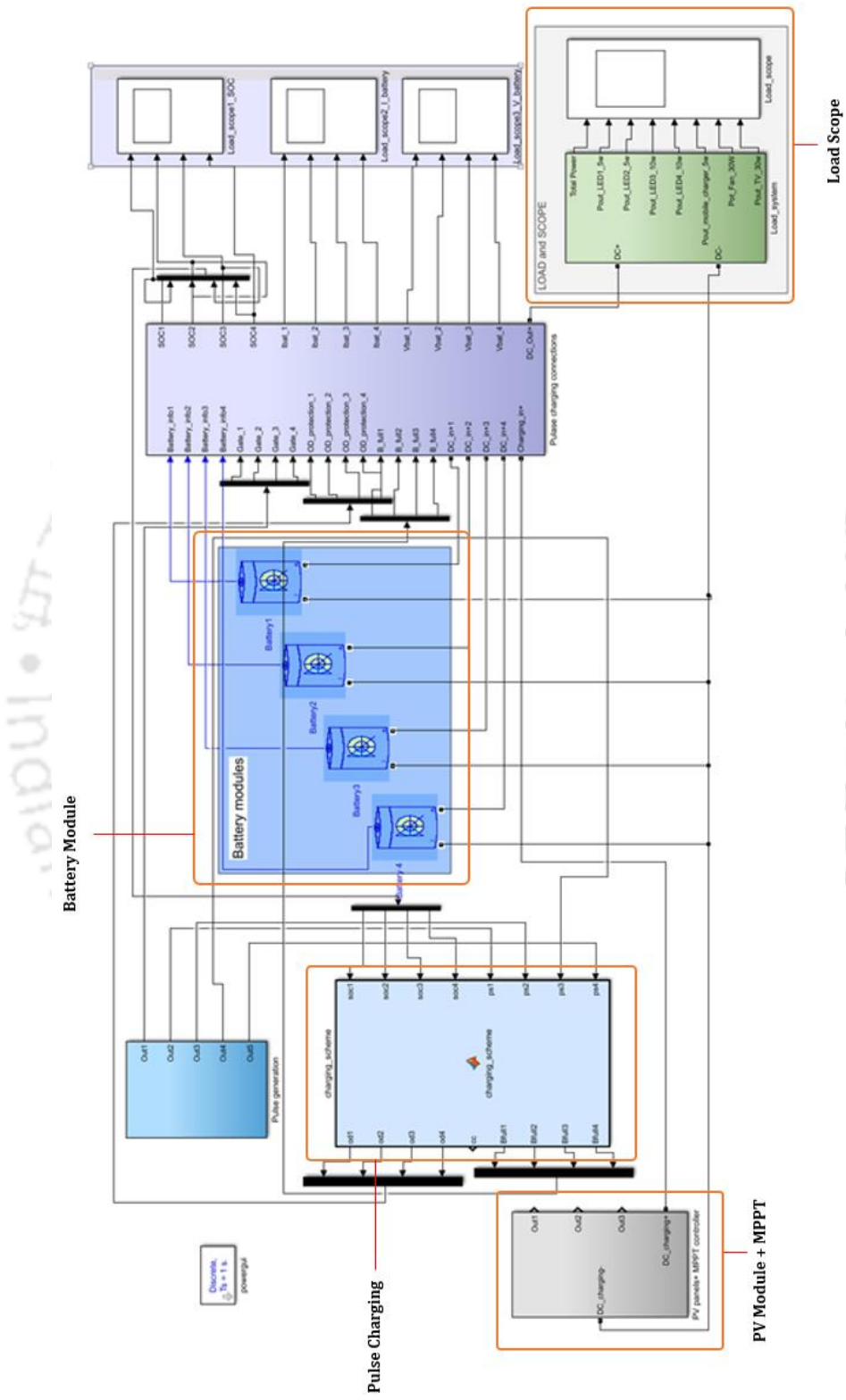


Fig 3.13 Simulation details of the proposed system showing details of PV Module, MPPT, Pulse Charging, Battery Module and Load Scope

**a) Battery Bank:**

For proposed model, one big battery (as used in the conventional model, Con Bt), is split into the four numbers of its equivalent capacity, namely Battery1 (B1), Battery2 (B2), Battery3 (B3), and Battery4 (B4) as shown in fig. 3.14 (a) and (b). The rating of each battery is 12 V, 25Ah, and is connected in parallel with reverse current flow protection. Hence, it is an equivalent capacity of the conventional scheme simulation (i.e., 100Ah), as discussed previously.

To study the battery performance, and possibility of mutual energy transaction (as discussed earlier), 24 hrs discharge profile of batteries used in the conventional and proposed system are given in fig 3.14 for the case when the battery fully charged and when the battery not fully charged (based on MATLAB@Simulink).

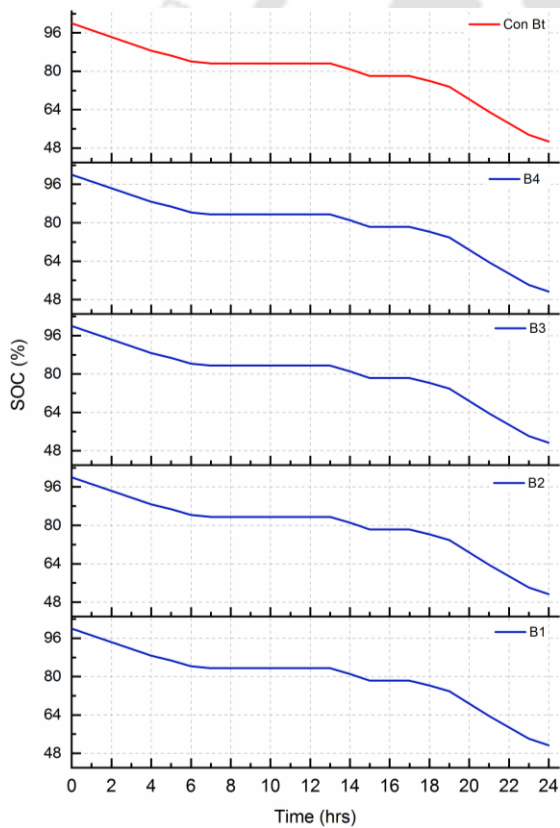


Fig 3.14a Equal SOC

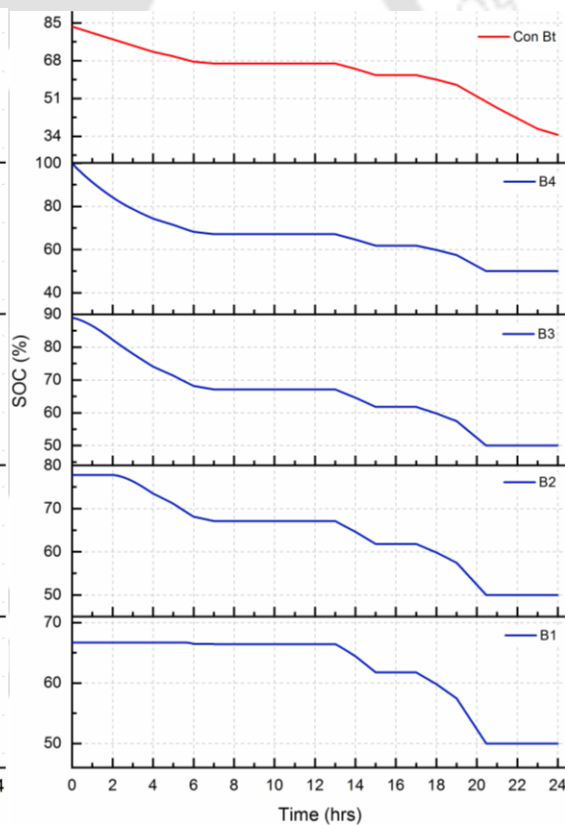


Fig 3.14b Unequal SOC

Fig 3.14 a and b shows comparison between equal and unequal state of charge SoC of batteries for conventional and proposed system

For the case when all the used battery (ies) in both the systems are fully charged (i.e., SoC is 100%), the discharge profile of both the systems can be found in fig 3.14. In this figure, the discharge profile of a conventional battery is represented in red color. In contrast, the discharge profile of batteries B1, B2, B3, and B4 used in the proposed system are represented in blue color. As noted, all the batteries (in both the systems) are following the same discharge pattern and powering the load safely for 24 hrs. Besides, it found that the battery of conventional and proposed systems discharged until 50% SoC<sup>9</sup> (safe discharged limit), as seen in 3.14a. SoC determines the battery charge.

Now, for the case when batteries are not fully charged in both the systems, a discharge profile can be found in fig 3.14b. In the proposed system, when the battery not fully charged means all batteries may have different SoC, then the battery with higher SoC will get discharged first, followed by the lower SoC. From the Fig.3.14b, the discharge profile of batteries B1, B2, B3, and B4 are different compared with the case when fully charged. It is also noted that the power drawn from the batteries is being cut-off at 50% SoC, as shown in fig. 3.14a, this is due to the over-discharge protection used in the proposed system. However, in the conventional system, if the battery is discharged from the average SoC of the four batteries (i.e., nearly 85% SoC), it gets discharged below the 50% SoC (i.e., 34% SoC remaining), as shown in fig 3.14b. From the same, it can also be seen that the proposed system fails to give power below 50% SoC, whereas the conventional system continues to supply power below 50% SoC.

The advantage of over-discharge protection in the proposed system is that it will improve the durability of the battery and makes the system more sustainable in the long run when compared with the conventional system. However, in the conventional system, delivering power below 50% SoC will not only decrease the battery performance and durability but also requires high charging current to bring the SoC above 50%. In this case, the maintenance of batteries becomes an issue considering the lack of services in the regional context of north-east India. Also, this will develop a lag for SPVHS based power supply to rural households. As far as the scope of energy lending is concerned, energy lending is not possible in the conventional system

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<sup>9</sup> State-of-charge (SoC) shows a battery's level of charge; usually measured in percentage. If a battery is fully charged, then battery's SoC is said to be 100%.

because it has a single battery source. Whereas in proposed system scope of energy lending is possible due to discrete batteries and especially for the case when batteries have different SoC, then battery with lower SoC can be utilized for energy lending, as it is not delivering power to the load, as shown in fig 3.14b. It is mainly due to the reason that in parallel connection with reverse current flow protection, the battery with higher SoC will discharge first.

#### **b) Charging Technology:**

Generally, in the conventional solar home system, the direct or pulse width modulation (PWM) technique is used for battery charging (Yatsui et al., 2012). Moreover, this charging technique cannot extract maximum power from the solar panel. Hence, to keep in mind the facts mentioned above, a time-distributed-MPPT-charging is used in the proposed system. Here, the time-distributed-charging is done in the form of high-frequency pulse power cyclically given to each battery. As a result, the maximum power extracted from the PV panel is utilized in each pulse. Thus, by doing the pulse charging of the battery bank, the proposed scheme does not require a large solar panel (as used in the conventional system), which reduces cost, ease logistics, and provides much-required portability for a geographically challenged region like North-eastern region of India.

The pulses, as shown in Fig. 3.15, are given for charging the four batteries, which is used in the simulation as well as in the prototype. The on-time of a pulse set at 1 ms with a 100% duty cycle and the remaining three pulses will be in the off condition and so on for other batteries. By doing this, the total charge current obtained from the solar panel can be fully utilized to charge one battery at a time. As a result, a smaller sized (about one-third from the conventional scheme) solar panel needed to run the system, dropping panel cost by more than half. During the charging process, when one battery is charged, and the other three are in rest condition with a resting period of 3 ms for each battery, It enables the battery's chemical activities to stabilize before charging starts again. This delay allows the chemical reaction to accommodate the rate of electrical input. Pulse charging can decrease undesirable chemical reactions like gas formation, crystal development, and passivation (Cheung et al., 2006). As a result, long-term damage to the battery can be minimized, and this improves the longevity of the Battery (Serhan & Ahmed, 2018).

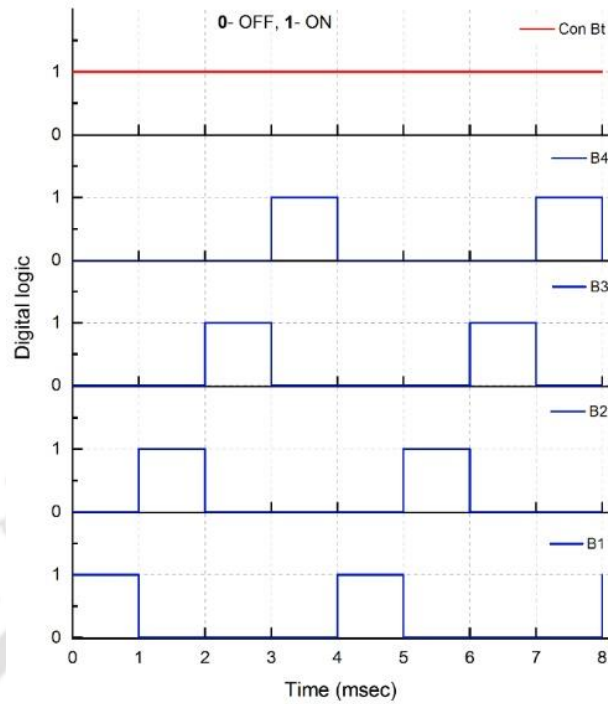


Fig 3.15 Simulation depicting state of pulse charging to batteries

Moreover, the other benefit of pulse charging is that the battery will not overcharge and, therefore, requires almost no maintenance. However, in the case of the conventional system, a constant (forced) charging is done to a battery (Con Bt), as shown in Fig. 3.15 (red curve), which does not allow efficient chemical reaction inside the battery and may overcharge and heat the battery. As a result, battery life gets shortened and requires proper maintenance in short intervals.

### 3.5.2 Hardware Realization

In this section, each hardware module used in the proposed SPVHS explained. The proposed SPVHS system has two modules;

- i. Smart battery module
- ii. Controller cum user interface module

#### 3.5.2.1 Smart Battery Module

The smart battery module consists of a PCB and a battery. The PCB will monitor the various parameters of the battery, such as battery voltage, charging and discharging current, SOC, and charge indicator. Besides, this module has multiple I/O ports, which is used for battery module charging, USB port as a mobile charging and other as a

lighting purpose. It transforms a conventional battery to a smart battery, therefore, named a smart battery module. Hence, this module can also be used as an independent unit, which makes this module eligible for mutual energy trading. In addition, this module can be used to perform both indoor and outdoor rural activities. Before going into detail about PCB used, let us look into the battery technologies used in this module.

### 3.5.2.2 Designed PCB Description

Figure 3.16a shows a PCB layout, used to convert a VRLA battery into smart VRLA battery module. A 12 V battery is used for the purpose. The battery has a microcontroller unit (MCU) to monitor and control the battery charging and discharging action. Besides, if battery capacity falls below 50% of SOC, it will stop the power at output ports.

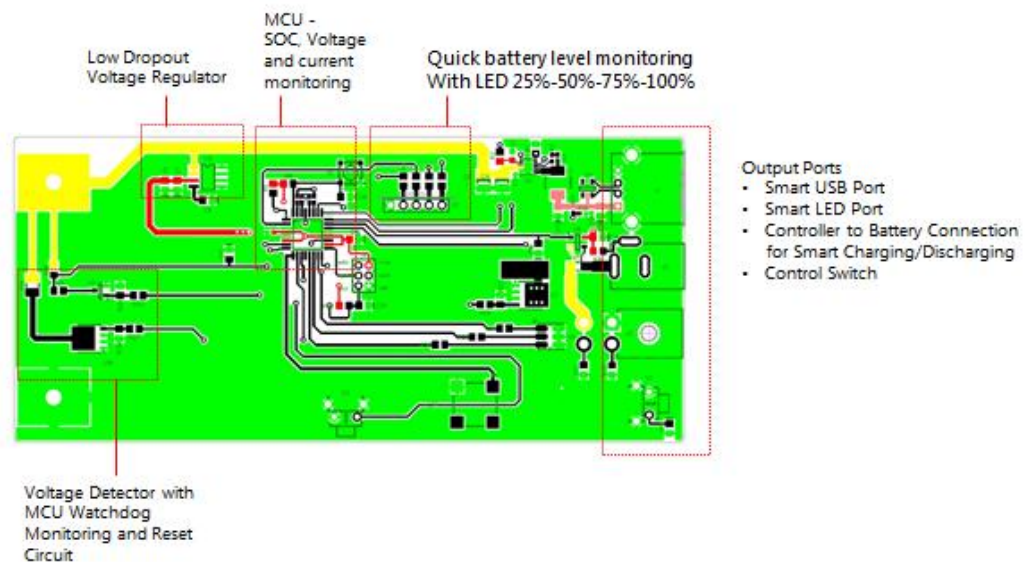


Fig 3.16a: Designed PCB layout description of lead-acid battery monitoring with multiple I/O ports

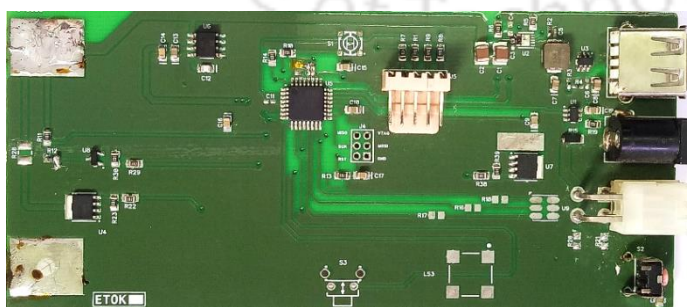


Fig 3.16b: Smart battery (VRLA) PCB Prototype

Moreover, a provision to show the charge status of the battery is given in the PCB. A LED indicator (four LEDs) used for this purpose with 25%, 50%, 75%, and 100% charge status and its working tabulated in table 3.18. It helps rural user making judicious use of batteries, primarily when it is used as an independent unit. Fig 3.16b shows the PCB prototype for VRLA battery. Similarly, to convert a Li-Ion battery pack into smart Li-Ion battery module, a PCB layout, as shown in fig 3.17a is used. This PCB is almost similar to VRLA case. The only difference is the battery voltage. Since a Li-Ion cell voltage is 3.7 V, four numbers of such cell are used to make a 12 V battery module. To maintain 12 V, a buck-boost converter is used. When the pack voltage is above 12 V the converter will do the buck, operation and vice-versa (Note that Li-ion has a high discharge rate). Fig 3.17b shows PCB prototype of Li-Ion battery.

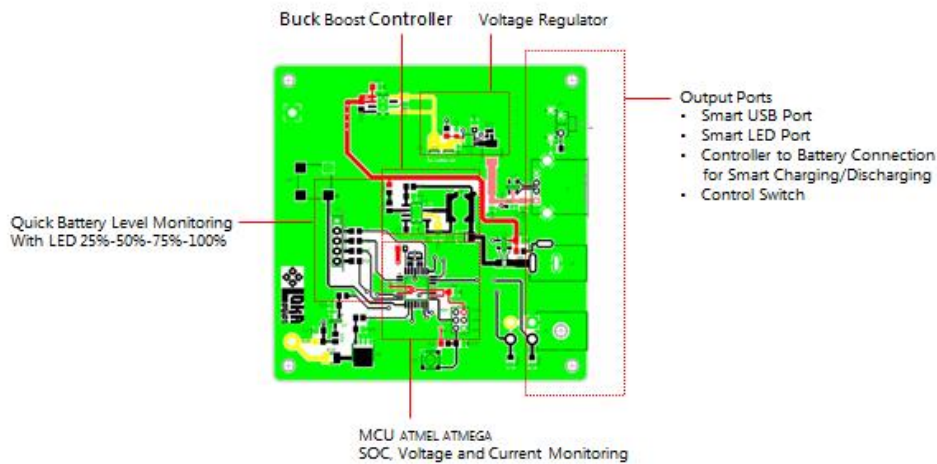


Fig 3.17a Designed PCB layout description of Lithium ion battery monitoring with multiple I/O ports



Figure 3.17b Smart battery (Li-ion) PCB Prototype

Table 3.18 LED Charge Indication

Case	LED 1	LED 2	LED 3	LED 4	Charge Status (%)
1	ON	ON	ON	ON	100%
2	ON	ON	ON	OFF	75%
3	ON	ON	OFF	OFF	50%
4	ON	OFF	OFF	OFF	25%
5	OFF	OFF	OFF	OFF	0%

### 3.5.2.3 Controller cum User Interface Module

The controller cum user-interface module is the heart of the SPVHS system. Smart battery modules, PV module, and hybrid input connected to a centralized hub, controller cum user interface module. The PCB layout description of this module is shown in Fig. 3.18. The prototype of the controller PCB is shown in fig 3.19a and b.

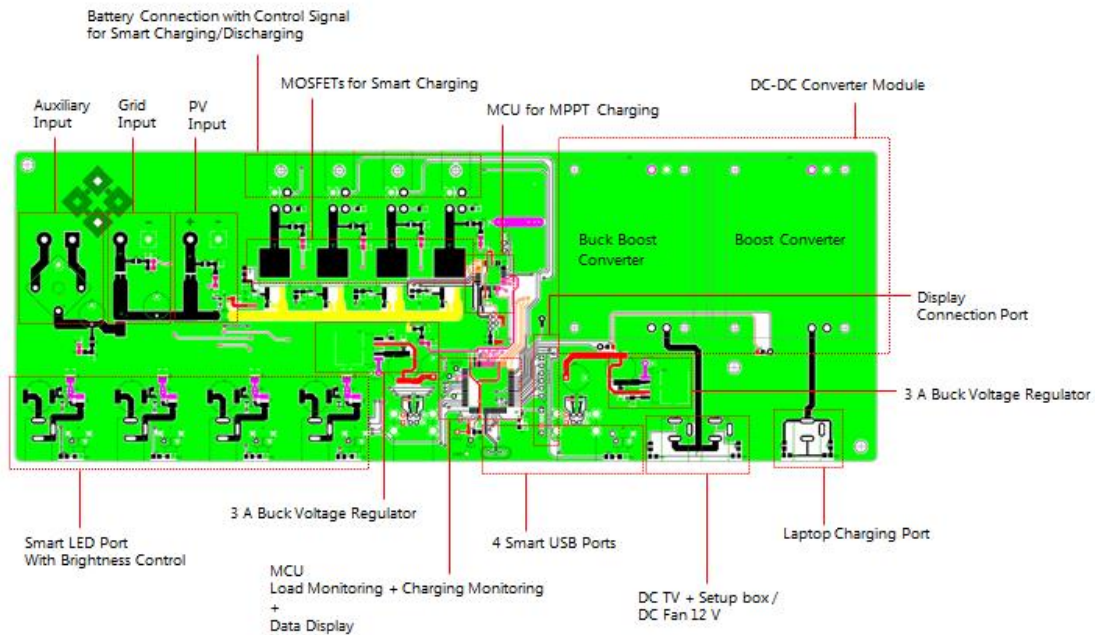


Fig 3.18 Designed PCB layout description of controller cum user interface board

The primary function of this board is to provide uninterrupted power to different types of load by smartly managing hybrid input sources such as PV, grid, auxiliary, and smart battery modules. The control motherboard has four smart LED ports with three different light control settings. Smart LED port will allow multiple wattages LED lights



a)

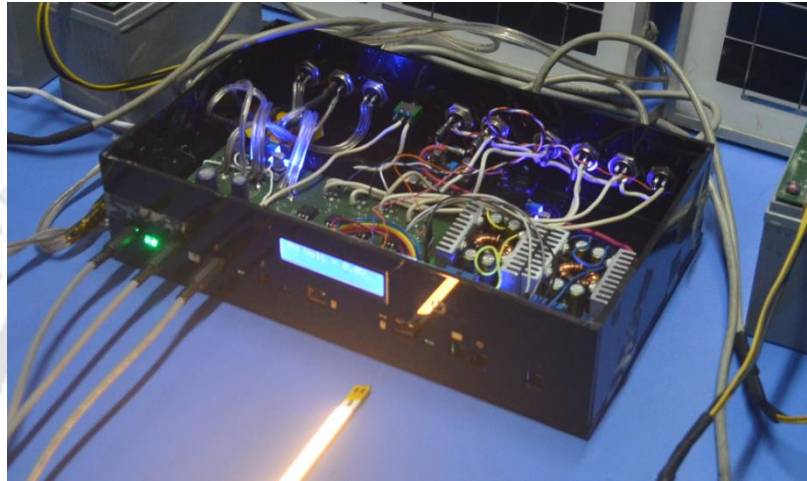


Fig 3.19 a) Controller cum user interface PCB and b) Controller cum user interface PCB assembled inside controller box

to use with port, which is not the case in the existing system. In the proposed system, when LED luminaire gets heated, it consumes more energy. Control hardware, in this case, will not allow more current (due to a current control driver) to pass hence saves it from consuming more energy. Controller board had ports to support DC TV with Setup box, Fan and laptop charging. The details of the output ports where the user will connect the different types of load shown in Table 3.19.

Table 3.19 Control board I/O port details

Types of output ports	No. of ports	Specification	Special Features
Smart LED	4	Current control with 330mA maximum current	Brightness control in three modes (High, Medium, and Low)
Smart USB	2+2	5 V, (3+3)Amp	Supports type C charging output
DC TV+ Setup box or DC fan	1	12 V, up to 5A	---
Laptop charging	1	19.2V, up to 5A	---

Moreover, an LCD is provided to show the input sources available, battery connection status, battery voltage, and charge status, LED brightness. It gives a better understanding to the user about the overall functioning of the system and hence reduces any chances of poor handling by the user, adding to the system reliability. Nevertheless, the proposed SPVHS system has a facility of hot-swapping for the smart battery modules even while charging and during operation. It is due to the individual monitoring of the battery modules. Besides, each battery module is charged with MPPT plus pulse charging technique. In the prototype, the total four numbers of battery modules can be connected in parallel. Hence, hot-swapping has an advantage for fulfilling multiple 'on-demand' rural needs. Hot swapping specifically defines the insertion or removal of components into the system without interruption. It can be simple to avoid the delay and inconvenience of shutting down and then restarting the system. However, hot-swapping is not possible in the conventional system because we need to shut down the system to take out the battery (ies) form the series/parallel string.

The controller accepts multi-source input from PV, Grid & Auxiliary for Hybrid Charging. Hybrid input is instrumental especially for climatically and geographically challenged remote regions of north-east India and relevant where solar irradiance is low or inconsistent and conventional grid is difficult to access due to geographic limitations. It will help to improve the efficiency of an off-grid PV system. Furthermore, the controller has a short-circuit protection feature. In case of short-circuit during operation; the controller will switch-off the entire system. This hazard protection will improve the safety of the system. The hardware was developed considering both energy scenario I and II, the only power rating of components and loads will change.

The batteries used for the proposed home photovoltaic system must be rechargeable, enable deep discharge, easy to maintain, and have high capacity and low self-discharge (Podder & Khan, 2016). Generally, in conventional SPVHS system, flooded lead-acid battery is used. One of the critical observations of a pilot study was that most of such batteries are damaged, due to user putting dilute acid instead of topping with distilled water. Besides, there was spillage of electrolyte due to frequent relocation of batteries in rural areas. In order to avoid such difficulties, a maintenance-free valve-regulated lead-acid battery (VRLA battery) used for smart

storage modules. The VRLA batteries are intended to recombine water with hydrogen and oxygen. In the battery, the valve provided regulates the pressure inside the battery. Since no water loss happens during the charge-discharge cycle, so no water refilling is required for sealed or VRLA batteries. (Berndt, 2006).

The advantages of such batteries over flooded lead-acid batteries are as follows:

- a. No topping up of distilled water is required. Easy for usage.
- b. No spillage of electrolyte as it is sealed. Acid-accident free and can be operated in any position.
- c. Releases significantly less hydrogen gas. Safe for health.
- d. It had low self-discharge than flooded lead-acid batteries.
- e. One of the prominent advantages is the charging time: up to five times faster than the flooded lead-acid batteries. Considering sub-tropical monsoon climate of northeast such batteries gets charge even in low solar irradiance.
- f. Lighter in weight by about 25% when compared to the flooded lead-acid batteries. It improves portability for geographically changed remote regions.

Besides, to increase the usability in terms of fast charging, deep-discharge, portability, and compactness, another chemistry type of battery called lithium-ion is also used as a smart battery module.

### **3.6 CAD Detailing of Proposed Design**

CAD detailing was done for the final design concept to realize design in actual. Overall dimensions were considered as per the physical size of the hardware, respective position of different input and output ports, and digital display unit. Ergonomic considerations were made concerning the overall dimensions of design to ensure handling convenience for controller and storage modules. Figure 3.20 shows the details of the controller unit, while figure 3.21 and 3.22 shows details of VRLA storage module and lithium-ion storage module, respectively.

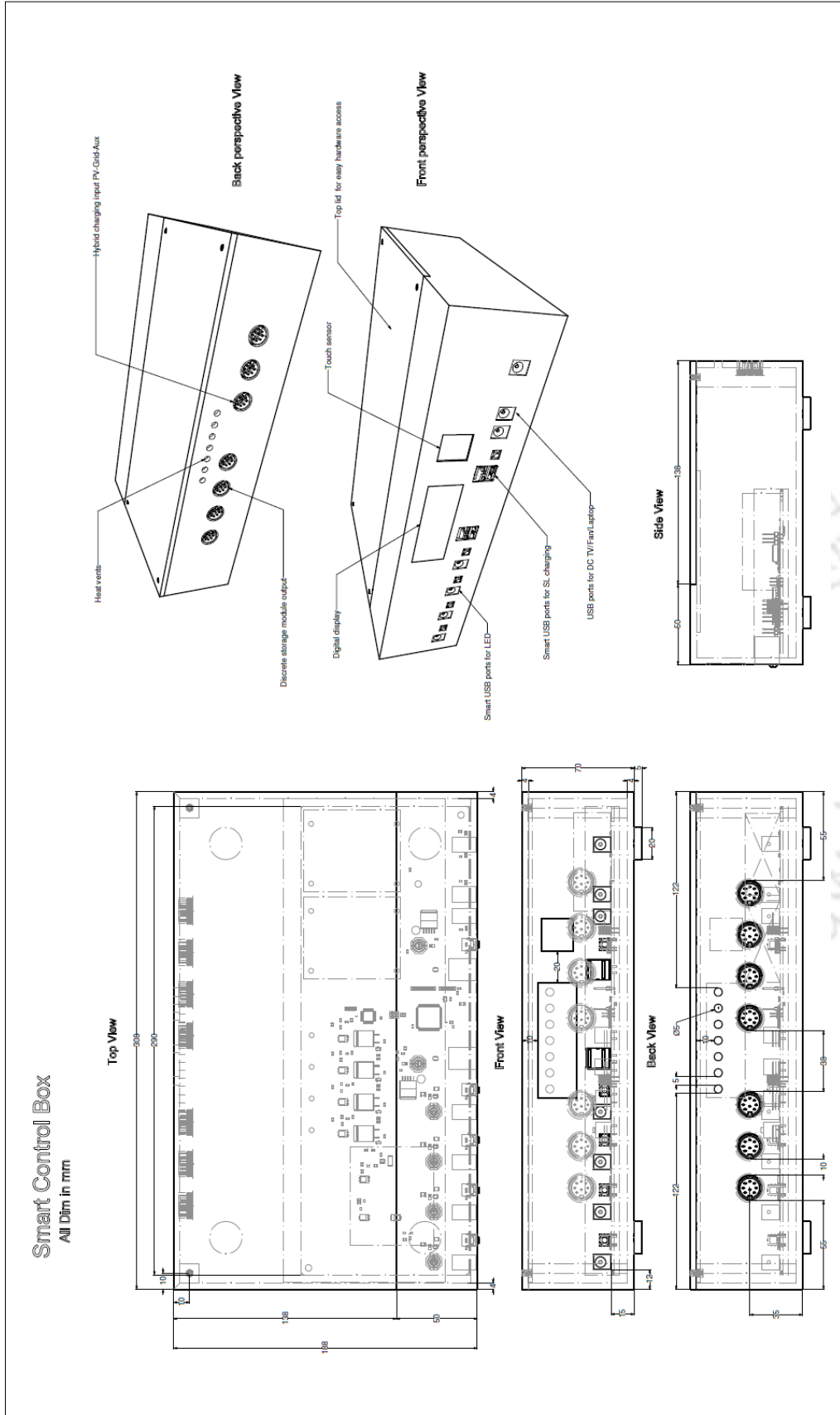


Fig 3.20 Details of smart controller unit

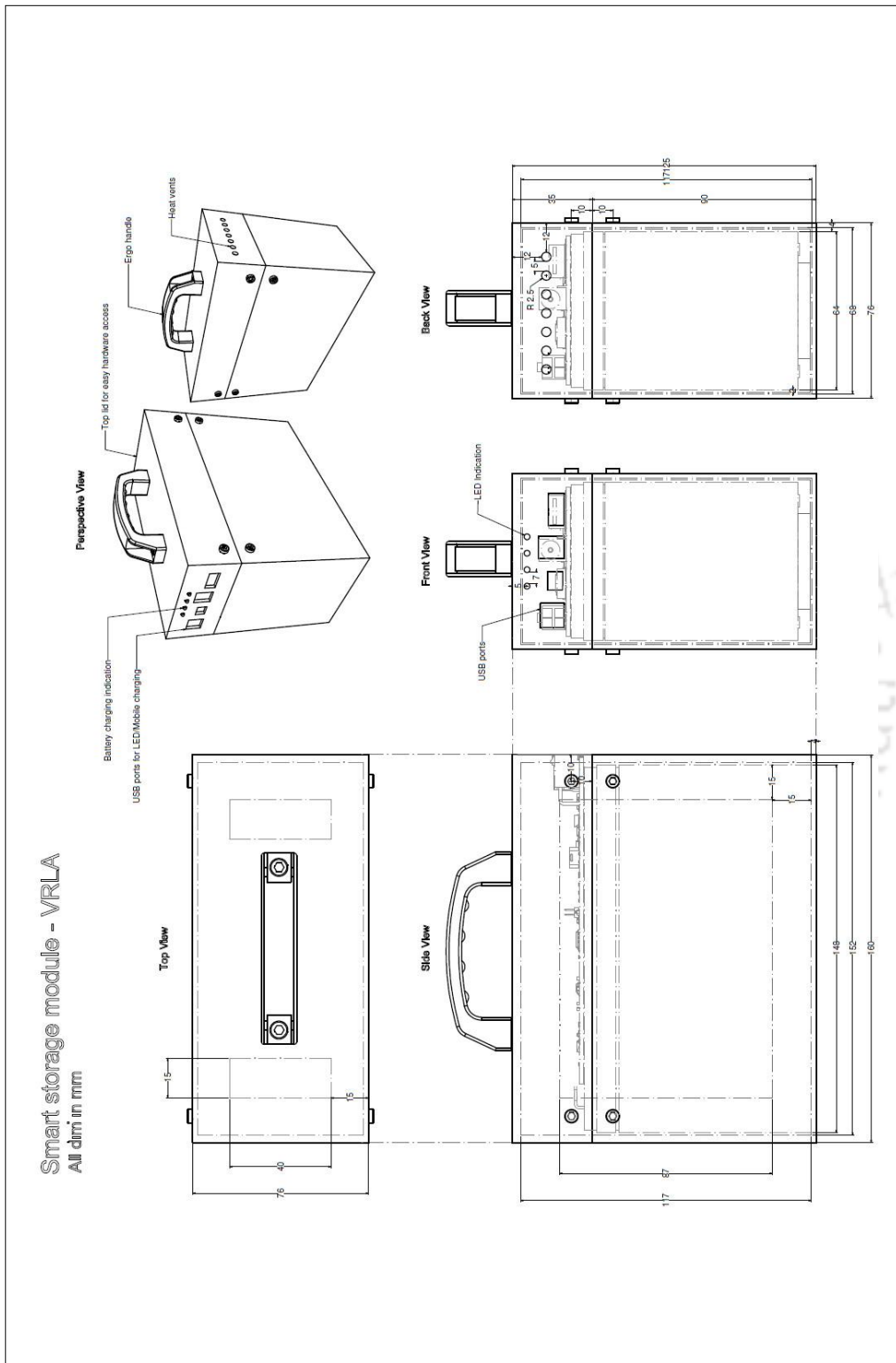


Fig 3.21 Details of smart VRLA storage module

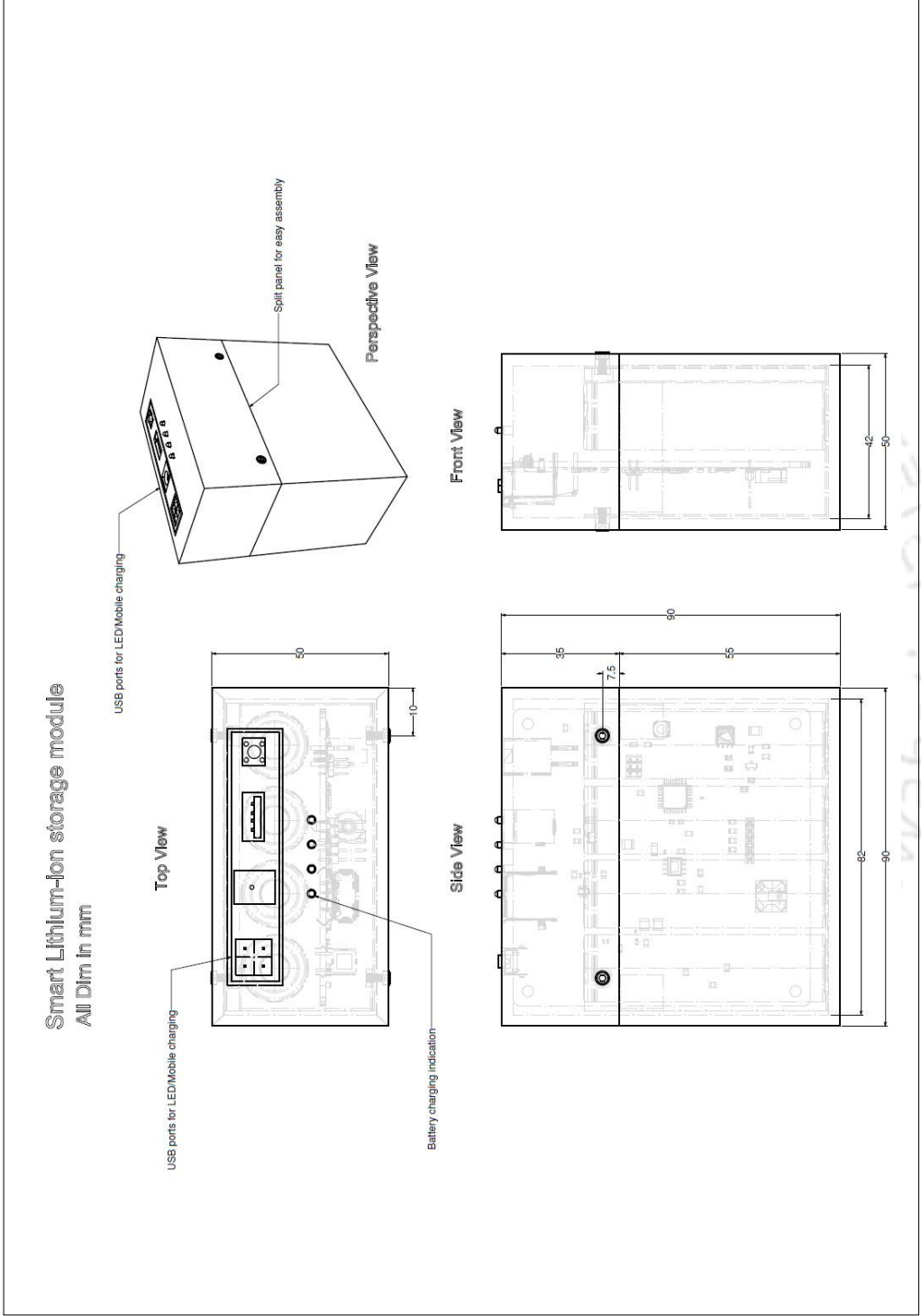


Fig 3.22 Details of smart Lithium Ion storage module

### 3.7 Design Details and Beta Prototype Testing

After assembling the hardware PCB's like controller motherboard and smart battery circuit board, the fabricated prototype tested for different functions. The prototype of the proposed design consists of two parts. Controller cum interface unit (legend 1) and discrete storage modules (legend 2), as shown in fig 3.23. Controller unit has four smart LED output ports (legend 3) with low, mid, and high brightness controls that are used depending upon the user requirement. The Controller unit has an LED display (legend 4), which shows battery charge status. It will allow the user to make responsible use of the system.

Total four numbers of 5V USB ports are given (legend 5) with type-C charging support. Type-C option is particularly useful for fast charging that can help user located in the region with low solar irradiance such as northeast region. The feature, as mentioned above, is given to enable PUE benefits to local stakeholders. Controller unit has two 12V, up to 5Amp output ports (legend 6) providing back-up for DC TV with setup box, DC Fan and one 19.2V up to 5 Amp port for laptop-charging (legend 7). Controller box has three input ports (PV, Grid, and Auxiliary) at rear for hybrid charging (legend 8) and four input ports to dock smart battery modules with controller unit (legend 9). Smart battery module has one 5V, 3Amp USB port for mobile charging (legend 10) and one 5V port for LED luminaire (legend 11). The module has one DC input (with smart control) jack for battery charging (legend 12) and one on-off switch for shutting down the smart battery module (legend 13). Heat Vents were given to reduce temperature arising due to overheating of hardware components inside (legend 14)

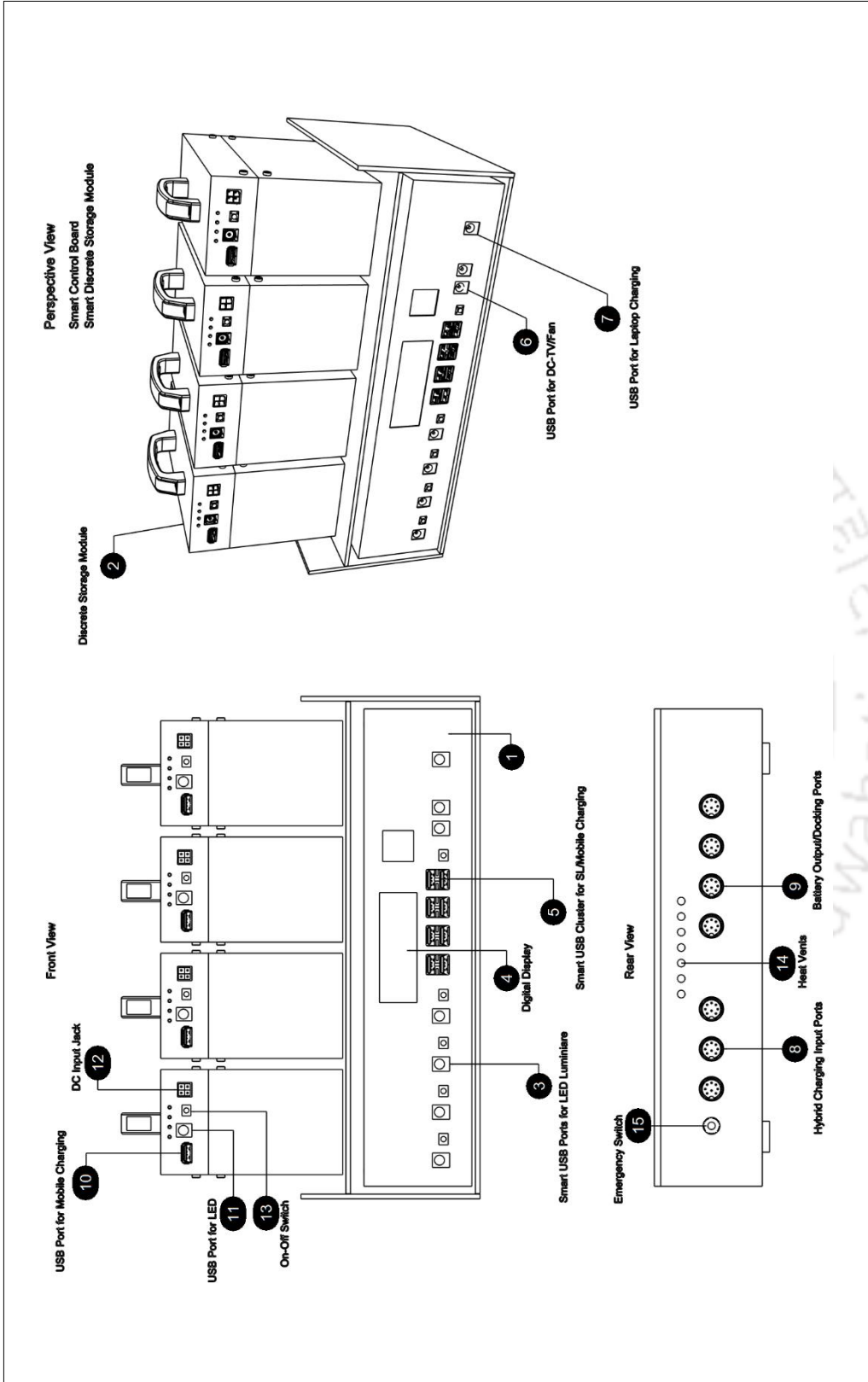


Fig 3.23. Design details of Proposed SPVHS Design

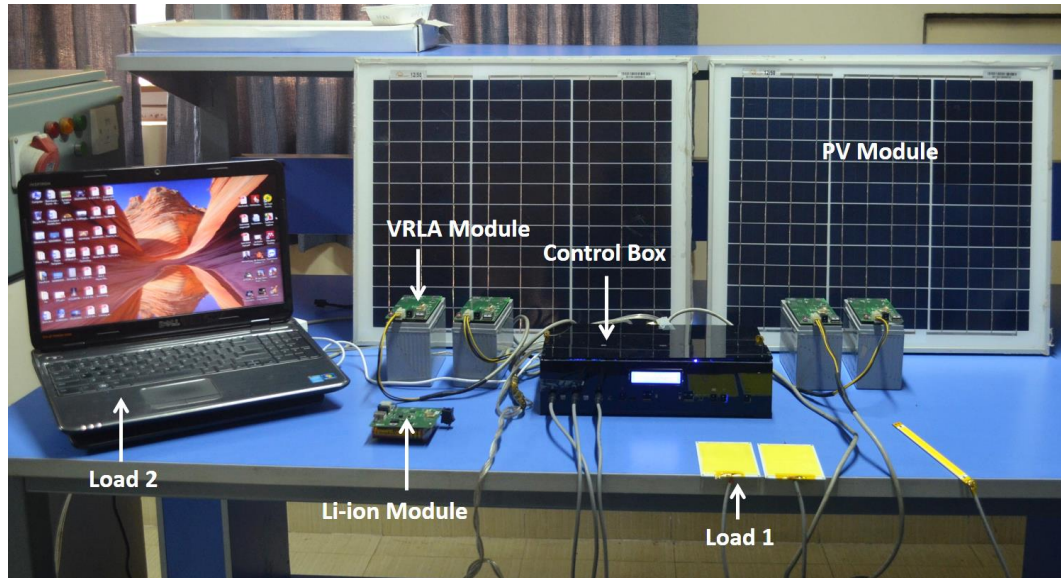


Fig 3.24 Beta prototype of solar photovoltaic home system showing VRLA and Li-ion storage modules along with controller box.

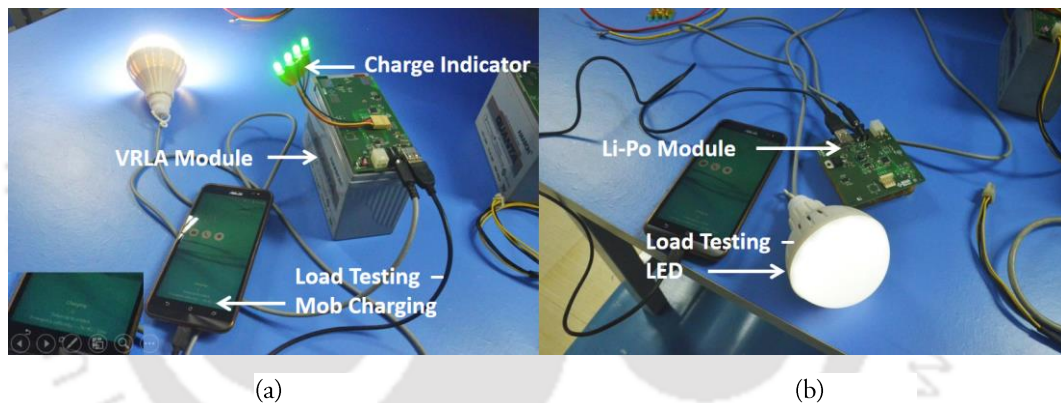
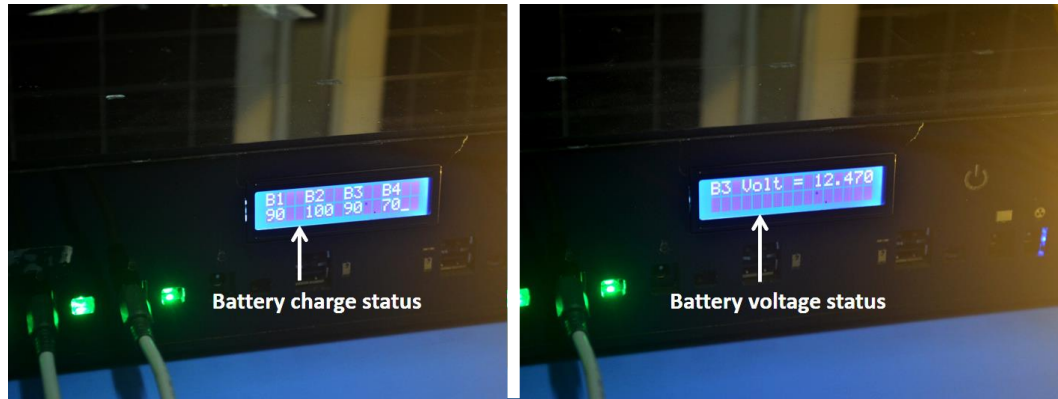


Fig 3.25. Load testing of (a). VRLA module, (b). Li-ion module

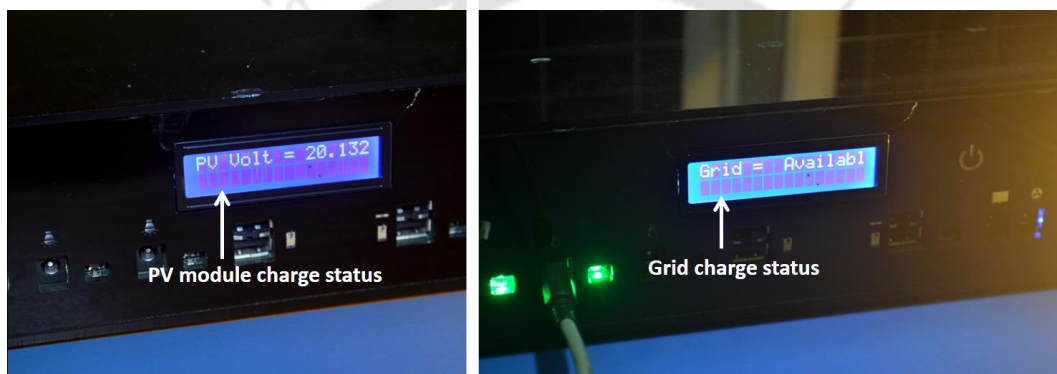
In fig 3.24, complete setup is tested under different load condition (as mentioned in scenario 1) with VRLA (fig 3.25a) and Lithium-ion storage modules (fig 3.25b). Four smart LED light output ports tested with two (2) @5 watt and two(2) @10 watt slim LED lights under Low-10%, Medium-50% and High-100% settings for brightness meant for custom use of LED lights. It provides flexibility to control light intensity depending upon the requirement. Such control reduced heat loss and improved longevity of luminaire for long-term usage. Ports for legend 6 and 7 tested for 12V, DC TV and laptop charging, as shown in fig 3.25. Digital display displaying the battery connection status (fig 3.26a) and SoC of respective batteries (fig 3.26b).



(a)

(b)

Fig 3.26 Testing digital display for a. battery charge status and b. battery remaining voltage



(a)

(b)

Fig 3.27 Testing functioning of hybrid-charging input for a. PV module and b. Grid

Setup tested for PV and grid-based hybrid-charging input fig 3.27. Experiment observed that batteries get consistently charged due to hybrid charging input in the night and under cloudy conditions in a day. Besides, storage modules tested individually for LED indication depicting the charging status of the battery. Both lithium-ion fig 3.28a and VRLA batteries fig. 3.28b tested under two set of conditions

1. Individual testing of batteries with output ports for light and mobile charging.
2. All smart battery modules docked with controller box (fig. 3.29) to test different loads like LED light, Laptop, DC TV, and Mobile Charging. Port for 19.2V laptop charging (legend 7) tested with a load of Dell Inspiron N 5010. Set of a basic (Nokia 207) and smartphone (Asus Zenfone 2) charged multiple times during lab testing.



Fig 3.28 a. Lithium-ion and b. VRLA smart battery modules

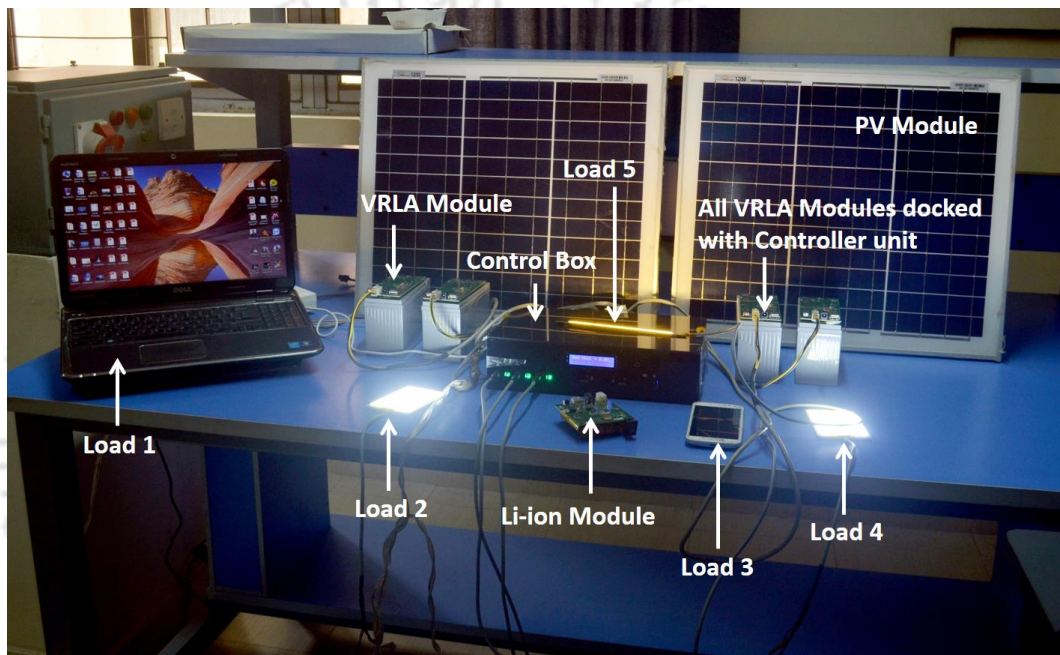


Fig 3.29 Beta prototype of proposed design of SPVHS. Smart battery modules docked to controller unit and tested under different load conditions.

Charging ports are tested thoroughly, keeping in view energy exchange practice as observed during the alpha trial, than merely using it to fulfill household energy needs. In addition, all the loads tested continuously for more than ten working hours for charging primary electronic devices like mobile phone, solar lamp, and laptop. The overall weight of the assembled controller box reported to be 1.25 kg, while the weight of each 12V VRLA module and 5V Lithium-ion module was 1.86 kg, and 0.20 kg, respectively. In comparison, it was found that the average weight of a single battery in a conventional system was between 19 to 24 Kg depending on system capacity — various lab tests and observation for intervention summarised in table 3.20.

Table 3.20 Lab tests and observation conducted for the prototype of proposed off-grid photovoltaic system.

Category	Tests and Observations
Solar Panel	<ul style="list-style-type: none"> <li>▪ Short-circuit Voltage, <math>V_{sc}</math></li> <li>▪ Open-circuit Current, <math>I_{oc}</math></li> <li>▪ Physical Orientation</li> </ul>
Smart Battery	<ul style="list-style-type: none"> <li>▪ Nominal Voltage</li> <li>▪ DC Output for Mobile, LED Bulb</li> <li>▪ Low Voltage Disconnect</li> </ul>
Charge Controller cum Monitoring Unit	<ul style="list-style-type: none"> <li>▪ Charge Indicator Functioning</li> <li>▪ Hybrid Input</li> <li>▪ Pulse Charging of Smart Battery</li> <li>▪ Overcharge Disconnect</li> <li>▪ Displaying Type and Number of Loads Connected</li> </ul>
Switches	<ul style="list-style-type: none"> <li>▪ Connectivity</li> </ul>
Wiring	<ul style="list-style-type: none"> <li>▪ Continuity</li> <li>▪ Voltage Drop</li> </ul>
Connected Load	<ul style="list-style-type: none"> <li>▪ Type</li> <li>▪ Rated Load</li> </ul>
Installation Quality	<ul style="list-style-type: none"> <li>▪ Ease of Installation</li> <li>▪ Ease of Operation</li> <li>▪ Safety</li> </ul>

After testing the high-fidelity beta prototype under lab conditions, a comparative analysis was done between conventional and proposed design, for subjective evaluation of human factor parameters such as safety, protection, and effort. Furthermore, to evaluate postures like bending, walking, and carrying, under the given load, OWAS analysis was adopted.

### 3.8 Portability and Postural Analysis for Storage Module Carrying Task

The main objectives of the study were 1. To analyze working posture adopted during regular usage and maintenance of battery modules for the conventional and proposed system. 2. To identify the most problematic postures related to different tasks performed. 3. To compare OWAS assessment for both systems, and to adopt necessary measures if any. The study observed that since the rural user has an active indoor and outdoor lifestyle, concerning it the use of a conventional system found quite restricted for outdoor activities. The study reported the average weight of a lead-acid battery is found to fluctuate between 19 (41.88 lbs) to 25 (55.12 lbs) kgs depending upon the capacity of the conventional system; load effort becomes a challenge for

routine handling tasks like bending, walking and carrying. The proposed photovoltaic system with split-storage provides a beneficial effect to 1. Improve portability for address local carrying for outdoor rural applications and 2. To address difficulties related to battery maintenance. In this regard, postural studies of a person lifting and carrying storage modules were conducted using OWAS method. The method mentioned above can evaluate posture involved to perform different tasks related to battery maintenance task like bending (task1), walking (task2), and load effort. The inclusion and exclusion criteria of this study consisted of the willingness to participate, lack of any diseases and MSDs, and at least two years of ownership of the solar home system. The users asked to perform task1 and task 2 using battery both in case of the conventional and proposed system.

### **3.8.1 OWAS Method**

The primary objective of this study was to identify problematic postures while lifting and carrying battery modules through the application of the OWAS (Ovako Working Posture Analysis System) method. The OWAS technique (Ovako Working Posture Analysis System) is an analytical method that allows postural conditions to be improved. It requires into account different back, arm, and leg positions. Each position of the body is encoded and categorized into four static injury risk groups. OWAS method considers load to:

- Back position,
- Arms position,
- Legs position and work,
- Load.

Based on the identified assessment factors for back, arms, legs, and load, the position code must be determined. Identifying the body position code using the OWAS method enables the risk class to be determined. The details of different OWAS codes for different body postures along with the action level category and load risks are given in appendix 3.

### **3.8.2 Experimentation Methodology**

#### **1. Selection of locale and sample**

In order to verify the lifting and carrying convenience for the proposed design, a small random sample size of ten (N=10) was used for OWAS analysis, around the remote

villages of Majuli district in Assam. Ten SPVHS owners, six male, and four females participated in the field study. Purposive and random sampling was used to select the study area and users of SPVHS. Most males and females owners were between the ages of 31-45 years.

## 2. Analysis of working posture

Using the Ovako Working Posture Analysis System (OWAS) and digital photography, the assessment of the different working postures for the battery lifting and carrying task evaluated. Stick diagrams were subsequently drawn from freeze-frame video and subjected to respondent evaluation for the most common postures adopted.

### 3.8.3 Results and Discussion

OWAS Scoring and description of posture adopted by the majority of respondents related to battery task 1 and 2 for both conventional and proposed SPVHS (table 3.21 and 3.22).

Table 3.21. Posture adopted by respondents while performing battery related tasks

OWAS Observed Activity Table				
Component	Conventional SPVHS Design		Proposed SPVHS Design	
	Task 1	Task 2	Task 1	Task 2
<b>Back</b>				
1 Straight	0 (0%)	2 (20%)	0 (0%)	8 (80%)
2 Bent	6 (60%)	8 (80%)	6 (60%)	2 (20%)
3 Twisted	0 (0%)	0 (0%)	0 (0%)	0 (0%)
4 Bent and Twisted	4 (40%)	0 (0%)	4 (40%)	0 (0%)
<b>Arm</b>				
1 Both Arms Below Shoulder	8 (80%)	10 (100%)	8 (80%)	10 (100%)
2 One Arm at or Above Shoulder Level	2 (20%)	0 (0%)	2 (20%)	0 (0%)
3 Both Arms at or Above Shoulder Level	0 (0%)	0 (0%)	0 (0%)	0 (0%)
<b>Leg</b>				
1 Sitting	0 (0%)	0 (0%)	0 (0%)	0 (0%)
2 Standing on Two Straight Legs	4 (40%)	4 (40%)	6 (60%)	4 (40%)
3 Standing on One Straight Leg	0 (0%)	0 (0%)	0 (0%)	0 (0%)
4 Standing or Squatting on Two Bent Legs	6 (60%)	0 (0%)	4 (40%)	0 (0%)
5 Standing or Squatting on One Bent Leg	0 (0%)	0 (0%)	0 (0%)	0 (0%)
6 Kneeling	0 (0%)	0 (0%)	0 (0%)	0 (0%)
7 Walking	0 (0%)	6 (60%)	0 (0%)	6 (60%)
<b>Load</b>				
1 < than 10 Kgs (22 lbs)	0 (0%)	0 (0%)	10 (100%)	10 (100%)
2 Between 10-20 Kgs (22-44 lbs)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
3 > than 20 Kgs (44 lbs)	3 (100%)	3 (100%)	0 (0%)	0 (0%)

The participants working postures while performing the routine outdoor activities and maintenance related to the battery were studied, and a code number is given to each posture using the posture coding sheet. The posture code sheet is adopted from K. Pandey & Vats, 2012. The position of the back, upper limbs, i.e., arms and lower

limbs, i.e., legs, as well as a load used in performing activities, were considered for posture evaluation.

Table 3.22. Description of postures adopted by majority of respondents.

OWAS Derived Activity Table				
Component	Conventional SPVHS Design		Proposed SPVHS Design	
	Task 1	Task 2	Task 1	Task 2
Back	2	2	2	1
Arm	1	1	1	1
Leg	4	7	2	7
Load	3	3	1	1

- 1. Conventional System** Posture adopted by the majority of respondents for task 1 were bent back, both arms below shoulder, standing and squatting on two bent legs and more than 20 kgs of load for lead-acid batteries. Furthermore, for task 2 posture adopted by the majority of respondents was walking legs while the rest of the components for back, arm, and load were the same as task 1.
- 2. Proposed System** Posture adopted by the majority of respondents for task 1 was bent back, both arms below shoulder, standing on two straight legs and less than 10 kgs of load for lead-acid batteries. Furthermore, for task 2 posture adopted by the majority of respondents was straight back and walking legs while the rest of the components for arm and load were the same as task 1.

The comparison of OWAS results of two designs reveals that the proposed design does not require any change in design. However, for a conventional design of the solar home system, corrective action required as soon as possible for both task 1 and 2 related to storage. Hence, the proposed design reported more effective than the conventional design for ease of carrying.

Furthermore, to understand the perceived protection, safety, and effort of the newly developed SPVHS prototype and the conventional SPVHS, a questionnaire study has been administered to 41 users in the villages, as seen in table 2.1. The study questionnaire was rated on a 5-point Likert scale, taking into account protection, safety, and effort, as shown in appendix 4, question number 2a till 2e. The result has analyzed using a paired comparison between conventional and proposed design for subjective evaluation of parameters like safety, protection, and effort using the non-parametric Wilcoxon test.

The Wilcoxon test conducted for the paired significance of 0.05. The study observes a significant difference in comparing the safety ( $Z=5.00$ ,  $p=0.001$ ) due to exposure of the system to potential dangers while in use (electrical, chemical, and physical), as seen in table 3.23. Besides, there observes a significant difference in protection ( $Z=5.06$ ,  $p=0.001$ ) while the use of the system in unsafe conditions and overall effort ( $Z=4.81$ ,  $p= 0.001$ ) to accomplish a task (carrying of the storage module, and installation of the system). Also, a significant difference ( $Z=5.00$ ,  $p= 0.001$ ) in perceived comfort for the workstation observed due to the use of proposed design.

Table 3.23. Paired sample evaluation for safety, protection, overall effort and perceived comfort.

Paired Sample Wilcoxon Test					
Variable	Mean Rank		Z	p-value	Sig
	Conventional	Proposed			
Safety	0.00	16.00	5.00	0.001	***
Protection	0.00	16.50	5.06	0.001	***
Overall Effort	0.00	15.00	4.81	0.001	***
Perceived Comfort	0.00	15.50	5.00	0.001	***

\*\*\* represents two-tailed significance at  $p \leq 0.001$

The comparison of the usability assessment discussed next.

### 3.9 Usability Evaluation for Proposed System Design

The usability evaluation was done for the conventional and proposed system, using the system usability scale and technology adoption model. The System Usability Scale (Brooke, 1996) has become acceptable for subjective usability assessments. The System Usability Scale (SUS) questionnaire modified from Bangor, Kortum & Miller, 2008; Lewis, 2018, and adapted to the context of the present study. The TAM questionnaire adapted from Venkatesh, & Davis, 2016; Sauro, & Lewis, 2012, for the technology adoption assessment.

#### 3.9.1 System Usability Scale based Comparative Evaluation

The System Usability Scale (SUS) is based on 10 items scored on a 5-point scale. The odd-numbered items have a positive tone, while even-numbered items are negatively toned. The score input is the scale position minus 1 ( $x_i-1$ ) for positively worded items

(odd numbers). The score input is 5 minus the scale position (5-xi) for negatively worded items (even numbers). To get the general SUS score, multiply the sum of the item score contributions by 2.5. Final SUS results may vary from 0-100, where higher scores imply improved usability for the product.

Products with higher SUS scores were regarded as acceptable in between 70 to the 80. Superior products have a score of more than 90. Products below the SUS score of 70 should need attention for usability analysis. Products with a score below 50 are considered unacceptable. Figure 3.30 denotes the acceptance score, quartile ranges, and the adjective rating scale.

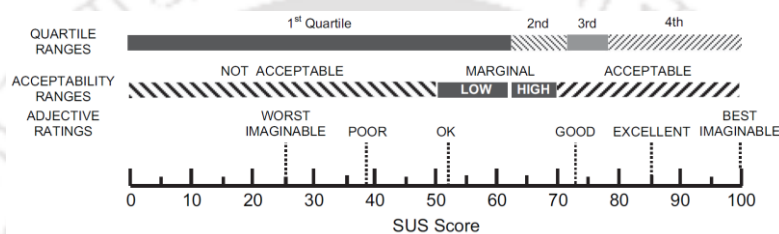


Fig 3.30 Comparison of mean System Usability Scale (SUS) scores by quartile, adjective ratings, and overall SUS acceptability score. (Bangor, A., Kortum, P. T., & Miller, J. T. (2008))



Fig 3.31 User interactions for SUS and TAM based usability evaluation conducted with users who indicated willing to adopt such systems in future and have volunteered for the study.

A comparative study conducted between conventional and proposed solar photovoltaic home systems for usability assessment (fig 3.31). Data was collected using the 5-point System Usability Scale (SUS). Considering the limitation of resources and remote area location, a sample size of 41 users (N=41) is achieved. The study made in Bhagunmari, Sikari-Chapari, and Gohpur villages in Majuli and Sonitpur districts of Assam using selective random sampling. Respondents were shortlisted

based on previous experience of a minimum of two years of using SPVHS. Data was collected administering the standard SUS questionnaire as given in appendix 4, question number 1a till 1j, adopted from Lewis, J. R., 2018, and modified in the context of the study. The mean SUS score for conventional SPVHS was 30.21 (SD=5.37), with a median value of 30 and range from 0-100. The mean SUS score was reported 75.40 (SD=6.51) for proposed SPVHS with a median value of 77.5 and a range of 0-100. Furthermore, concerning the SUS scale (fig 3.30), the SUS score (30.21) for conventional SPVHS was found unacceptable and poor, while in the case of proposed SPVHS reported SUS score (75.40) found acceptable and good.

Table 3.24 Summary of System Usability Scores

Summary for SUS Score		
	Conventional SPVHS	Proposed SPVHS
N	41	41
Mean	30.2	75.4
Median	30	77.5
SD	5.38	6.51
Range	0-100	0-100

The results for the proposed solar photovoltaic home system reported significance in terms of its usability. Table 3.24 summarizes the SUS data, as reported during the study. Besides, during field testing, the average installation time for the complete setup of proposed SPVHS found to be 2.75 minutes while the installation time (to complete wiring diagram for PV module, charge controller, storage, and luminaire) in case of the conventional system was 14.30 minutes. Due to plug-n-play, installation time reduced in the proposed design; also, about 74.6% of users during the trial strongly agreed that it facilitated ease of operation. The study also reported that 82.36% of users strongly agreed that discrete design enabled outdoor and indoor activities, related to rural lifestyle for the studied region. Besides, the majority of users (70.54%) agreed that hot-swapping and hybrid charging was tremendously helpful and facilitated PUE in the rural context. Furthermore, user acceptance for proposed and conventional SPVHS assessed using technology acceptance.

### 3.9.2 Technology Acceptance Model Evaluation

The Technology Acceptance Model (TAM) suggests that perceived usefulness and perceived ease of use are the primary factors, contributing to the user's intention to

use technology. In the TAM, perceived usefulness is the level to which an individual believes technology encourages work efficiency, and perceived ease of use is the level to which an individual thinks it is effortless to use the technology. TAM has become a valid model for the assessment of customer acceptance. Adequate knowledge of perceived usefulness indicators would enable us to design interventions that would enhance customers' acceptance and use of new products. TAM was conducted to evaluate user acceptance for SPVHS design intervention concerning conventional SPVHS for a total sample size of 41 users. Five-point Likert scale used for TAM evaluation. Data was collected administering standard TAM questionnaire adapted from Venkatesh, & Davis, 2016; Sauro, & Lewis, 2012, as given in appendix 5, question number 1a till 1j, modified in the context of the study.

### 3.9.2.1 Descriptive Results

For the TAM evaluation of conventional SPVHS, the mean value for Intention to use was 5.38 (SD=1.09); the mean value for perceived ease of use was 9.0 (SD=1.19) while the mean value for perceived usefulness found 9.35 (SD=2.34). For TAM evaluation for proposed SPVHS the mean value for Intention to use was 8.39 (SD=0.920), the mean value for perceived ease of use was 16.91 (SD=1.73), the mean value for perceived usefulness found 17.81 (SD=1.76). Overall mean values for TAM items in case of proposed SPVHS found higher than conventional SPVHS, as seen in table 3.25. TAM items include Intention to use (IU), Perceived ease of use (PEW), and Perceived usefulness (PU).

Table 3.25 TAM descriptive values

	Conventional SPVHS		Proposed SPVHS	
	Mean	SD	Mean	SD
IU	5.38	1.09	8.39	0.92
PEW	9	1.19	16.91	1.73
PU	9.35	2.34	17.81	1.76

### 3.9.2.2 Paired T-Test Evaluation

Non-parametric paired t-test performed to the observed significant difference between TAM items of two systems. Wilcoxon ranking test conducted for a paired significance level of 0.05. The high significant difference observed for the intention to use between conventional and proposed SPVHS ( $p \leq 0.001$ ,  $Z=5.74$ ), perceived ease of use ( $p \leq 0.001$ ,  $Z=5.78$ ) and perceived usefulness ( $p \leq 0.001$ ,  $Z=5.79$ ), respectively. It

depicts that there was a significant difference in user acceptance for proposed SPVHS design when compared with convention SPVHS.

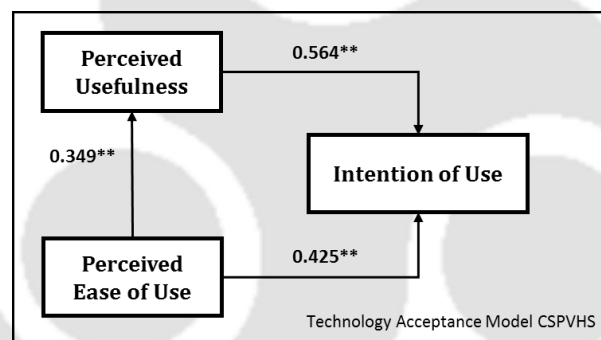
### 3.9.2.3 TAM Correlation

The non-parametric Kendell's tau-b test ( $T_{\beta}$ ) used for correlation study of Intention to use, Perceived ease of use, and Perceived usefulness between two systems. Correlation values for the Technology acceptance model shown in table 3.26.

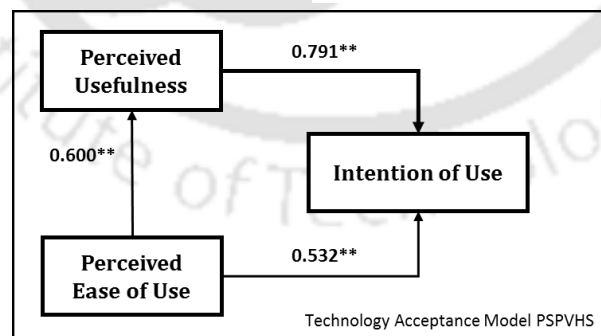
Table 3.26 TAM Correlation values

	Conventional SPVHS		Proposed SPVHS	
	$T_{\beta}$	p	$T_{\beta}$	p
IU-PU	0.564	$p \leq 0.001$	0.791	$p \leq 0.001$
IU-PEU	0.425	$p \leq 0.001$	0.532	$p \leq 0.001$
PU-PEU	0.349	$p \leq 0.001$	0.600	$p \leq 0.001$

\*IU-Intention to Use  
 PU-Perceived Usefulness  
 PEU-Perceived Ease of Use



a)



b)

Fig 3.32 Technology acceptance model correlation results a) for conventional SPVHS and b) for proposed SPVHS. Note \*\*  $p \leq 0.001$

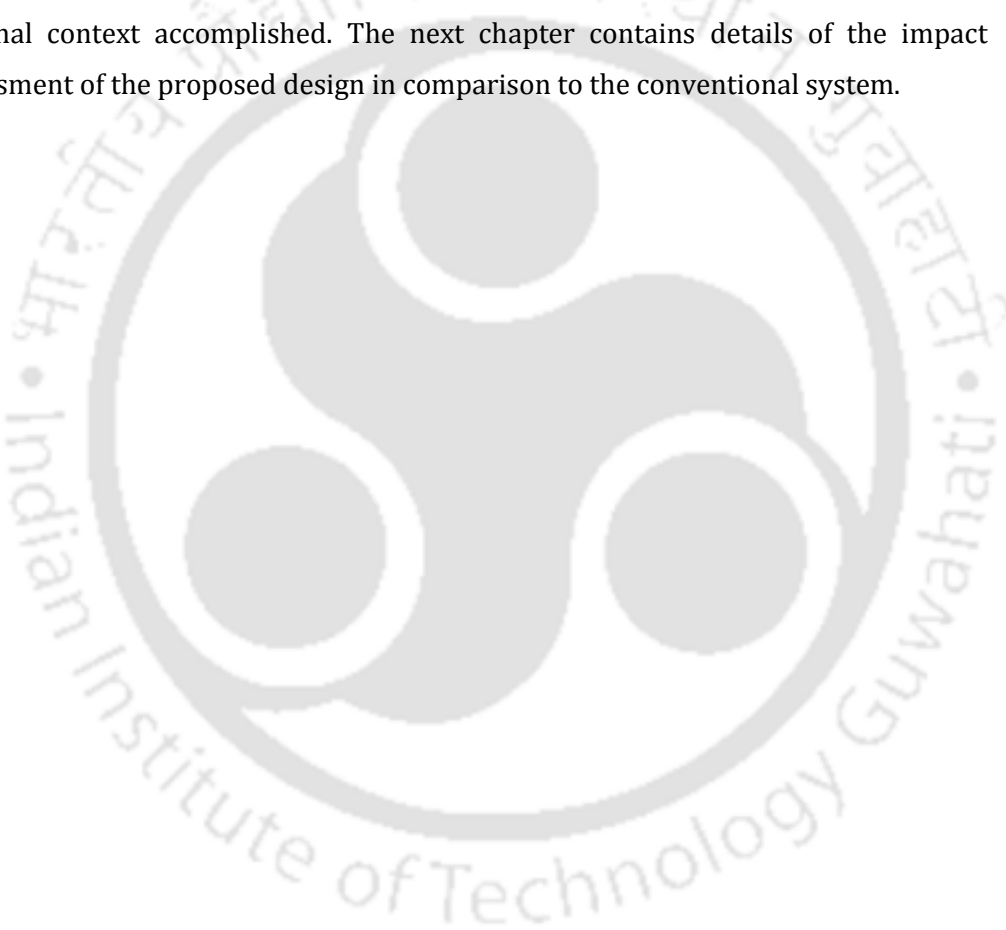
In the TAM, perceived usefulness (PU) is the extent to which a person believes technology will enhance job performance, and perceived ease of use (PEU) is the extent to which a person believes that using the technology will be effortless. TAM has become a robust model for predicting user acceptance.

TAM results would enable us to design, interventions that would increase user acceptance and usage of new systems. Actual use of technology is affected by the intention to use (IU), which itself affected by the perceived usefulness and usability of the technology.

The study reported that for the proposed photovoltaic system, perceived usefulness (0.791\*\*) was a strong determinant for intention of use. It facilitated user acceptance for design intervention when compared with perceived ease of use (0.532\*\*). The outcome indicated that the user's intention of use for the proposed design was acceptable. Also, study reported significant correlation (0.600\*\*) between perceived usefulness and perceived ease of use. From results, it was evident that significant correlation observed between IU-PU, IU-PEU, and PU-PEU in the case of both the systems. However, the correlation values for the proposed SPVHS found higher and more significant as compared to conventional SPVHS (fig 3.32). It depicts that user acceptance was comparatively higher in the case of the proposed off-grid home system. It was observed that 72.68% of users indicated a willingness to adopt the proposed design of the off-grid photovoltaic system compared to the conventional system.

### 3.10 Summary

System architecture and design concepts were shortlisted using the rigorous method for multi-criteria decision-making to avoid the scope of any error in decision-making. The concept for the discrete design was shortlisted using Fuzzy TOPSIS. Furthermore, testing of alpha prototype indicated coherence with the rural lifestyle. In consideration of the above, context-specific hardware development was undertaken to test a high-fidelity prototype for its efficacy. Evaluation of human factors and usability found significant for proposed SPVHS design. Thus, research objective three of the design and development of a discrete off-grid photovoltaic home system in a regional context accomplished. The next chapter contains details of the impact assessment of the proposed design in comparison to the conventional system.



# Chapter 4

## Design Evaluation of Discrete Photovoltaic System: Results and Analysis

**Chapter Four** involves the experimental field trials of the proposed off-grid photovoltaic system with the conventional one. The chapter includes the theory of change based evaluation for the proposed intervention in a rural lifestyle context. Both qualitative and quantitative analysis has been adopted to interpret the impact of proposed design under given field conditions. The evaluation witnessed productive use of energy specific to rural household-enterprise and energy exchange between households as an outcome of design intervention.

## **4.0 Introduction**

Productive use of energy is assumed to realize usefulness (Best, 2016), leading to a positive impact on beneficiaries' lifestyle (Best, 2018; Mayer-Trasch, 2013). The high expectation for the beneficial impact, have negligible evidence (Mayer-Trasch, 2013), which needs to be examined further.

Since small-scale photovoltaic applications indicate potential to rural support communities (Diouf & Pote, 2013), so it is appropriate to evaluate systematically, how intervention encourages productive use of energy. The present study aims to address this question and, by doing so, to contribute to reinforcing evidence of the role of design intervention to facilitate PUE and how it can contribute towards achieving rural lifestyle impact in the regional context.

### **4.1 Research Objectives for Study**

Consequently, the research question attempt to answer are; whether and how design intervention results in the productive use of energy; and whether such intervention contributes to gaining impact on rural mode of life; concerning above, the detailed research objectives are (a) to identify impact pathways for the productive use of energy and (b) to evaluate linkages, assumptions with concluded impact pathways, thereby (c) to validate and reinforce evidence regarding the anticipated effect of design intervention beyond merely a provision of providing energy access. For the reasons as mentioned above, the proposed design needs to be formalized through field trial, investigating rural lifestyle benefits due to design intervention.

### **4.2 Localized Context of Solar Photovoltaic Energy**

The impact pathways of ToC indicates the scope of peer-to-peer energy exchange for design intervention. The study observed the peer-to-peer exchange of energy between two households as 'mutual.' Mutual energy exchange describes a social and personal transaction of energy between an energy-donor or giver and energy-receiver. Mutuality refers to people's capability to associate and formulate symbiotic relations with each other. By engaging in an energy transaction, two householders, form a mutual exchange of energy. The study reported two types of energy exchange, as 1) mutual energy sharing and 2) mutual energy trading. Reciprocal sharing of

energy is a social and personal exchange of energy between energy-donor and energy-receiver to engage on a non-monetary basis by taking the social relationship into account. Mutual energy trading, on the other hand, is a reciprocation of energy where an energy-donor and energy-receiver engage in return for monetary benefits. Compared to energy trading, which functions in a commercial domain, mutual energy trading differs from energy trading as it is involved in the respective sphere of the home and community.

In the recent literature on energy, 'mutual energy trading' is widely regarded as an ingenious approach to encourage and keenly involve households towards off-grid energy systems (Camarinha-Matos, 2016b; Ilic, Da Silva, Karnouskos, & Griesemer, 2012b; Rathnayaka, Potdar, Hussain, & Dillon, 2011b). Trading of energy is acknowledged when a family sells (or purchases) energy generated in a localized context. Energy scholars foresee such energy systems to become more social, with households playing a prominent role in generating and distributing local energy (Bellekom, Arentsen, & van Gorkum, 2016; Parag & Sovacool, 2016; Saad et al., 2016; Zhou, Yang, & Shao, 2016). Future energy scenarios will allow households to exchange locally produced energy (Parag & Sovacool, 2016; Saad et al., 2016; Van Der Schoor et al., 2016). The above scenario offers a reasonable scope for design intervention, to take into account the involvement with stakeholders for productive use of energy in the local context. Definition of "productive use of energy" been adopted from Kapadia (Kapadia, 2004) as "utilization of both electric and non-electric energy for activities that enhance income, human productivity, and welfare." As design and technology lacked in recognizing such emerging needs of rural society, it leads to quite limited success for the majority of attempts for photovoltaic energy interventions in northeast India (Barman et al., 2017).

### **4.3 Background: Discrete Design for Productive Energy Usage**

In context to the rural engagement in a regional context, energy primarily needed to meet shortly to medium duration, elementary needs of users. Also, due to the poor conventional grid network in the northeast region, the natural pattern of energy usage, as witnessed during the study, encourages the local energy transaction among rural households for monetary and non-monetary purposes, given deprived socio-economic background. Concerning the above, the study witnessed local vendors

selling fruits, vegetables, and fish used the smart power modules of the proposed off-grid photovoltaic system to fulfill short duration, primary energy needs. In addition, the availability of energy was critical to sustain household enterprises prevalent across many parts of the NER; that as handloom weaved mekhla-chaddar, bamboo crafts, pickle, and handmade incense-stick making. Field evaluation reported the proposed design to be suitable to fulfill specific rural lifestyle needs, as seen in fig 4.1.

Many researchers have indicated that in the context of energy research for developing countries, its social influence on rural communities is under-represented in the energy literature (Sovacool, 2014; Hancock, 2015; Cloke et al., 2017). In addition to techno-economic understanding, many scholars in energy studies stress the need for energy research to explore its social dimension (Delina & Janetos, 2018; Sovacool, 2014; Ulsrud et al., 2015), in particular, peer-to-peer energy exchange. Ruotsalainen et al. (Ruotsalainen, Karjalainen, Child & Heinonen, 2017) argued that decentralized energy systems should be approached in the broader social context to enhance the productive use of energy.

Concerning the above, the intervention was submitted as an antecedent to investigate users' engagement with it. The outcome recorded through the ToC logic model resulted in the assumption that the proposed design assists in peer-to-peer energy exchange and facilitates the productivity of the rural household enterprise, which is precisely the presumed causal relationships lacking evidence and needs to be verified. There are also opportunities, as observed in the literature, about investigating the positive impact of productive use initiated by promoting the decentralized energy. However, the actual evidence of such an impact is quite limited. (Mayer-Trasch et al., 2013). For the reasons mentioned above, it was desirable to investigate the effect of discrete design to enable rural productive usage. The Theory of Change (ToC) framework was used for design evaluation, as discussed in detail in the succeeding sections.



a)



b)



c)

Fig 4.1 Productive use of proposed SPVHS design as observed during field study;  
a) Local energy trading, by means of charging of mobile phone and solar lamp b) use in rural household enterprise, handloom weaved mekhla-chadder and c) for making handmade incense sticks

#### 4.4 Study Area and User Demographics

The total of seven villages in the district of Sonitpur and Majuli (table 4.1) in the state of Assam, India at the longitude from 89.42 ° E to 96.0 ° E and the latitude from 24.8 ° N to 28.2 ° N studied for ToC based assessment of the proposed design intervention. Electricity consumption per person is modest 314 kWh in Assam, whereas the nationwide average is 1010 kWh (CEA, 2016). The state of Assam has 803 un-electrified villages, while the north-east region has 4,169 (as of August 2016) out of a total of 19,706 un-electrified villages in India (GOI, 2016). About 93% of the state villages have electrified formally, but only 34.22% of rural households have access to electrical energy (as of September 2016) as per ADDCL data.

Most of the off-grid photovoltaic systems installed in these villages fulfill the primary household energy requirement, as other sources of decentralized energy are not found viable in the northeast region (Palit, 2013). Considering the majority of these villages are situated remote locations, having low and dispersed population density makes photovoltaic interventions economically feasible. This study was carried out in Sonitpur and Majuli districts of Assam, the details of which presented in table 4.1. The Sonitpur district demography is a semi-homogeneous since several linguistic, religious and ethnic communities reside here. Besides, the Majuli district of Assam is the largest river island in the world and first island district of the country, having almost no access to the national grid due to its challenging geography. Of the total sample studied (n=194), Agriculture (50.51%) is the main livelihood activity in the surveyed households, followed by daily wage labour (12.88%) and self-employment (7.73%) in local places. While a smaller percentage of respondents employed with state government (6.18%). Besides, about 18.04% of participants were involved in small rural enterprise activities as self-employed, while the remaining 4.66% were involved in different activities. The reported average monthly family income for 20.61% of respondents was below Rs 2,500/- while for 29.89% of respondents, monthly family income was between Rs 2,501-5000. For the majority of respondents (38.65%), monthly family income was Rs 5,001-7,000/-. While relatively smaller (10.85%) respondents had a family monthly income above Rs 10,000. The reported average monthly family income includes an overall monthly salary of all the household members.

Table 4.1 Details of the area of field study for the proposed design validation

District	District Literacy Rate	Latitude and Longitude	Village name	Electrification Status
Sonitpur	67.34%	26.67 ° N, 92.85° E	Bherveri Pathar	Un-electrified
			Gohpur	Electrified
			Barigaon	Electrified
			Gopalpur	Electrified
Majuli	78.56%	27.00 ° N, 94.22° E	Sikari Chapari	Un-electrified
			Bhagunmari	Un-electrified
			Ban Fukwa	Un-electrified

\* District literacy rate as per 2011 census

## 4.5 Material and Methods

For the study, the villages were recognized in the chosen districts from the data provided by AEDA (AEDA, 2016). The two representative districts of Assam, where vital numbers of photovoltaic systems have already installed and represent distinct socio-economic characteristics, have chosen. From these two short-listed districts, villages were chosen based on selective random sampling. Finally, households so have chosen had inclusion criteria that the conventional photovoltaic system was installed two years before the study period to guarantee that the system is adequately old to evaluate actual field performance. The independent sample study was made based on a sample size of a total of 194 participants for non-core benefits, including household enterprise productivity (n=120), and mutual energy trading (n=74), respectively. The sample size for the survey (Bartlett et al., 2001)<sup>10</sup> calculated with a confidence level of 90% and ± 5% margin of error. The hypothesis tested for household-enterprise work-productivity, and peer-to-peer energy trading for monetary benefits, also posit was validated for observed core benefits like mutual energy sharing and lending having primarily non-monetary benefits. Intervention impact evaluated by studying the difference between proposed and conventional off-grid photovoltaic systems. Keeping in view, the modest sample size and nature of variables, it was anticipated

<sup>10</sup> Sample size (n) is calculated using following formulae;

$$n = \frac{z^2 \times \hat{p}(1-\hat{p})}{\epsilon^2}$$

z is the z score,  $\epsilon$  is the margin of error,  $\hat{p}$  is the population proportion, N is population size  
For finite population corrected sample size( $n'$ ) becomes;

$$n' = \frac{n}{1 + \frac{z^2 \times \hat{p}(1-\hat{p})}{\epsilon^2 N}}$$

that the requirement for normality might not be fulfilled for the study. Mann-Whitney U test applied to assess significant differences for ordinal considering two independent samples as existing and proposed SPVHS design. Statistical significance set at  $p \leq 0.05$  for each case. A similar method considered in Singh, Meena, & Chaudhary, 2019. Selected families briefed on the details of the experiment. Before testing, the demonstration was given to users regarding proposed design necessary knowhow about system installation and operation, as seen in fig 4.2.



Fig 4.2 Field demonstrating of a) Installation of proposed SPVHS design and b) giving basic operational know-how to user about handling of prototype for daily usage

The information for work productivity and mutual trading and lending recorded on a scale measure, besides perceived user benefits used five-point Likert scale — data

analysis involved both qualitative and quantitative methods using descriptive and inferential statistics. In literature, a similar type of energy studies reported using ethnographic techniques, such as participant observation. (Musante, K., & DeWalt, B. R. 2010), interviews and conversations (Bernard, H. R. 2017), and field-notes. The study presented based on (a) the empirical findings from design intervention using the theory of change framework, (b) the data which includes an in-depth analysis of proposed design, and (c) the relevant literature review. The study conducted for about one and a half years, with a total of ten prototypes installed at various study locations on a rotational basis. The pattern of energy usage, along with impact pathways, is studied for design intervention applying the ToC framework for design evaluation. The study area selected represents typical rural characteristics of Assam away from urban facilities and has unreliable and poor grid connectivity. The objective of the 'design intervention' was to investigate the productive use of energy in the context of peer-to-peer energy exchange and rural household enterprise, applying the theory of change.

#### **4.6 Theory of Change based Design Evaluation**

The study applies a ToC-based evaluation approach to look into the causality connections observed in the field due to proposed design intervention. The outcome resulted in peer-to-peer energy exchange and household enterprise productivity in the rural context of the studied area. Therefore, it is crucial to analyze how design intervention supports productive use and whether it can be translated into a positive impact on the rural lifestyle under localized settings. In the context of the above, there is minimal evidence available on the causality chain as a whole, so the investigation has been made from the design intervention point of view. Besides, energy literature also indicated quite limited evidence in the case of the prolific use of energy (Terrapon-Pfaff et al., 2018).

##### **4.6.1 Theory of Change Methodology**

To address how the discrete design of the photovoltaic home system results in productive usage, and contribute towards attaining a positive outcome, the causal relationship between the observed changes and the intervention is crucial to establish. For establishing causality, the study implements an impact evaluation

based on the theory of change (ToC), which focuses on the question "how" design intervention caused desired outcomes by examining the chain of causation from inputs to impact (Befani & Mayne, 2014; Crosby & Lau, 2005).

The applied contribution assessment strategy developed by Mayne (Mayne, 2012) is a systematic evaluation approach for assessing and reporting data on impact. Five steps implemented for contribution analysis shown in figure 4.3. It includes setting cause and effect, develops theory framework, to gather evidence for assumption, to assess contribution claim, and final recommendation. The researcher performed an empirical analysis following these steps and systematically linked the outcome to design intervention — the Toc framework widely used as an instrument for designing, planning, and evaluating interventions. ToC logic model explicitly illustrates the causal pathways between input, outputs, outcomes, and objectives(Lovely Dhillon & Sara Vaca, 2018). ToC helps to define the assumption underlying the hypothesis and monitor the outcome predicted to achieve its objective (Weiss, 1995). It can assist in understanding the intervention and its contribution towards creating an impact during design evaluation.

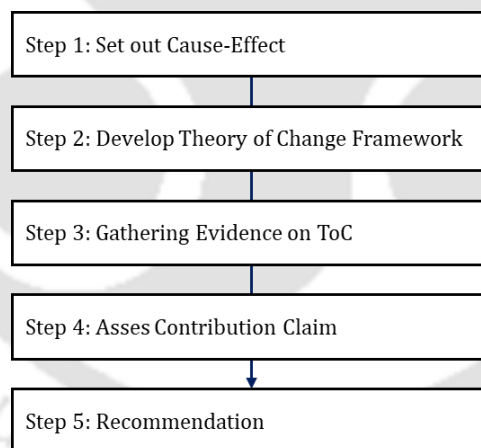


Fig 4.3 Methodical approach to the contribution analysis

It supports a model for logical intervention that shows how outputs are expected to result in an impact through empirical verification, considering the given evidence and other influencing factors (Mayne, 2012; Terrapon-Pfaff et al., 2018). The ToC makes the design more reliable by examining its internal coherence concerning its expected outcome. Using a theory for design evaluation provide valuable information about how the intervention will contribute to the change and how and why it is expected to

function. In general, ToC framework consists of four parts; Input as what has introduced, Output as what user will get, Outcome as what user does after receiving the intervention, and finally, what was the Impact of intervention. The above results in the contribution claim, as discussed next.

#### **4.6.2 Establishing Contribution Claim of ToC**

Concerning the present study, the contribution claim postulates that access to discrete photovoltaic home system contributes to rural lifestyle benefits. These benefits are in the form of a) value creation or facilitating additional income due to peer-to-peer energy exchange and b) improving rural household enterprise work productivity. For the validation of the contribution claim, the first step is to create the theory of change (ToC) framework, presenting the relationships of cause-effect between inputs, outputs, outcome, and impact, as seen in Fig. 4.4. The proposed design for the off-grid photovoltaic system was intervened in rural households to verify contribution claims. The intervention explains what the stakeholder gets as input to achieve the desired outcome. Attributes like hybrid-charging facility, discrete smart battery modules, and multi-device charging and lighting facilities received as physical inputs, as in what user access due to proposed design intervention.

Once the intervention implemented, ToC allowed the researcher to know the short-term, intermediate, or long-term outcomes expected to be triggered by output. The output is what the user gets. After input preconditions met, access to the discrete design of off-grid photovoltaic home system resulted in multiple outputs; a) required SPVM size and wattage got reduced due to MPPT pulse-charging resulting in reducing balance of system cost to user b) mobile phone, solar lamps, and Li-ion battery banks were charged and used for lighting and relevant, productive purposes. c) an efficient battery charging achieved due to hybrid charging support, and d) use of low weight high endurance Li-ion and VRLA batteries enhanced the portability of the system. It resulted in lower maintenance costs of system e); furthermore, hot-swapping resulted in suitability for 'on-demand' access to energy. Those mentioned above set the stage for an outcome to investigate the research objective. The outcome is what the user did with the proposed design intervention. Mapping outcome establishes a specific causal link, with a clear indication of which attribute is caused by or resulted

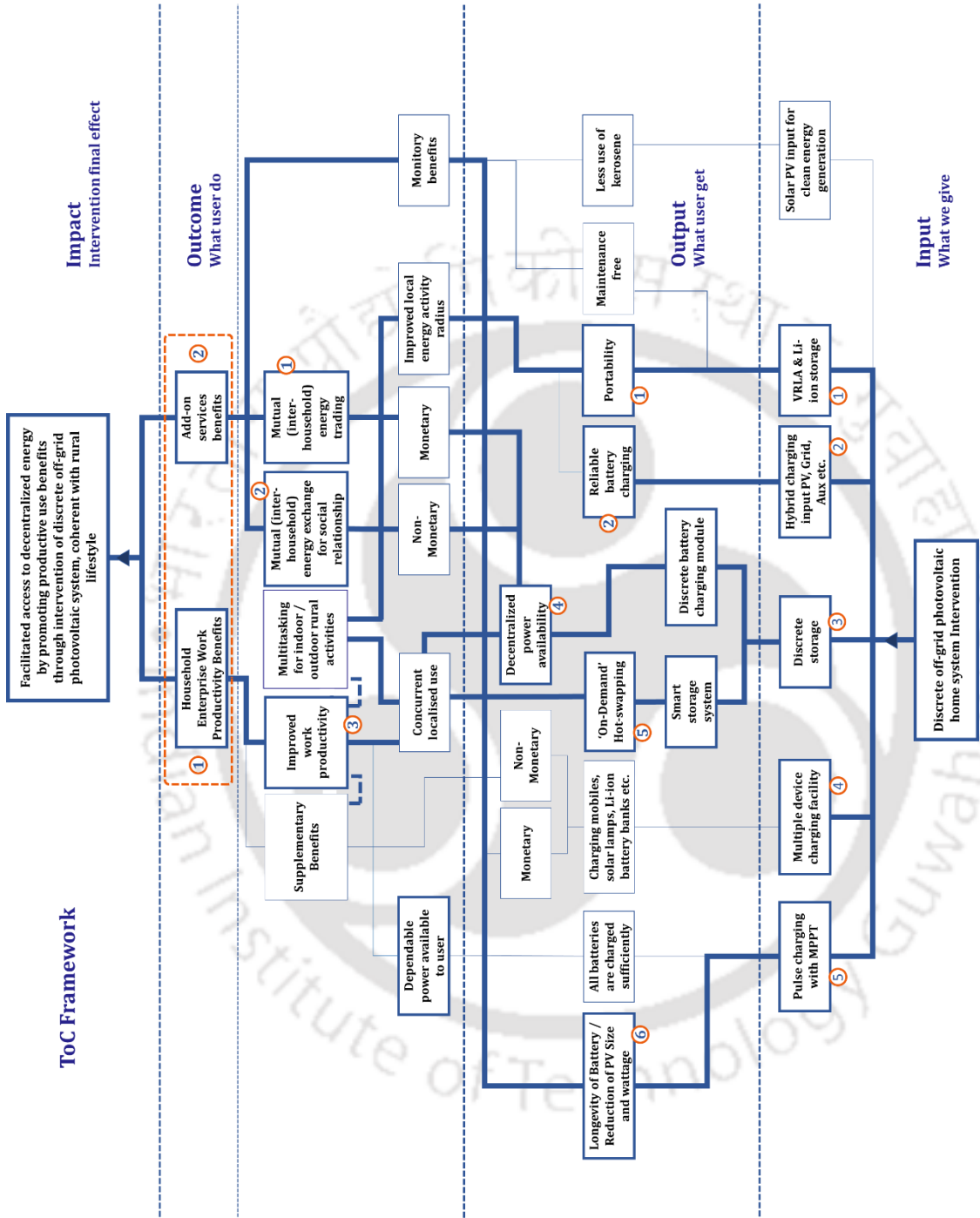


Fig 4.4: Theory of change based logic model showing impact pathways due to proposed design intervention

from which element (Lovely Dhillon & Sara Vaca, 2018) as evident in the logic model of ToC in fig 4.4. The outcome is the control variable, which is measured to evaluate intervention effectiveness. Access to the design intervention resulted in the outcome as follows; a) mutual energy trading benefits concluded due to the charging of mobile phones, solar lamps, and power banks using multi-device charging ports. b) Also, the study witnessed the lending of discrete power modules on the monetary and non-monetary basis and c) non-monetary benefits observed specific to the proposed intervention. This type of energy exchange witnessed to enable goodwill and rapport amongst rural households. d) The intervention of the proposed design resulted in enabling diversity in the type of energy transactions e) the design intervention resulted in facilitating work productivity for rural household enterprise as the study observed it in case of handloom weaved mekhla-chaddar and handmade incense sticks. The study observed that supplementary benefits due to intervention played a quintessential role in encouraging workplace comfort, which indirectly affected work productivity.

Table 4.2 Assumptions associated with the impact pathways for proposed intervention

Link Impact Pathway	Assumptions
Multitasking for indoor and outdoor rural activities is improved	Proposed design is coherent with rural mode of life
Proposed intervention improve work productivity for rural household enterprises like handmade incense sticks and handwoven mekhla chadder	Proposed design is functioning well to meet demand of productive use of energy  Time for livelihood activities should be within operable time of battery  Improved commodity production is less time-intensive <b>Extended working hours or opening time</b>
Existing productive activities are improved	Beneficiaries are motivated and able to apply skills and knowledge systematically and make use of opportunities provided
Proposed intervention resulted in non-monetary mutual energy exchange among rural household	Mutual energy sharing provide scope to promote social cohesion between households  Non-monetary exchange will help growing local energy network in rural scenario of north-east
Energy trading benefits like charging and module lending indicated pattern of localized energy usage for proposed intervention	Proposed design is appropriate and sensitive to local social conditions  Local energy trading result in add-on services  Battery module will come back to same facility for charging  Beneficiaries are capable and willing to take-up, new productive activities

The ToC impact pathways were based on certain assumptions, which must be convinced to result in rural lifestyle benefits. Assumptions were understood as circumstances necessary for the realization of causal connections. The details of the assumptions associated with the impact pathways are presented in table 4.2. The logic model developed for ToC before developing a log frame matrix to make sure that the causal relationship between input, outputs, outcomes, and objectives is well established and logical. Once the logic model clarified with input, outputs, outcomes, and objectives, the log frame matrix was developed. Details of the log-frame matrix discussed under section 4.6.4 and shown in appendix 6. The subsequent section discusses research questions, hypotheses, and posit resulted from the causal connection.

#### **4.6.3 Research Questions, Hypothesis, and Posit**

Based on an extensive review, Sovacool states, “Energy production, distribution, and consumption all have both technical and human components. Energy analysis needs to look beyond the dimensions of technology to include the social elements” and offer energy scholars to explore the scope of social dimension for energy systems (Sovacool, 2014).

The following research questions pose a prominent investigation to be carried out whether the proposed intervention contributes to achieving a positive impact on the rural mode of life in the regional context of northeast India. In order to validate the causal relationship between the outcome and impact following research questions raised along with hypothesis and posit.

❖ **RQ3:** Can the discrete design of an off-grid photovoltaic system be suitably used to expedite rural household enterprise productivity, and to support add-on services for a cross-section of rural users towards achieving impact on rural lifestyle in a localized context?

**SubRQ1:** Does discrete design facilitate work efficiency in the context of handloom weaved mekhla chaddar and handmade incense sticks as a typical household enterprise in rural northeast India?

**SubRQ2:** Does the proposed intervention result in mutual energy trading benefits due to mobile and solar lamp charging in comparison to the conventional off-grid photovoltaic system?

**SubRQ3:** Does discrete photovoltaic home system results in inter-household energy exchange benefits like mutual energy lending and mutual energy sharing?

### **Hypothesis and Posit**

- ❖ **H<sub>1</sub> (a):** Discrete Design of the off-grid photovoltaic home system improves the household enterprise work productivity when compared to a conventional system given the rural settings of north-east India.
- ❖ **H<sub>1</sub> (b):** Discrete design for the off-grid solar photovoltaic home system has a positive impact on inter-household mutual energy trading for a cross-section of the rural prosumers in the context of rural northeast when compared with a conventional off-grid system.
- ❖ **P<sub>1</sub>:** Discrete design for off-grid solar photovoltaic home system encourages mutual energy sharing and mutual energy lending between households facilitating social cohesion, and stimulates decentralized energy distribution network in rural background.

Consequently, the research questions attempt to answer are; whether and how design intervention leads to productive use of energy; and whether such intervention contributes to a positive influence on rural mode of life in a localized context.

#### **4.6.4 Log-frame Matrix for Empirical Analysis**

The present section is responsible for the empirical findings on whether, why, and how proposed photovoltaic intervention contributes to the rural lifestyle benefits. The log frame outlines the primary indicators that are used to measure the outcome and assumptions critical for the assessment of design intervention. Logframe matrix has key attributes described as research goal and objectives, level, criteria, sub-level, indicator, measure, and assumptions. Please refer to appendix 6 for relevant details of Log frame matrix important for empirical analysis of design intervention. The research goal is what intervention will achieve finally, by fulfilling objectives. For the present study, the goal is to facilitate access to decentralized power with productive use benefits through discrete design intervention of an off-grid photovoltaic home system, coherent with the rural lifestyle. The goal of rural lifestyle benefits achieved through following ToC objectives framed as a research hypothesis, the details of

which discussed in the previous section. It summarised as; (a) proposed design intervention would encourage mutual energy trading, lending and sharing in the rural context, and (b) discrete design facilitates household enterprise work efficiency. The resulting outcome validates and strengthens the evidence concerning the PUE due to intervention. An indicator is used as a criterion to measure the effectiveness of the outcome, which is discussed in the next section. An indicator referred to as a measurable and observable phenomenon furnishing the evidence of meeting the research goal effectively, as discussed in the next section.

#### 4.6.5 Operationalization of indicators to measure the outcome

The effectiveness of ToC depends on its ability to demonstrate progress towards achieving an outcome. Evidence of realization validates the theory and indicates an effective intervention. Indicators operationalize the outcome – and make it understandable in concrete, observable, and measurable terms (Taplin, Clark, Collins, & Colby, 2013).

For mutual energy sharing, operationalized indicators were, perceived social cohesion between households, frequency of in-kind transactions occurred per day, and social acceptance of proposed intervention. For mutual energy trading and lending, indicators were the frequency of mobile phone and a solar lamp charged per day, the amount charged per device, and overall income earned due to charging or

Table 4.3 Details of indicators as observed for proposed design evaluation

Description	Indicators	Measure
Multitasking for indoor/outdoor rural activities ; Use for various indoor and outdoor rural activities	1 Frequency of activities performed/day 2 Type of activities performed / day	Scale Scale
Rural household enterprise productivity; (in reference to) 1 Handloom weaved mekala chadder 2 Handmade incense sticks	1 Production cost per unit 2 Production time per unit 3 Number of units produced /day or / week 4 Profit Earned per month 5 Evening work hours / day	Scale Scale Scale Scale Scale
Mutual energy sharing benefits ; 1 Social Connectedness 2 In-kind exchange	1 Social cohesion among neighbours 2 Frequency of In-Kind Transactions 3 Social Acceptance for Design	Nominal Scale Nominal
Mutual energy trading benefits related to charging ; 1 Charging Mobile Phone 2 Charging Solar Lamp	1 Frequency of devices charged / day 2 Amount charged / device / transaction 3 Income Earned (1x2)	Scale Scale Scale
Mutual Energy Trading Benefits related to Lending ; 1 Module lending to neighbours 2 Module lending to local vegetable, fruit and fish vendors	1 Frequency of module lending / day 2 Number of hrs storage module lended 3 Willingness to pay 4 Capability to pay 5 Income Earned (1x2x3)	Scale Scale Nominal Nominal Scale

lending. Besides, willingness and capability to pay were supplementary indicators for mutual energy lending. After indicators were identified and operationalized in

measurable terms, the significance of design intervention validated through experiments. Details of the indicators for design evaluation shown in table 4.3. The non-parametric independent test was used for comparison between conventional and proposed off-grid photovoltaic systems. Particulars of the questionnaire based on indicators given in appendix 7. The following section discusses experiments overview concerning a contribution claim.

## 4.7 Study Experiments Overview

Findings and interpretation of experiments were given and discussed under section 4.7.1. Indicators for independent studies are compared for the significance between conventional and proposed design intervention. The experiment resulted in two types of benefits a) non-core-benefits (monetary), which were observed both in the conventional and proposed system, and b) core benefits (non-monetary), which are observed explicitly in case of the proposed system only. Non-core benefits like rural household enterprise work productivity and mutual energy trading formed the basis for a hypothesis. While core-benefits like mutual energy sharing and lending formed the basis for posit, as seen in figure 4.5.

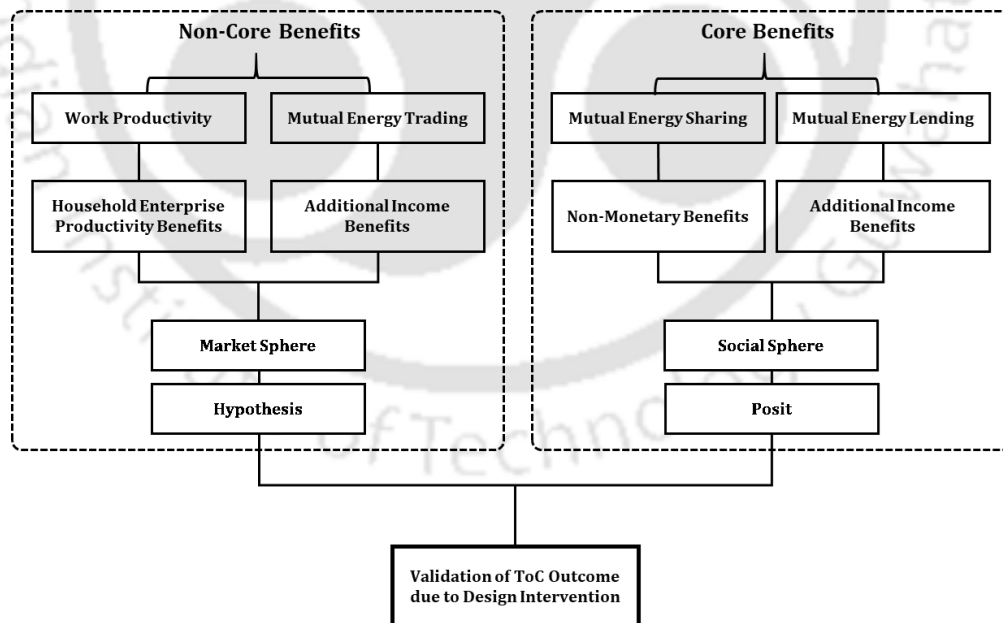


Fig 4.5 Types of benefits resulted due to experiments performed for comparative study between conventional and proposed design.

### 4.7.1 Experiment Design

In this quasi-experiment study, data of the sample subjected to a reliability test. Cronbach's alpha is measured to assess the reliability, or internal consistency, of a set of scale or test items. Higher the coefficient, the more the items have shared covariance and correctly measures the same underlying concept. The recommended minimum  $\alpha$  coefficient is 0.60. Data of the sample subjected to the Kolmogorov-Smirnov test for normality  $\geq 0.50$ . Since the data did not pass the Kolmogorov-Smirnov normality test (Appendix 8), it was subjected to a non-parametric statistical method. The final response rate was significantly high ( $> 95\%$ ) for the study. Collected data underwent Mann Whitney's 'U' test for an independent group of samples to check whether there was any significant difference between the ranked set of data. Statistical significance set at  $p \leq 0.05$ . Data analysis carried out using SPSS for Windows version 22.0. Off-grid photovoltaic home system (conventional and proposed) considered as independent variables. At the same time, production cost per unit, production time per unit, units produced per day, profit earned per month, and extended evening working hrs were considered the dependent variables for hand-woven mekhla chaddar and handmade incense sticks for rural household-enterprise work productivity experiment. The dependent variables in dominant directions between the conventional and prototype handle compared using Mann Whitney's 'U' test.

Furthermore, in context of peer-to-peer energy trading experiment independent variables remains the same as above while the frequency of mobile charging per day, frequency of solar lamp charging per day, amount charged per mobile phone for charging, amount charged per solar lamp for charging, income earned from mobile charging per day, income earned from solar lamp charging per day and overall earning per month was considered the dependent variables. The dependent variables in dominant directions between the conventional and prototype handle compared using Mann Whitney's 'U' test. On average, about one month taken per household for SPVHS prototype testing. As the time required per household was high, the modest sample size was achieved. Data was collected using a face-to-face questionnaire and semi-structured interview method. A total of ten off-grid prototypes were installed in the different field locations. All the experiments were investigated from April 2017 until October 2018 to obtain the required set of data. Assam Energy Development

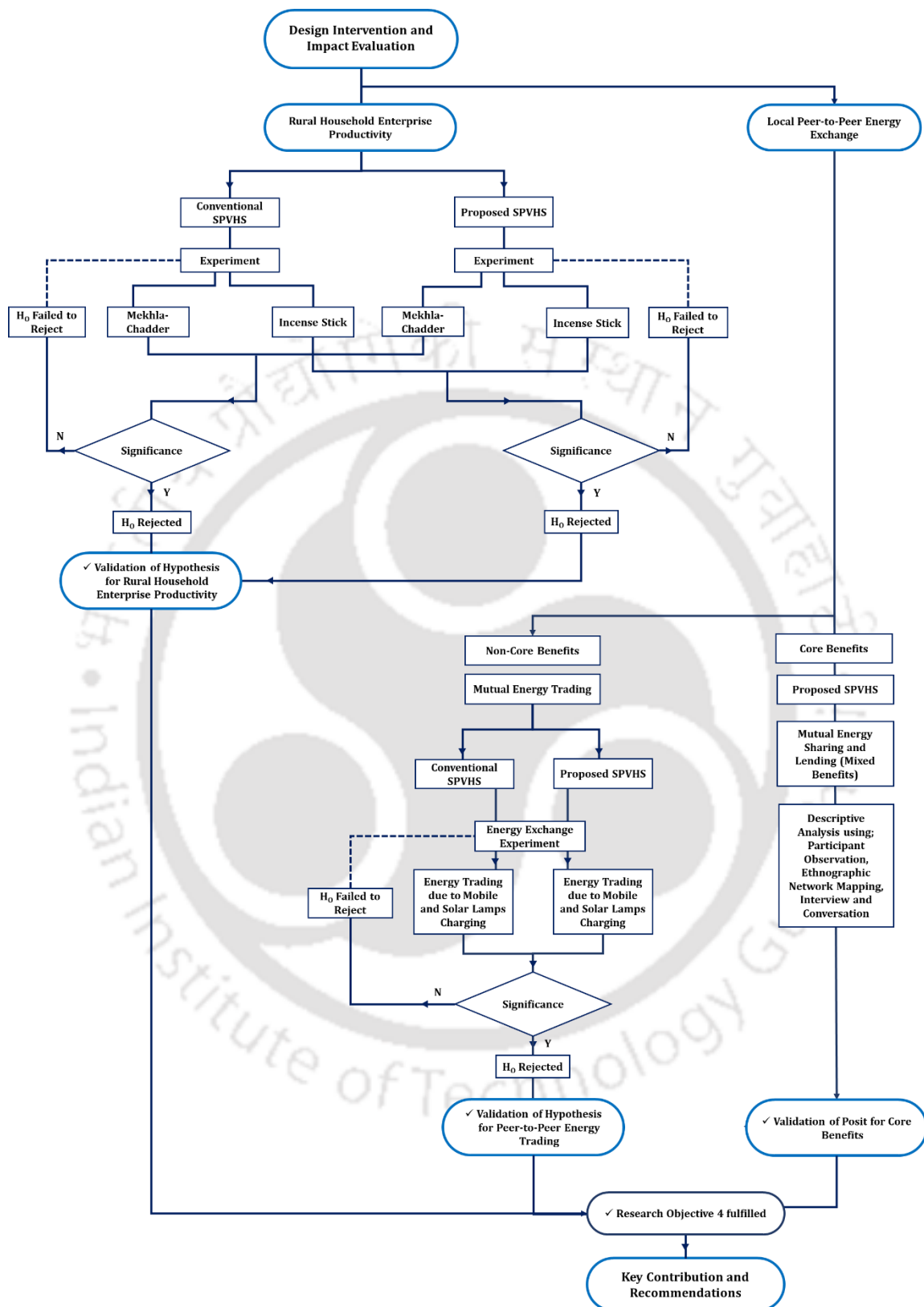


Fig 4.6 Experiment design to study impact of proposed design intervention in comparison to conventional system.

Agency (AEDA) duly sponsored all the prototypes under R&D fund, AEDA/409/201413/612. The study examines both core and non-core benefits resulted in the validation of ToC outcome due to design intervention. Flowchart of experiment design shown in fig 4.6.

#### **4.7.2 Experiment Details for Work Productivity Benefits**

Work productivity experiments conducted for handloom woven mekhla-chaddar and handmade incense sticks. The subject selected were typical of rural household enterprises for the studied area. A similar household enterprise is prevalent across many villages of Assam and other northeastern states of India. The experiment compared the result between convention and proposed solar photovoltaic home system. The indicators for work productivity referred from Kamel et al., 2002. The Outcomes of experiments discussed in the following section.

##### **4.7.2.1 Overall Work Productivity Benefits**

The findings of the overall work productivity for the rural household enterprise achieved using the following methodology.

###### **4.7.2.1.1 Methodology**

All the indicators have different units (e.g., table 4.4), so the direct aggregation of indicators was not possible. To create dimensional indices, it required data normalization. Minimum and maximum values were set in order to transform the indicators expressed in different units into a rational value. The rational value is a pure number without any unit. Normalization method directly adopted from UNDP, 2018; Baruah, 2010. The formula used for dimensional indices for normalization is as follows;

$$\text{Dimension index} = \frac{\text{actual value} - \text{minimum value}}{\text{maximum value} - \text{minimum value}}$$

Aggregation is done after the ideal normalized values were achieved both for the conventional and proposed system. The non-parametric independent test applied after that.

###### **4.7.2.1.2 Results**

Mann-Whitney U test conducted for the significance level of 0.05. Mann-Whitney U

difference in overall work productivity for Ovr<sub>al</sub>\_Mc (U=266, p=0.006) and Ovr<sub>al</sub>\_Is (U=207, p=0.001) elicit a statistically significant difference in overall work productivity for independent study of mekhla-chaddar and handmade incense sticks respectively. Ovr<sub>al</sub>\_Mc compared the overall work productivity for handloom weaved mekhla-chaddar, besides Ovr<sub>al</sub>\_Is compared the overall work productivity for handmade incense sticks between conventional and proposed design. The following section discusses the details of rural enterprise productivity explicitly in case of handmade incense sticks.

#### 4.7.2.2 Work Productivity for Independent Sample Study

The Independent Samples Mann-Whitney U test compared the means of two independent groups of handloom weaved mekhla chaddar (Case 1) and handmade incense sticks (Case 2) for conventional and proposed design to determine whether the sample means are significantly different..

##### 4.7.2.2.1 Handloom Weaved Mekhla-Chadder (Case 1)

Independent sample Mann-Whitney U test conducted for the significance level of 0.05. Test indicated that in the case of proposed SPVHS design, the difference was significant for production time per unit per week (U=324, p=0.047), the number of units produced per week (U=330, p=0.038), profit earned per month (U=294, p=0.019) and extended evening work hours (U=220, p=0.001) as compared to conventional system (table 4.4). However, the test indicated no significant difference in production cost per unit (U=388, p=0.328) between the conventional and proposed design.

Table 4.4 Mann-Whitney U test showing mean ranks for conventional and proposed system

<b>Mekhla-Chadder Independent Sample</b>					
Variable	Mean Rank		U	p-value	Sig
	Conventional	Proposed			
PCPU	28.43	32.57	388.0	0.328	NS
PTPU	34.70	26.30	324.0	0.047	*
UPW	26.50	34.50	330.0	0.038	*
PEPM	25.30	35.70	294.0	0.019	**
EEW	22.83	38.12	220.0	0.001	***

\*, \*\*, \*\*\* represents two-tailed significance at  $p \leq 0.05$ ,  $p \leq 0.01$ ,  $p \leq 0.001$ , NS stands for Non-Significant

- PCPU Production cost per unit (Rs)
- PTPU Production time per unit per week (hrs)
- UPW Units produced per week (Value)
- PEM Profit earned per month (Rs)
- EEW Extended evening working hrs (hrs)

A similar study also conducted to observe work productivity benefits in case of handmade incense sticks to verify the consistency of the results.

#### 4.7.2.2.2 Handmade Incense Sticks (Case 2)

Independent sample Mann-Whitney U test conducted for the significance level of 0.05. Test indicated that in the case of proposed SPVHS design difference was significant for production time per unit per ( $U=163.50$ ,  $p=0.001$ ), total units produced per day ( $U=261.50$ ,  $p=0.004$ ), profit earned per month ( $U=306$ ,  $p=0.032$ ) and extended evening working hours ( $U=274$ ,  $p=0.005$ ) compared to the conventional system, as seen in table 4.5. However, the test indicated no significant difference in production cost per unit ( $U=405$ ,  $p=0.440$ ) between conventional and proposed systems.

Table 4.5 Mann-Whitney U test showing mean ranks for conventional and proposed system

Handmade Incense Sticks Independent Sample					
Variable	Mean Rank		U	p-value	Sig
	Conventional	Proposed			
PCPU	29.50	31.50	405.0	0.440	NS
PTPU	40.05	20.96	163.50	0.001	***
UPD	24.22	36.78	261.50	0.004	**
PEPM	25.70	35.30	306	0.032	*
EEW	24.63	36.37	274.0	0.005	**

\*, \*\*, \*\*\* represents two-tailed significance at  $p \leq 0.05$ ,  $p \leq 0.01$ ,  $p \leq 0.001$ , while NS stands for Non-Significant

- PCPU Production cost per unit (Rs)
- PTPU Production time per unit (hrs)
- UPD Units produced per day (Value)
- PEM Profit earned per month (Rs)
- EEW Extended evening working hrs (hrs)

The study reported that due to the unreliable or no power, the time required to accomplish the given job was high, which increased the labor time and added to inefficient costing per unit. Since the photovoltaic home system provided a reliable

and continuous supply of power, therefore; the overall time to accomplish the job gets reduced along with lessened labor time; this decreased the production cost and made costing more efficient per unit. For the reasons mentioned above, the production cost per unit included as one of the indicators of work productivity. The supplementary benefits due to proposed design intervention played an imperative role in indirectly adding to the impact, as discussed next.

#### **4.7.2.3 Supplementary Benefits of Proposed Design**

During design assessment, supplementary benefits observed due to proposed intervention. The study reported usage-flexibility for the multiple-location concurrent access to decentralized power due to the discrete nature of smart storage modules. The proposed design resulted in the use of storage modules to address the requirement for various lifestyle activities like listening to regional songs, news, weather updates and mobile charging along with docking 12-volt DC fan, allowed flexibility for placement of light in the workspace, and use of luminaire in proximity to job reducing visual stress. The supplementary benefits due to improved perceived workspace comfort ( $U=4.97$ ,  $p=0.032$ ) assisted household enterprise work productivity. The study did not report aforementioned supplementary benefits in the case of a conventional off-grid photovoltaic system.

#### **4.7.2.4 Validation of Hypothesis**

**H<sub>1</sub>** (a): Discrete Design of the off-grid photovoltaic home system improves the household enterprise work productivity when compared to a conventional system given the rural settings of north-east India.

#### **Interpretation of Results**

The proposed SPVHS design elicit a statistically significant difference in overall rural household enterprise work productivity for independent study ( $U=204$ ,  $p=0.001$ ). In specific, proposed SPVHS design elicit a statistically significant difference in work productivity for handwoven mekhla-chaddar and handmade incense sticks, as discussed in section 4.7.1.1. Thus, the null hypothesis of equal difference rejected, and it concluded that there was a significant difference in work productivity for the rural household enterprise due to proposed design intervention.

### 4.7.3 Experiment Details for Mutual Energy Trading Benefits

Findings and interpretation of experiments related to mutual energy trading (MuET) discussed in section 4.7.3.2. The experiment compared results between convention and proposed solar photovoltaic home system.

#### 4.7.3.1 Overall Mutual Energy Trading Benefits

In order to find overall mutual energy trading benefits, the methodology followed is the same as discussed under section 4.7.2.1.1.

##### 4.7.3.1.1 Results

Mann-Whitney U test conducted for the significance level of 0.05. Mann-Whitney U - test indicated that proposed design intervention elicit a statistically significant difference in overall mutual energy trading benefits as MuET\_Ovrall\_Indep (U=501, p=0.001) when compared to a conventional photovoltaic system. The following section discusses the details of independent study for mutual energy trading benefits.

#### 4.7.3.2 MuET for Independent Sample Study

The Independent Samples Mann-Whitney U test compared the means of two independent groups for conventional and proposed design in order to determine whether the associated sample means are significantly different for mutual energy trading benefits. Independent sample Mann-Whitney U test conducted for the significance of 0.05.

Table 4.6 Mann-Whitney U test showing mean ranks for conventional and proposed system

MuET Independent Sample					
Variable	Mean Rank		U	p-value	Sig
	Conventional	Proposed			
FMC	19.80	55.20	29.50	0.001	***
FSLC	37.35	37.65	679	0.949	NS
ACMP	37.11	37.89	670	0.830	NS
ACSL	37.45	37.55	682	0.979	NS
IEMC	20.95	54.05	72	0.001	***
IESLC	36.57	38.43	650	0.702	NS
OEM	29.81	50.19	215	0.001	***

\*, \*\*, \*\*\* represents two-tailed significance at  $p \leq 0.05$ ,  $p \leq 0.01$ ,  $p \leq 0.001$ , while NS stands for Non-Significant

FMC	Frequency of mobile charging per day
FSLC	Frequency of solar lamp charging per day
ACMP	Amount charged per mobile phone for charging
ACSL	Amount charged per solar lamp for charging
IEMC	Income earned from mobile charging per day
IESLC	Income earned from solar lamp charging per day
OEM	Overall earning per month

The test indicated that in the case of proposed design intervention difference was higher for a frequency of mobile charging per day ( $U=29.50$ ,  $p=0.001$ ), income earned due to mobile charging per day ( $U=72$ ,  $p=0.001$ ), and overall earning per month ( $U=215$ ,  $p=0.001$ ) as compared to conventional system (table 4.6). However, the test indicated no significant difference for the frequency of solar lamp charging per day ( $U=679$ ,  $p=0.949$ ), amount charged per mobile phone charging ( $U=670$ ,  $p=0.830$ ), amount charged per solar lamp for charging ( $U=682$ ,  $p=0.979$ ) and income earned due to solar lamp charging per day ( $U=650$ ,  $p=0.702$ ) between conventional and proposed system.

#### 4.7.3.3 Validation of Hypothesis

**H<sub>1</sub> (b):** Discrete design for the off-grid solar photovoltaic home system has a positive impact on inter-household mutual energy trading for a cross-section of the rural prosumers in the context of rural northeast when compared with a conventional off-grid system.

#### Interpretation of Results

The proposed SPVHS design elicit a statistically significant difference in overall MuET independent ( $U=501$ ,  $p=0.001$ ) sample study. Thus, the null hypothesis of equal difference rejected, and it concluded that there was a significant difference in benefits related to mutual energy trading due to proposed design intervention.

The following section discusses the core observations and benefits (as seen in fig 4.6) explicitly reported in the case of proposed design intervention and were not observed in the case of the conventional photovoltaic system.

#### **4.8 Observed Pattern of Energy Exchange**

For design intervention, the local pattern of energy-exchange examined regarding the social context of decentralized energy. It led to a second-generation research question concerning what types of returns energy-givers and energy-receivers had when they were given control of an off-grid intervention. The study used a technique called 'ethnographic network mapping' (Schensul et al., 1999). The method mentioned above emphasizes individuals and investigates their community network concerning local energy transactions. The ethnographic information, reveals three types of energy exchanges, namely - monetary, mixed (involved both monetary and non-monetary), and non-monetary, observed as part of the rental structure during the study (Table 4.7). The priority of the people for the type of energy exchange varies with social interaction amongst each other. For monetary exchange, profit intended from socially distant in relation. This type of energy return observed in the case of Mutual Energy Trading (MuET). Concerning MuET, energy-giver, and energy-receiver engaged for the sake of a monetary gain.

While the mixed exchange observed for mutual energy lending (MuEl), where profit was intended from distant in relation while profit avoided from close in relation. Concerning the mixed type of exchange of energy, payment is made by an energy receiver to energy-giver for the energy received in the form of money or commodities of equivalent economic value. The exchange of local agricultural yields such as lentils, rice, vegetables, and the dairy item observed in the case of MuEl. Mixed returns were observed with both 'socially distant' as well as 'socially close' receiver, depending upon the availability of money. The study reported that it facilitated much-required flexibility for energy transactions in the rural scenario.

An energy-receiver makes the non-monetary exchange in favour of energy-giver for the energy provided as a goodwill gesture or social support concerning very close social relations. For non-monetary exchange, profit was absent. This type of energy exchange is observed in mutual energy sharing (MuES). In the context of the above, the study observed that the diversity in energy exchange provided a better fit for users involved in the off-grid energy systems than the only money-centric returns. The critical factor that differentiates non-monetary returns from monetary and mixed returns is that the giver and receiver did not monetarily measure returns due to the



Table 4.7 Types of energy returns as observed during field assessment of proposed intervention

Dimension	Monetary Exchange	Mixed Exchange	Non-Monetary Exchange
Money Involved	Yes	Yes	No
Social Relation	Distant in Relation	With both 'Distant in relation' and 'Close in relation'	'Very Close in relation'
Profit	Profit Intended	Profit Intended from Distant in relation ; Profit Avoided from Close in relation	Profit Avoided
Type of Energy Exchange	Mutual Energy Trading (MuET)	Mutual Energy Lending (MuEL)	Mutual Energy Sharing (MuES)
Entity of Return	Money	Agriculture Yield such as Lentils, Rice, Vegetables and Home Food	Goodwill, Social Support, Favour



very close social relationship between energy-receiver and energy-giver. The next section deals with the details of the study.

#### 4.8.1 Descriptive Overview of Returns

In the context of the aforementioned, fig. 4.7 indicated an overview of the distribution percentage of receivers having monetary, mixed, and non-monetary returns, resulted due to design intervention. The figure depicts the distribution percentage of receivers having monetary, mixed, and non-monetary returns. During the study, 71 households received proposed SPVHS design intervention from the giver in Benfakuwa, Gopalpur, Bherveri Pathar, Sikari Chappari, and Bhagunmari villages of district Sonitpur and Majuli in Assam. The proposed intervention was investigated for the total duration of a year to obtain the required set of data. Table 4.8 provides details of the distribution of receiver in context to the type of energy returns observed in the villages, as mentioned above of district Sonitpur and Majuli in Assam with an overall response rate of about 54%. For the study, one questionnaire (response of receiver) means one household record, the overall total number of responses means the same thing in percentage.

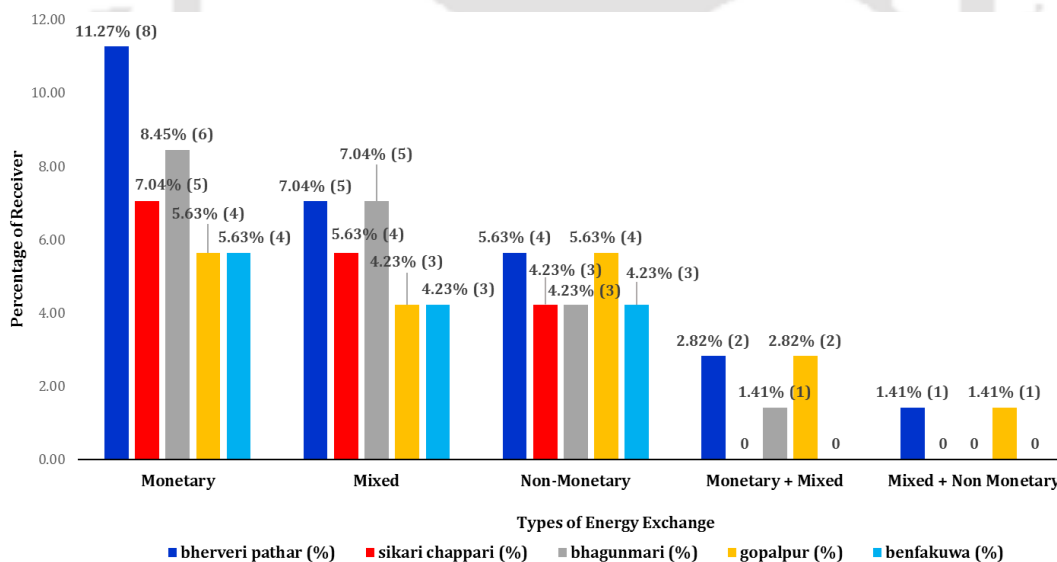


Fig 4.7 Overall distribution percentage of receivers (along with number of receivers) by type of returns as observed during impact assessment, along with the number of receivers

The studied villages have a heterogeneous population belonging to different tribes. The different responses were recorded due to varied socio-economic status among villagers.

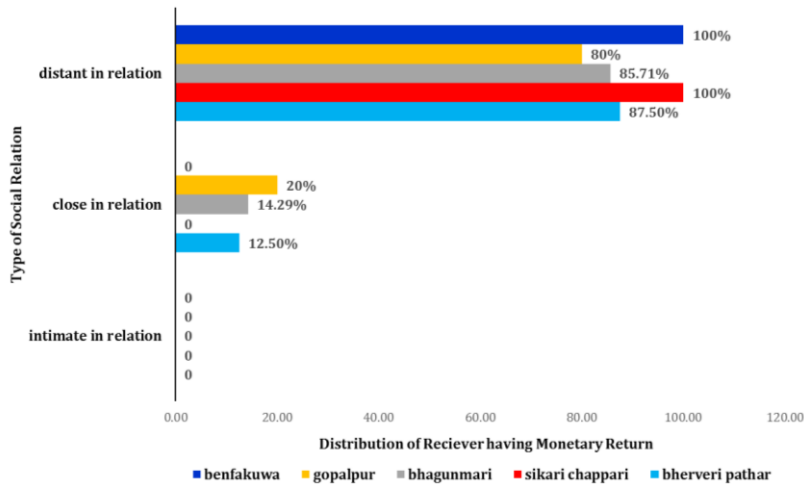
Table 4.8 Frequency chart of distribution of receiver with respect to type of return and their social relationship with giver in the studied villages.

	<b>Monetary Return</b>			
	<b>intimate in relation</b>	<b>close in relation</b>	<b>distant in relation</b>	
bhverri pathar	0	1	7	8
sikari chappari	0	0	4	4
bhagunmari	0	1	6	7
gopalpur	0	1	4	5
benfakuwa	0	0	4	4
				<b>28</b>
	<b>Mixed Return</b>			
	<b>intimate in relation</b>	<b>close in relation</b>	<b>distant in relation</b>	
bhverri pathar	1	5	1	7
sikari chappari	0	4	0	4
bhagunmari	1	5	0	6
gopalpur	1	3	0	4
benfakuwa	0	3	0	3
				<b>24</b>
	<b>Non Monetary Return</b>			
	<b>intimate in relation</b>	<b>close in relation</b>	<b>distant in relation</b>	
bhverri pathar	4	1	0	5
sikari chappari	3	0	0	3
bhagunmari	3	1	0	4
gopalpur	4	0	0	4
benfakuwa	3	0	0	3
				<b>19</b>
<b>Total Number of Respondents</b>				<b>71</b>

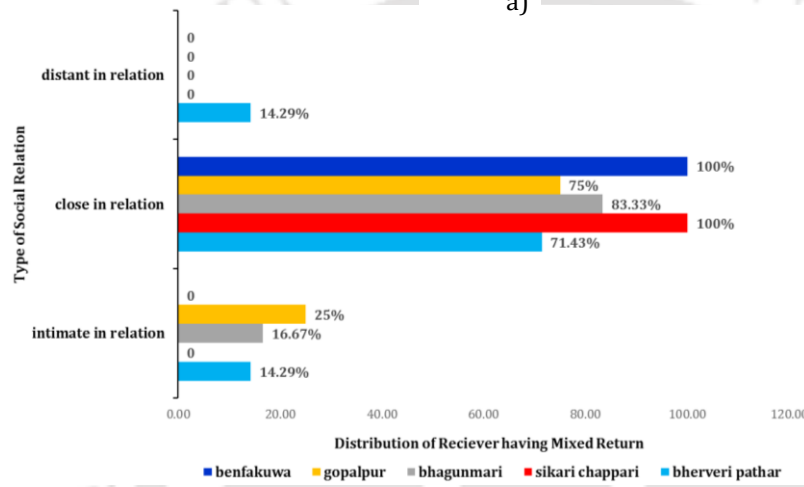
Table 4.9 Overall percentage of distribution of receiver with respect to type of return in the studied villages.

<b>Type of Return</b>	<b>Overall Receivers Distribution (%)</b>
Monetary	38.02
Mixed	28.17
Non Monetary	23.95
Monetary + Mixed	7.05
Non Monetary + Mixed	2.81
	100

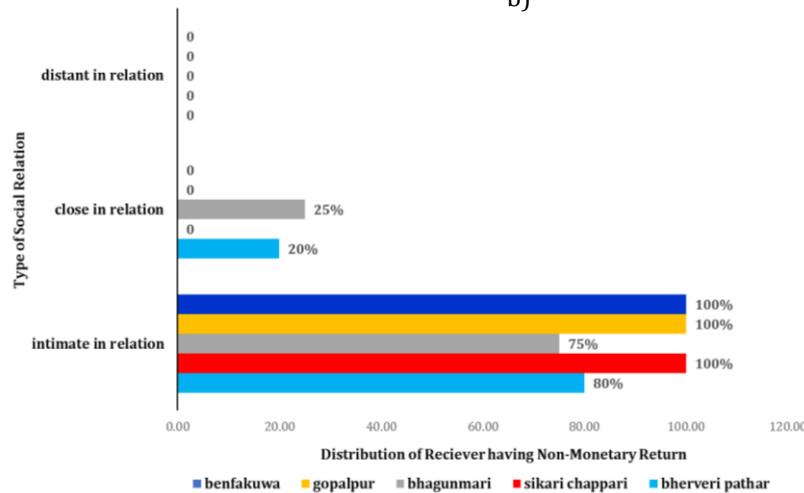
The study observed that type of energy exchange, namely monetary, mixed, and non-monetary, depends upon the social relationship of a receiver with the giver. Table 4.9 shows that the monetary return was the most common (38.02%) type of return used. While 28.17% of receivers respectively used mixed return. Mixed returns involved both money and agricultural yields such as lentils, rice, vegetables, etc. as an exchange. The study reported that this provides better flexibility to rural households to engage with the off-grid solar energy system.



a)



b)



c)

Fig 4.8 a) Shows the distribution percentage of householders for monetary returns was more frequent in energy exchanges with distant relationships b) Shows householders distribution percentage for mixed returns that involved both distant in relation as well as 'close in relation c) Shows the distribution percentage of householders indicating that all recipients with intangible returns were socially intimate.

Also, 23.95% of the overall receivers in the studied villages used non-monetary return. Non-monetary energy transactions reported to enable goodwill and support between rural households. A total of 7.05% receivers used both monetary and mixed returns, and the remaining 2.81% used non-monetary and mixed returns. Besides, figure 4.8 – a, b, and c show frequency of receivers who provided monetary, mixed, and non-monetary returns, concerning the type of their social relations with the givers. Fig. 4.8 a indicates that monetary returns were more typical in energy exchanges with ‘distant in relation.’ Fig. 4.8 b emphasizes that mixed returns mainly observed with ‘close in relation.’ Fig. 4.8 c reports that all the beneficiaries having non-monetary returns were ‘intimate in relation’ to the givers.

Besides, fig 4.8 shows the distribution of receivers to the type of energy exchange concerning their social relationships. As evident from the bar chart that monetary returns were more prevalent with receivers distant in the relationship. Furthermore, the household percentage for mixed returns engaged both distant as well as close relationships among users. Intangible returns observed in case of mutual energy sharing among socially close users. In context to aforementioned, the researcher considers that design intervention enabled the following benefits;

- i. First, discrete design intervention facilitated the off-grid set up to become more user-centric. Moreover, intervention allowed flexibility in rural energy exchange, making it coherent with the needs of a rural mode of life.
- ii. Second, design intervention enabled multiplicity in exchange, which helped in addressing rural household's limited ability to pay, one of the significant challenges found in the literature for the dissemination of off-grid energy systems ( Singh et al., 2018; Palit et al., 2015; Chaurey et al., 2012). The diversity in energy exchange enabled householders to choose from a suitable return in case of scarcity of money.

The following section discusses the core benefits reported due to design intervention.

#### **4.9 Core Benefits of Proposed Design Intervention**

The literature on energy in off-grid settings is primarily limited to a discussion on monetary returns (Kobayakawa & Kandpal, 2014; Palit, 2013a; Pode, 2010) and lacks an understanding of different types of (monetary and non-monetary) returns possible

and its usefulness in a rural setting. To respond to the knowledge, as mentioned above, the gap, the researcher brings a product design perspective to develop a social understanding of peer-to-peer returns. Addressing the given gap can help the researcher and practitioner to have a realistic understanding of the social and cultural preferences of the rural participants. Ruotsalainen et al. argued more specifically to approach energy systems with a broader social and cultural context, rather than relying narrowly on the technical understanding (Ruotsalainen, Karjalainen, Child, & Heinonen, 2017). Concerning above the visionary systems like 'decentralized energy systems' (Fuchs & Hinderer, 2016), provides flexibility to householders to have specific control and active participation in energy distribution in the local context. Such systems facilitate reciprocity in local energy distribution, allowing peer to peer energy exchange to enable rural relevance of photovoltaic applications, as discussed under section 1.9 and 1.10, respectively, in chapter 1.

Furthermore, energy literature predicted decentralized energy systems to become more social by allowing householders to play a prominent role in energy production, consumption and distribution (Bellekom, Arentsen, & van Gorkum, 2016; Parag & Sovacool, 2016; Rosen & Madlener, 2016; Van Der Schoor, Van Lente, Scholtens, & Peine, 2016). The study refers to an 'energy exchange' as a transaction of energy between an energy-giver and energy-receiver. Technically, literature reported that one of the significant ways in which energy exchange can take place is through storage devices (Singh et al., 2018). Concerning it, initiatives that configure such energy exchanges are Ikisaya Energy Centre in Kenya, Lighting a Billion Lives initiative, and Rural Spark in India.

The study reported mutual energy sharing (MuES) and mutual energy lending (MuEl) are observed to be a type of energy exchange amongst energy-giver and energy-receiver for the sake of social relationships between them. The MuES observed to be non-monetary. While MuEl reported having both monetary and non-monetary benefits. The intervention consisted of an energy distribution support consisting of small-scale discrete design intervention at the giver's household. The intervention setup offered ownership and total control of the energy distribution without requesting the giver to pay for the intervention facility provided. It allowed the giver to work as per local social and cultural beliefs without the compulsion of making the setup monetarily profitable. The findings mentioned above led to a

second-generation question of what types of energy exchanges emerge when householders are given control of an off-grid intervention. The study used qualitative analysis; also, literature suggested the use of ethnographic techniques, such as participant observation. (Musante, K., & DeWalt, B. R. 2010), interviews and conversations (Bernard, H. R. 2017), self-reporting, and field-notes for a similar type of energy studies. The intervention observed for about a month per household, and the data was recorded. The core benefits resulted due to proposed design intervention are discussed as follows.

#### 4.9.1 Mutual Energy Sharing

For the core-benefits observed, in the case of the MuES, the average time for inter-household energy sharing was reported 3.8 hrs per week, along with an average of 2.0 modules shared per week. Proposed design incited mutual energy sharing (as participants were able to utilize decentralized power modules for multiple rural needs due to flexible nature of design) between two households as a goodwill gesture, favour, and social support, recognized by 66.19% of users. In the context of the MuES, the majority of users (70.42%) reported that non-monetary sharing of energy abetted social-cohesion between rural households (fig 4.9).



Fig 4.9 Schematic representation of MuES, A is energy donor, and B is energy recipient. Such transaction took place on non-monetary basis.

#### 4.9.2 Mutual Energy Lending

Another type of core benefit observed was Mutual energy lending (MuEl). It involved the exchange of decentralized power modules between the giver and receiver involving both monetary and non-monetary benefits. The study reported MuEl transactions for an average period of 2.93 hours per day. Receivers in the case of MuEl were neighbours, local vegetable and fish vendors, and the local community. Such type of local energy transactions helped to facilitate social acceptance of the proposed

off-grid photovoltaic system. Besides, the study witnessed giver-receiver and giver-receiver-sub receiver types of lending mechanisms. The details of the same are discussed as follows;

#### 4.9.2.1 Donor-Receiver lending mechanism

The study reported that local fruit-vegetable and fish vendors, also small shopkeepers were one of the primary beneficiaries of MuEl (fig 4.10). They took decentralized power modules on rental for the average period of 2.79 hours for post-dark usage. The study witnessed that for local vendors, their primary motivation behind MuEl transactions was to get additional income benefits by providing the charging facility to customers on a paid basis. Besides, smart power modules used as a reliable light source for running their business post dark. Lent modules were charged between five to seven rupees per hour.

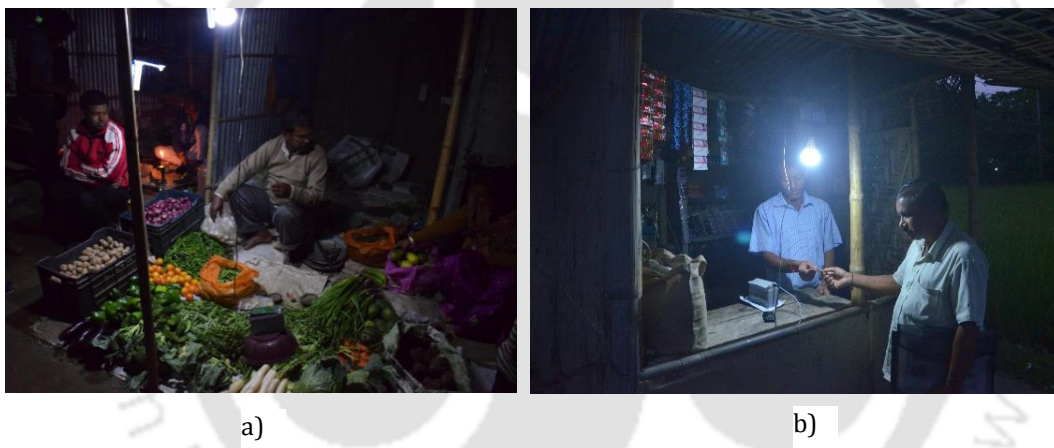


Fig 4.10 Local energy exchange, Giver-receiver mechanisms of local MuEl transactions as observed during field trials a) local fruit vendor took decentralized power module on lending basis to run his shop and b) rural shopkeeper using decentralized power module to charge mobile phones of the customer for supplementary income benefits, other than lighting shop.

The study reported the mean income earned by giver due to module lending to be Rs 30 to 40 per day, while, on average, two decentralized power modules leased for lending @ 3 hrs (appx) per day. Furthermore, the mean income earned by the receiver due to mobile charging to a rural customer was Rs 25 per day. Local vendors also reported assistance in sales due to the flexibility of location-specific concurrent use of decentralized power modules. The schematic representation of the localized energy distribution mechanism, as mentioned above, is shown in fig 4.11a.

#### 4.9.2.2 Donor-Receiver-Sub Receiver lending mechanism

The second type of energy exchange witnessed was sub-lending of discrete power modules from the giver to the receiver, and further to sub-receiver. A schematic representation giver-receiver-sub receiver mechanisms of local energy exchange shown in fig 4.11b.

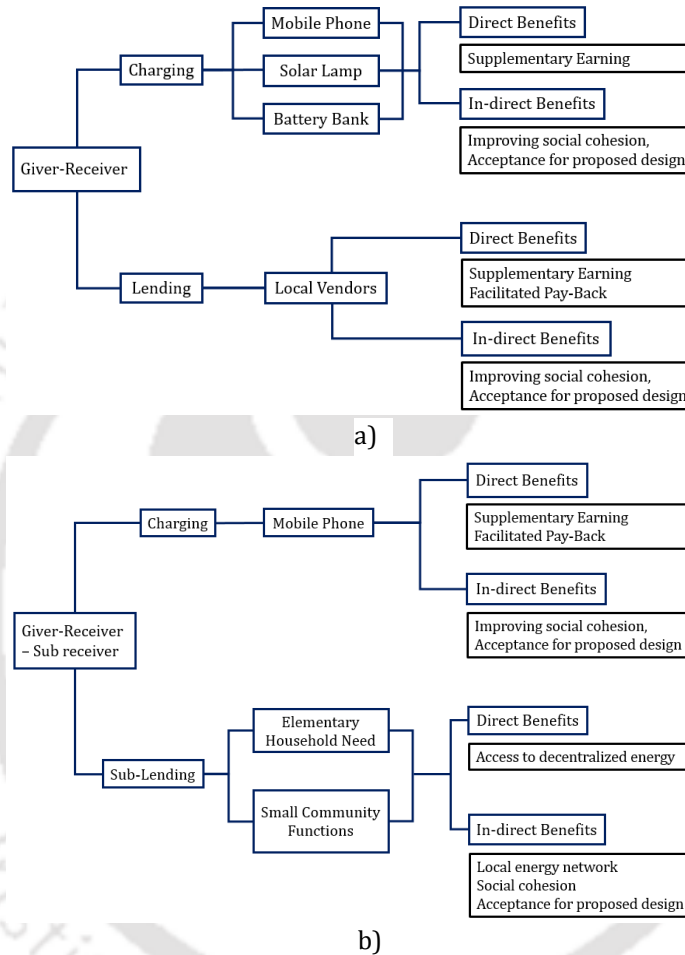


Fig 4.11 a. Giver-receiver and b. Giver-receiver-subreceiver mechanisms of local MuEl transactions as observed during design validation

This type of transaction was observed, where the sub-receiver does not have direct access to the giver due to the limitation of the remote location or inadequate access to energy resources in the area. The study reported that the sub-letting of modules on a commission basis was the primary motivation behind such transactions. The received modules were sub-let on commission basis between 3-5 rupees per transaction, in addition to the rental charges of 5-7 rupees an hour. The study observed add-on benefits both to the giver and receiver. Concerning proposed design intervention, the 67.60% of households shown willingness to pay for energy lending,

while 83.09% of users reported the ability to pay. The benefits resulted from discussed above indicated the user acceptance and practicality for peer-to-peer energy transactions in a localized context.

Furthermore, the study witnessed that user who received a storage module on a sub-let basis, used it primarily for the following two purposes; a) docking with existing DC wiring set-up, to fulfill elementary household, and small rural workplace energy needs, secondly b) the decentralized power modules are rented for small community functions, among villagers. MuEl transactions not only resulted in monetary benefits but also facilitated social acceptance for the proposed photovoltaic design, as the majority (73.23%) of rural householders acknowledged the proposed photovoltaic design for soon in-future use. The aforementioned discussion witnessed that discrete design coherently fulfilled most of the energy-based needs for the rural mode of life in the studied region (fig 4.12).



Fig 4.12 Giver-receiver-sub receiver mechanisms of local MuEl transactions as witnessed a) Sub receiver beneficiary fulfilling rural work-space needs and b) fulfilling elementary rural household energy needs by docking smart storage module with existing DC network.

### 4.9.3 Validation of Posit

**P<sub>1</sub>:** Discrete design for off-grid solar photovoltaic home system encourages mutual energy sharing and mutual energy lending between households facilitating social cohesion, and stimulates decentralized energy distribution network in rural background.

### Interpretation of Results

For the proposed photovoltaic intervention, 66.19% of users incited MuES between two households as a goodwill gesture, favor, and social support. Concerning design intervention, 67.60% of households acknowledged a willingness to pay, while 83.09% of users reported the ability to pay for MuEl transactions; the resulted benefits indicated a positive effect for peer-to-peer energy transactions in a localized context. Mutual energy transactions facilitated the social acceptance for the proposed photovoltaic intervention, as 73.23% of rural householders shown readiness for the proposed design for soon in-future use.

The diversity in energy exchange enabled householders to choose from a suitable return in case of scarcity of money. The 64.78% of rural households accepted that multiplicity in local energy transactions due to discrete design enables small-scale photovoltaic applications to become sustainable in a localized context. Besides, 71.83% of rural households recognized that local energy transactions like MuES and MuEl stimulated inter-household energy distribution network due to flexibility of returns. Furthermore, the study witnessed that the proposed design intervention of an off-grid photovoltaic system enabled social cohesion between households (70.89%) as it was found coherent to rural lifestyle needs. It is pertinent from the discussion above that the results form the basis for the validation of posit.

#### **4.10 Analyzing Energy Exchange Continuum**

Design intervention resulted in additional income and social capital<sup>11</sup> benefits, like improving productivity and goodwill among rural households. Besides, the energy exchange-continuum indicated that user's preference for a type of exchange varies with the type of their social relationship. While looking at the monetary benefits of energy exchange, the non-monetary benefits usually not given much attention. The study observed that non-monetary benefits are critical for effective intervention. It indicated that non-monetary energy sharing did not sustain any immediate benefits but found indirectly persuading monetary benefits due to the improved social connectedness. Non-monetary returns observed to create goodwill and social support. The study reported that the giver had the non-monetary type of exchange while engaged in mutual energy sharing with the 'intimate in relation' receivers. The

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<sup>11</sup> Social capital is the relationship network among individuals living and working in a rural community, encouraging society to work efficiently (Putnam, 2001; Sabatini, 2009).

non-monetary returns indicated togetherness and solidarity amongst rural households. In such a context, rural household seems to value further their social affability other than having any monetary benefit. In addition, during the study, the non-monetary exchange of energy seemed to affect the community in such a way that the households supported and interacted positively with each other, and provided necessary social support based on the sense of cohesion among them, is said to encourage community vitality<sup>12</sup> (Dale, Ling, & Newman, 2010). The majority of rural households (64.78%) accepted that multiplicity in local energy transactions due to discrete design enables small-scale photovoltaic applications to become sustainable in a localized context.

Besides, design intervention witnessed monetary return, as a vital constituent for mutual energy trading. The study observed that the giver usually followed monetary exchange when participating in MuET with the 'distant in relation' receivers. The study revealed that one of the ways to connect a household to the rural economy was through income benefit. Using the cash from a practical view seems to make energy exchange more accessible and useful in addressing various necessities of rural life. Furthermore, mixed returns (having both monetary and non-monetary returns) noticed for users participated in MuET with the 'distant in relation' as well as for MuES with the 'close in relation' receivers. The discrete design of the off-grid photovoltaic system provided a useful alternative by facilitating diversity in energy exchange in case of cash scarcity. Also, the study revealed that the rural exchange of energy would have collapsed without a multiplicity of returns and that many families would have restricted their access to photovoltaic energy. In the given energy scenario, people were enabled to transact items they required due to the flexibility of using the type of return. In total, the study indicated that mixed returns required in the number of contexts: (a) addressing cash scarcity and (b) making use of locally produced goods and services for access to energy. Furthermore, the social cohesion witnessed to enhance among participants as energy transactions evolved from monetary towards non-monetary exchange.

Post design intervention, it was reported that one should not only look towards concrete benefits in monetary terms while designing off-grid photovoltaic products

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<sup>12</sup> Literature (Flora et al, 2001) summarizes community vitality as, to facilitate the ability of people to realize a positive social outcome in context to community development.

but also consider the non-concrete benefits. The study found them to be a significant feature of rural engagement, impacting rural mode of life. While monetary benefits outline concrete benefits, non-monetary benefits characterize non-concrete benefits. The diversity of observed energy exchange seems critical for the proposed design

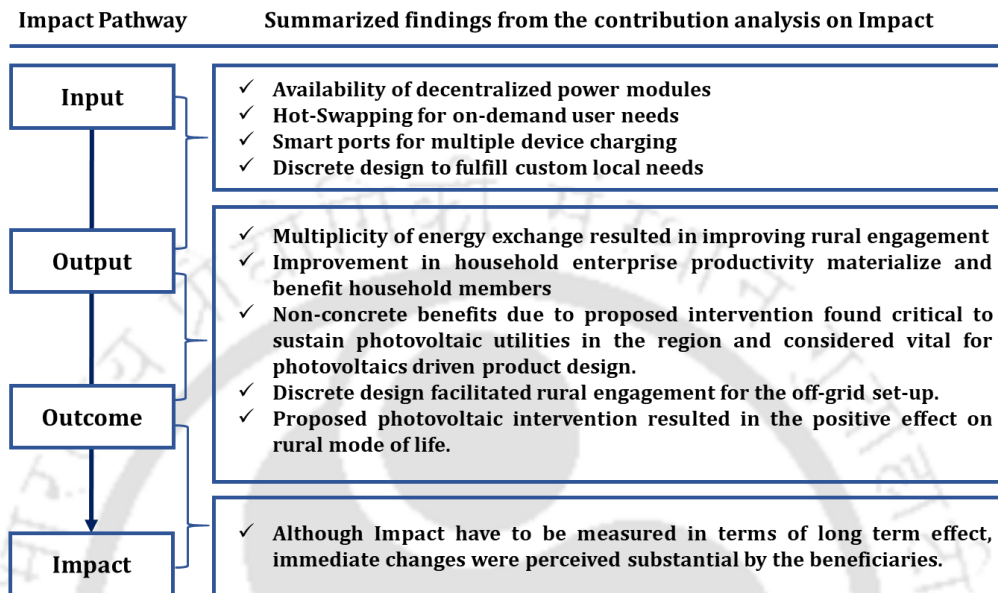


Fig 4.13 Summary of findings on contribution claim for proposed design intervention.

intervention as it enriched social capital — summary of contribution claim presented in fig 4.13. The study observed that an incentive-based off-grid photovoltaic system necessitates critical motivation for the adoption of the off-grid photovoltaic utility. In context to above, break-even analysis indicates the payback period for proposed intervention, as it encourages the adoption of the proposed intervention to rural users. The details of break-even analysis are discussed next.

#### 4.11 Break-Even Analysis of the Proposed System

Break-even point analysis was reported for the discrete photovoltaic home system as per energy scenario 1, having a storage requirement of 60 Ah. However, considering the cost of PV components and their ease of availability in the market fixed cost of the proposed system calculated approximately to be 13,500 Rs for the nearest 75 Ah, 12 volt System. Also, the variable cost of Rs 500/- has been added as annual maintenance and miscellaneous charges for the intervention. Approximate total cost resulted in 14,000 rupees.

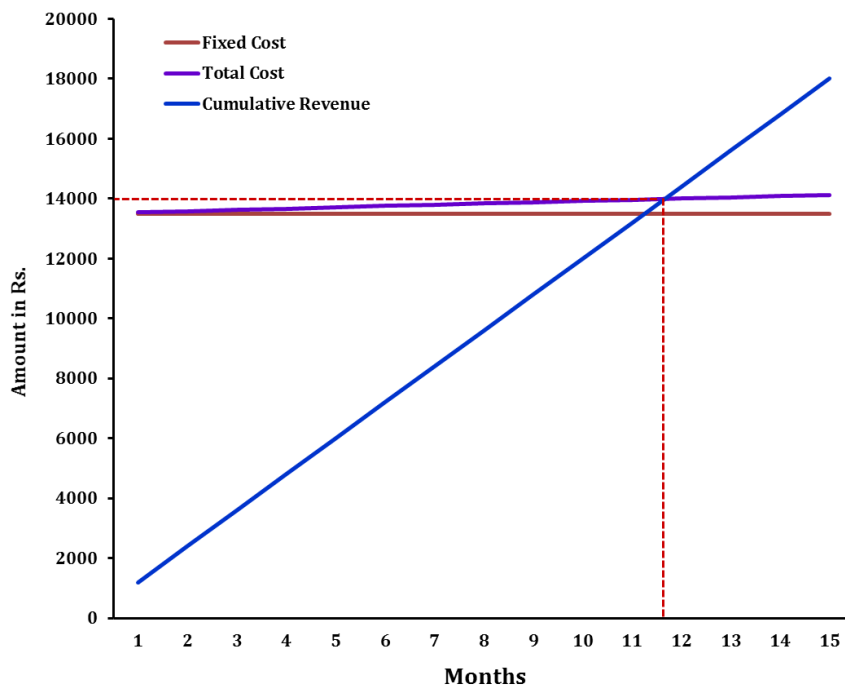


Figure 4.14 Break-even point analysis showing period to recover total cost of discrete photovoltaic system design.

The study reported that a cumulative mean revenue of 1200 Rs/month resulted due to add-on services like mutual energy trading and mutual energy lending. Concerning those as mentioned above, the break-even point for the recovery of the total cost of the proposed system resulted in a period of 11.5 months, as shown in figure 4.14. The study indicated that rural users were willing to adopt the proposed design, which complemented their intrinsic motivation for an incentive-based system. The intervention resulted in add-on benefits to the users resulting in a payback period of about one year (11.5 months). Besides, no such benefits observed for the conventional photovoltaic system. The incentive-benefits abetted the dissemination of photovoltaic utilities to rural grassroots in the studied region, as reported during co-investigation with AEDA (Appendix 9). A cost-benefit analysis addressed next to compare the overall cost of the conventional and proposed system with its anticipated benefits.

#### 4.12 Comparative Cost-Benefit Analysis

The study observed a difference in initial fixed cost between the conventional and proposed photovoltaic home system for the given configuration of 75 Ah, 12 volts, as

Table 4.10 Comparison of fixed and maintenance cost between conventional and proposed photovoltaic system.

Conventional System				Proposed System			
Initial Cost	Specification	Unit	Cost (Rs)	Initial Cost	Unit	Cost (Rs)	
Lead Acid Battery	75 Ah@12 volt	1	6400	VRLA Battery	18 Ah@12 volt	4	6900
Polycrystalline PV Panel	80 wp@12volt	1	3400	Polycrystalline PV Panel	40 wp@12volt	2	3600
Charge Controller	5 amp@12volt	1	500	Smart Controller Unit	5 amp@12volt	1	1800
DC Wire	14 amp@12volt	10 mtrs	450	DC Wire	14 amp@12volt	10 mtrs	450
CFL	8 Watt	2	190	LED	8 Watt	2	230
Misc			300	Smart Battery Housing		4	200
				Misc			300
<b>Initial Fixed Cost</b>			<b>10940</b>				<b>13480</b>
Battery Malfunction (19.48%)			400	Contingent Cost (Miscellaneous Variable Cost)			
Charge Controller Malfunction (27.12%)			200				500
CFL Blow-off (27.89%)			200				
Misc (25.51%)			100				
<b>* Repair and Maintenance Cost</b>			<b>900</b>	<b>* Contingent Cost</b>			<b>500</b>
<b>Overall Annual Operational Cost</b>			<b>11840</b>	<b>Overall Annual Operational Cost</b>			<b>13980</b>
			<b>Appx 11,900</b>				<b>Appx 14,000</b>

\* Mean values of repair and maintenance cost is as reported during the duration of study

\* Contingent cost of Rs 500 added as anticipated variable cost despite no reported component malfunction for proposed system during study

seen in table 4.10. The difference, as mentioned above in terms of the higher initial cost for the proposed system, was observed due to the intervention of technically advanced, more reliable, and energy-efficient components in design like VRLA battery, smart controller unit, LED luminaire, and smart battery housing. In the case of a conventional system, mean value (for the percentage observed out of total) of repair and maintenance cost was observed to be 900 rupees. The percentage observed for major component malfunction were charge controller (27.12%), battery malfunction (19.48%) along with CFL blow-off (27.89%) as discussed in section 2.7. The contingent cost of 500 Rs was added as an anticipated variable cost in the case of a proposed photovoltaic system. At the same time, no component malfunction was reported for proposed SPVHS during the period of the study. Despite the lower initial fixed cost, the overall annual operational cost in the case of the conventional system was reported higher due to the use of quality un-verified components and un-optimized system configuration. In the case of the proposed system, the study reported improvement in rural household enterprise productivity, add-on benefits like additional income, and overall usefulness.

### 4.13 Summary

Experimental field trial of proposed design intervention conducted in case of both independent and paired studies, when compared to a conventional system. The theory of change framework provided evidence concerning the anticipated impact of design by investigating PUE benefits due to design intervention. A quasi-experimental study was conducted, and the difference of impact studied between two groups. The study witnessed that discrete design improved household enterprise work productivity. Besides, the intervention resulted in mutual energy trading benefits when compared with the conventional system; hence, hypothesis  $H_1$  (a) and  $H_1$  (b) was established.

Furthermore, the study witnessed that MuES and MuEI enabled social cohesion amongst households and assisted energy distribution networks due to the proposed intervention. It formed the basis for the validation of posit  $P_1$ . Break-even and cost-benefit analysis indicated that rural users were willing to adopt the proposed system that matched with their intrinsic motivation to adopt an incentive-based system. The discussion above accomplished the last research objective to investigate the intervention impact on productive usage of energy for the rural mode of life. The research outcome presented next will be valuable for the diffusion of off-grid photovoltaic utility to the rural grassroots in the regional context.



# Chapter 5

## Discussion and Conclusion

**Chapter Five** consists of discussion abridging complete research work and highlights novel contributions to its limitation and future scope. Besides, the chapter describes how the objectives of the present research fulfilled, hypothesis, and posit was validated. Finally, design recommendations incorporating the contribution of the research work also presented.



## 5.0 Conclusion

Given India's energy deficiency, the democratization of decentralized energy in particular solar photovoltaics is of utmost significance; in this regard, the potential avenues must be investigated (Narula et al., 2012; Palit & Sarangi, 2015). Many scholars documented instances that existing energy literature underrepresents rural societal context, furthermore, in comparison to techno-economic understanding, there exists a significant scope for energy research to explore its social dimension (Sovacool, 2014; Hancock, 2015; Cloke et al., 2017).

From the literature (Barman et al., 2017; Dhiman et al., 2017; Palit, 2005), pilot study and interactions with various stakeholders multiple challenges identified for the dissemination of solar photovoltaic applications in the north-eastern region of India. The study reported that one of the most significant challenges is to integrate solar photovoltaic applications with social significance in the rural context. The suitability of decentralized energy applications to the beneficiary is usually not considered. The existing applications promoted with the consideration that rural users will adapt their mode of life as per the given design, resulting in negligible success for most of the decentralized energy interventions in regional context of northeast India (Barman et al., 2017; Dhiman et al., 2017; Palit et al., 2010).

Thus, there exists an opportunity to address the research gap by bridging the rural relevance of decentralized energy with design intervention. This chapter describes and reflects on a doctoral study intended to construct an impetus of research to look into the design and development of a discrete off-grid solar photovoltaic home system considering imperative local needs in the context of the rural background of northeast India. There exists scope for research on how design can integrate decentralized energy with PUE for end-use benefits. This mutually cohesive design development can overcome multiple challenges needed to disseminate the efficacy of decentralized energy applications, especially solar photovoltaics, to rural grassroots. Furthermore, this provides scope for systemic design in the broader context of rural engagement.

The hypothesis formulated in chapter-1 validated through the research endeavours, as discussed in chapter 2 to chapter 4. The hypothesis was tested based on design research carried out in the northeastern state of Assam and relevant. In this

regard, the photovoltaic ecosystem studied for establishing design criteria. A pilot study made to investigate rural prerequisites for energy needs, usage patterns, and existing issues for off-grid photovoltaic application were understood in chapter 2, fulfilling research objective1. During study 73.70%, respondents felt the need for context-specific design for a solar photovoltaic home system, which should be able to fulfill rural mode of living needs. About 70.91% of users were highly dissatisfied with the conventional off-grid photovoltaic home system. The study witnessed the 300 watts, and 750-watt rural energy scenarios emerged based on critical load estimation, and subsequently, assisted in concluding design criteria and specifications for design development. Besides, the feasibility of design conceptualization for the solar photovoltaic home system studied in chapter-3. System architecture and design concepts assessed using a fuzzy multi-criteria decision-making method. Concerning the above, Fuzzy TOPSIS was used to evaluate off-grid photovoltaic system architecture concepts. Expert ideation shortlisted discrete system architecture ( $Cc_i$  0.748), given its advantage for system usability, human factors, and efficacy to address rural lifestyle PUE needs. Based on system architecture, design concepts for SPVHS were formalized. The design concept for the adaptive off-grid photovoltaic system based on discrete system architecture formalized ( $Cc_i$  0.780) for high-fidelity prototype development. The concluded design concept has multiple advantages for the rural mode of life, as discussed in section 3.4. The salient features of the finalized off-grid photovoltaic design are as follows:

1. From a usability point of view, it is more convenient to move and carry discrete storage form one place to another place compared to the one big battery, as used in the conventional photovoltaic system.
2. From the charging point of view, if we can charge one battery at a time (cyclic charging of four battery), then the charging current requirement is lesser compared to the continuous charging current of a big battery (used in the conventional scheme). It minimizes the size and cost of the PV panel.
3. From the design economics point of view, since the discrete architecture provides flexibility in the use of (two plus two) smart storage modules. Therefore, the user can buy only two modules initially; this saved the initial purchase cost. Remaining two modules can be upgraded later, depending upon user requirements.

4. 'Hot-Swapping' of modular storage proposed to address multiple rural lifestyle needs. Unlike in the conventional solar home system, charging has to be stopped before taking the battery out, which is quite a time consuming and inconvenient.
5. In the context of PUE, storage modules of the off-grid photovoltaic system were conceptualized as 'smart' to address short duration usage independently, and elementary energy needs augmented with the local pattern of energy usage.

Concerning the above, MATLAB@Simulink based simulations were realized for context-specific hardware development, as discussed under section 3.5. Hardware assembly and testing were done for the prototype fabrication of the high-fidelity off-grid photovoltaic system. Assam Energy Development Agency (AEDA) duly sponsored all the prototypes via R&D fund number AEDA/409/201413/612. After testing a high-fidelity beta prototype under lab conditions, it was subjected to human-factor evaluation. Paired evaluation observed a significant difference between proposed and conventional photovoltaic system design, comparing the safety ( $Z=5.00$ ,  $p=0.001$ ) due to exposure of the system to potential dangers while in use (electrical, chemical, and physical). Besides, there observes a significant difference in protection ( $Z=5.05$ ,  $p=0.001$ ) while using the system in unsafe conditions and for the overall effort ( $Z=4.81$ ,  $p=0.001$ ) to accomplish a task (carrying of the storage module, installation of the system). Also, a significant difference ( $Z=5.00$ ,  $p=0.001$ ) in perceived comfort for the workstation observed due to the use of proposed design. Furthermore, to evaluate postures like bending, carrying, and load OWAS analysis done. OWAS test indicated no corrective action in case of proposed design intervention, while corrective action required for the given tasks in case of the conventional system.

The mean SUS score for the conventional system was 30.21 ( $SD=5.37$ ), with a median value of 30 and range from 0-100. THE mean SUS score was reported 75.40 ( $SD=6.51$ ) for the proposed system with the median value of 77.5 and a range of 0-100. Furthermore, the SUS score (30.21) for the conventional system found unacceptable and inadequate, while in the case of the proposed system, the reported SUS score (75.40) found acceptable and useful. In addition, for technology acceptance model (TAM) paired evaluation between conventional and proposed SPVHS a highly

significant difference is observed for intention to use ( $p \leq 0.001$ ,  $Z=5.74$ ). Furthermore, a highly significant difference observed for perceived ease of use ( $p \leq 0.001$ ,  $Z=5.78$ ) and perceived usefulness ( $p \leq 0.001$ ,  $Z=5.79$ ), respectively. The non-parametric correlation study for TAM found that for the proposed photovoltaic system, perceived usefulness (0.791\*\*) was a strong determinant for intention of use. It facilitated user acceptance for design intervention when compared with perceived ease of use (0.532\*\*). The outcome indicated that the user's intention of use for the proposed design was acceptable. Also, study reported significant correlation (0.600\*\*) between perceived usefulness and perceived ease of use. From results, it was evident that significant correlation observed between IU-PU, IU-PEW, and PU-PEW in the case of both the systems. However, the correlation values for the proposed SPVHS found higher and more significant as compared to conventional SPVHS. It depicts that user acceptance was comparatively higher in the case of the proposed off-grid home system. The study also reported that 82.36% of users strongly agreed that discrete design of photovoltaic system enabled outdoor and indoor activities, related to rural lifestyle for the studied region.

Chapter 4 studied the feasibility of proposed design intervention in the context of the rural mode of living. The Theory of change framework is widely used as an instrument for designing, planning, and evaluating interventions. It supports a model for logical intervention that shows how outputs are expected to result in an impact through empirical verification (Mayne, 2012; Terrapon-Pfaff et al., 2018). ToC provides evidence concerning the anticipated impact of design, in understanding the significance of design intervention. In this quasi-experimental study, to validate and reinforce evidence regarding the anticipated effect of design intervention, conventional and proposed design groups selected as two user groups. Pre-intervention and the post-intervention difference was studied between the groups. As observed during the field study, design intervention was evaluated based on actual field situations.

The field experiments resulted in two types of benefits a) non-core-benefits (monetary), which were observed both in the conventional and proposed system, and b) core benefits (non-monetary), which are observed explicitly in case of the proposed system only. Non-core benefits like rural household enterprise work productivity and mutual energy trading formed the basis for a hypothesis. While core-

benefits like mutual energy sharing and lending formed the basis for posit In consideration of the above, a comparative study made and the rural enterprise work productivity experiments formalized for handwoven mekhla-chaddar and handmade incense sticks. The subject selected were typical of rural household enterprises for the studied region. A similar household enterprise is prevalent across many villages of Assam and other northeastern states of India. Study witnessed that discrete SPVHS design facilitated the household enterprise productivity. The proposed intervention also resulted in mutual energy trading benefits. Concerning the above, the Mann-Whitney U test indicated that proposed SPVHS design elicits a significant difference in overall work productivity for Ovrall\_Mc (U=266, p=0.006) and Ovrall\_Is (U=207, p=0.001) for independent sample comparison of mekhla-chaddar and handmade incense sticks respectively. It validated the hypothesis  $H_1$  (a). Also, for mutual energy trading, the Mann-Whitney U test indicated that the proposed SPVHS design elicit a statistically high significant difference in overall mutual energy trading benefit for MuET\_Ovrall\_Indep (U=501, p=0.001). It validated the hypothesis  $H_1$  (b).

Design intervention reported enabling the diversity of energy exchange in a localized context as mutual energy sharing (MuES) and mutual energy lending (MuEl). The study reported it as core benefits, as no such benefit reported in the case of a conventional system. While MuES found to be non-monetary, MuEl found both monetary and non-monetary. For MuES majority of households (66.19%) of the total sample reported that such type of energy transactions happened as a goodwill gesture and social support. In the context of intervention, 67.60% of households shown willingness to pay for MuEl transactions, while 83.09% of users reported the ability to pay for MuEl transactions; the resulted benefits indicated a positive effect for peer-to-peer energy transactions in a localized context. Mutual energy transactions facilitated the social acceptance for the proposed photovoltaic intervention, as 73.23% of rural householders shown readiness for the proposed design for soon in-future use.

Local energy transactions like MuES and MuEl were perceived, stimulating inter-household rural energy networks by the majority of the user (71.83%). Furthermore, the user-perceived (70.89%) that design intervention encouraged the social cohesion between households, and found coherent to address rural lifestyle needs in the studied region. It is pertinent from the above discussion that results form the basis

for the validation of posit **P<sub>1</sub>**, stating that Discrete design for off-grid solar photovoltaic home system encourages mutual energy sharing and mutual energy lending between households facilitating social cohesion, and stimulates decentralized energy distribution network in rural background. The break-even analysis indicated that rural users were willing to adopt the proposed SPVHS design that was found appropriate with their intrinsic motivation to adopt an incentive-based photovoltaic system. The incentive-benefits abetted the dissemination of photovoltaic utilities to rural grassroots in the studied region. Also, the cost-benefit analysis indicated that despite the lower initial fixed cost, the overall annual operational cost in the case of the conventional system was higher, which made the conventional system more expensive in a longer duration. Also, design intervention resulted in additional income and social capital benefits, like improving productivity and goodwill among rural households. The ethnographic information, reveals three types of energy exchanges, namely - monetary, mixed (involved both monetary and non-monetary), and non-monetary, observed as part of the rental structure during the study. For monetary exchange, profit is intended from socially distant in relation. This type of energy return observed in the case of Mutual Energy Trading (MuET). Concerning MuET, energy-giver, and energy-receiver engaged for the sake of a monetary gain. While the mixed exchange observed for mutual energy lending (MuEl), where profit was intended from distant in relation while profit avoided from close in relation. Concerning the mixed type of exchange of energy, payment is made by an energy receiver to energy-giver for the energy received in the form of money or commodities of equivalent economic value. While in mutual energy sharing (MuES) an energy-receiver makes the non-monetary exchange in favour of energy-giver for the energy provided as a goodwill gesture or social support with very close in social relations. For non-monetary exchange, profit was absent. In the context of the above, the study observed that the diversity in energy exchange provided a better fit for users involved in the off-grid energy systems than the only money-centric returns. The study observed that non-monetary benefits are critical for effective intervention and that non-monetary energy sharing did not sustain immediate benefits but found indirectly persuading monetary benefits due to the improved Interhousehold social cohesion.

Concerning the discussion above, the last research objective gets accomplished by investigating the impact of the proposed intervention in a rural lifestyle context.

The research objectives are shown in table 5.1. Also, the research hypothesis and posit shown in table 5.2. Besides, a comprehensive flow chart of the thesis overview shown in fig 5.1a and 5.1b along with respective research objectives.

Table 5.1 Research objectives references clarification table

Research Objectives	References
To determine the rural gap and issues related to the existing product for small scale photovoltaic application in terms of energy needs and usage pattern	Chapter 2
To determine the feasibility of conceptualization for solar Photovoltaic Home System in the regional context.	Chapter 3
To explore design and develop a discrete, off-grid home system considering local beneficial use for inter-household energy exchange and work productivity in a localized context.	Chapter 3
To determine the effectiveness of the impact of proposed design intervention for an off-grid photovoltaic home system in the context of the rural lifestyle with specific reference to the north-east region of India.	Chapter 4

Table 5.2 Research hypothesis and posit clarification table

Research Hypothesis and Posit	References
<b>H<sub>1</sub> (a)</b> Discrete Design of the off-grid photovoltaic home system improves the household enterprise work productivity when compared to a conventional system given the rural settings of north-east India.	Chapter 4
<b>H<sub>1</sub> (b)</b> Discrete design for the off-grid solar photovoltaic home system has a positive impact on inter-household mutual energy trading for a cross-section of the rural prosumers in the context of rural northeast when compared with a conventional off-grid system.	
<b>P<sub>1</sub></b> Discrete design for off-grid solar photovoltaic home system encourages mutual energy sharing and mutual energy lending between households facilitating social cohesion, and stimulates decentralized energy distribution network in rural background.	

The following flowchart presents a comprehensive overview of the doctoral study summarizing the various studies undertook to validate the research hypothesis and posit, resulting in key contributions and design recommendations.

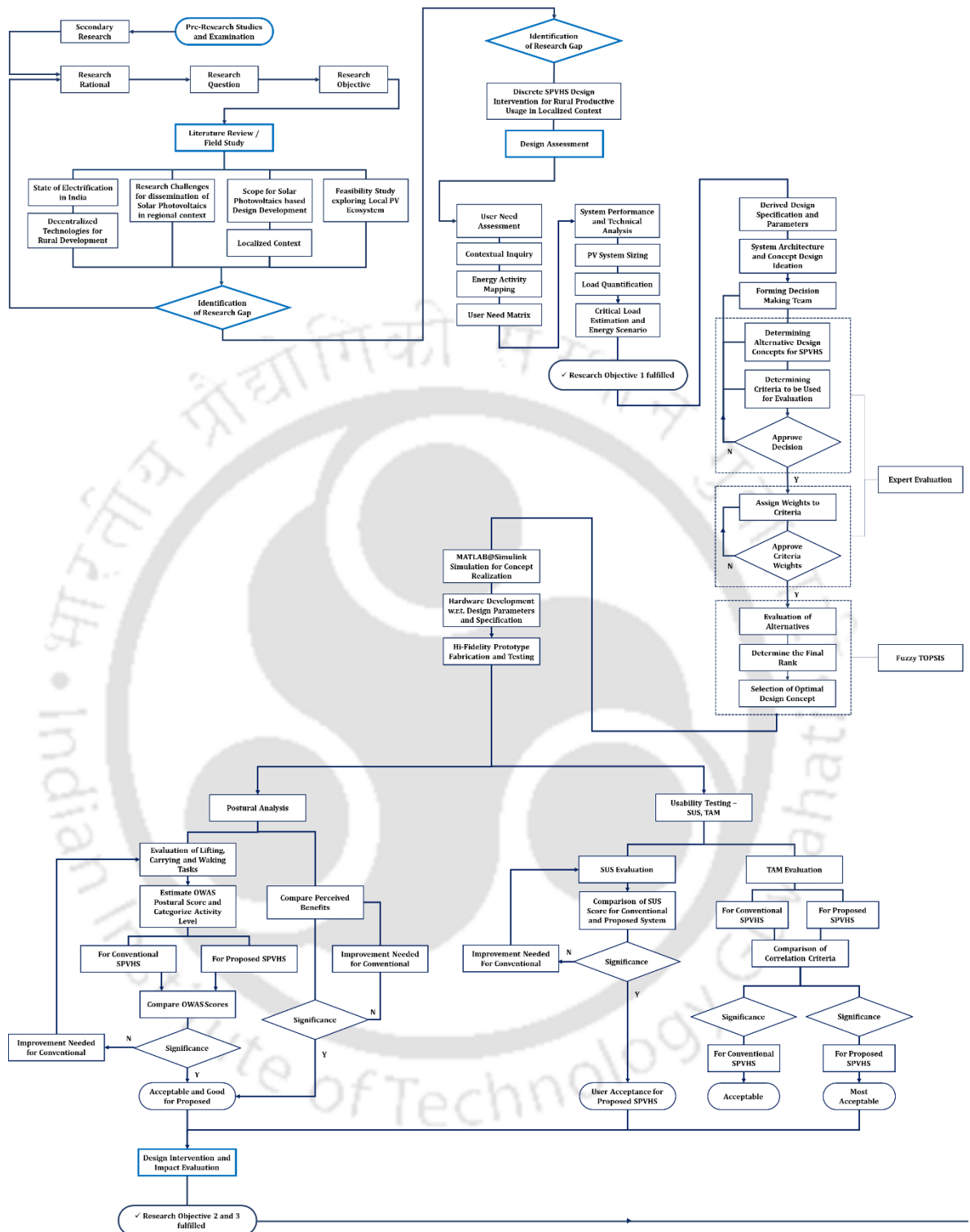


Fig 5.1 a) Comprehensive overview of various studies undertaken in context of the thesis along with accomplishment of respective research objectives. a) Shows particulars of identification of research gap and design assessment.

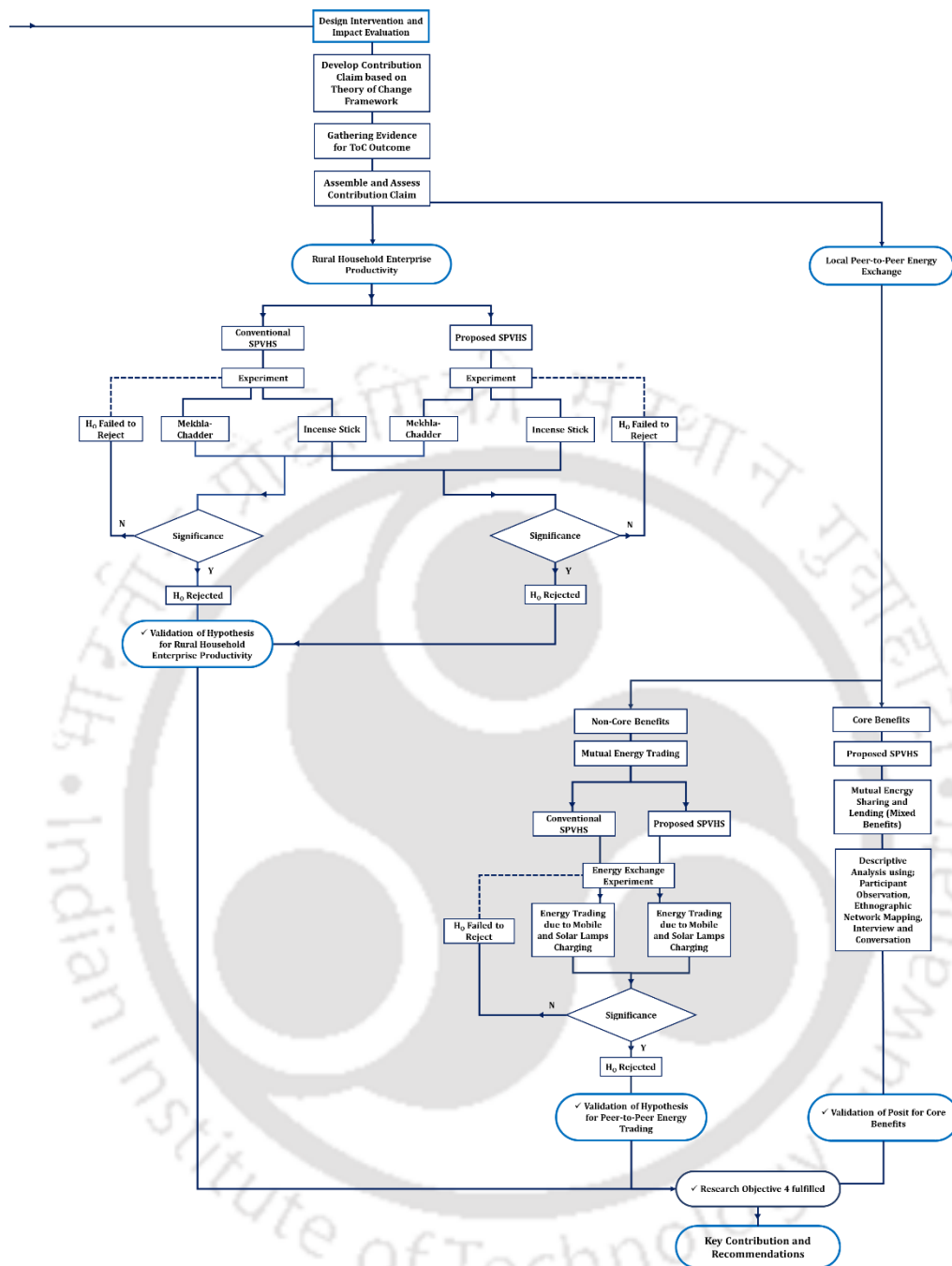


Fig 5.1 b) Shows details of design intervention and impact assessment along with specifics of the study to validate contribution claim resulting in key contribution and design recommendations.

As observed in figure 5.1, the photovoltaic ecosystem studied for user needs assessment followed by system performance and technical analysis, which includes critical load estimation and development of rural energy scenarios. Based on the localized design parameters, an optimal solution for system architecture and concept

design evaluated using a multi-criteria decision making based Fuzzy-Topsis method. The shortlisted system design concept was technically apprehended using MATLAB@Simulink. Besides, hardware realization was done based on simulation results. The prototype then subjected to human-factor evaluation like postural analysis for carrying and lifting of storage modules using OWAS. Besides, SUS and TAM based evaluation methods used for usability testing of the proposed design. Intervention outcome, along with impact pathways, is studied for the rural mode of life to evaluate off-grid photovoltaic system design applying theory of change framework. The study involves field trial experiments comparing the proposed design with the conventional system. In the end, recommendations were made based on the consequences of intervention outcomes. The following section discusses the salient findings of the research—details of the flowchart also given in appendix 10.

## **5.1 Salient Findings of Present Research**

- ❖ In the study, related to proposed intervention indicated that design activities need to go beyond mere energy access, and achieve its context-specific use. The results from the field trial underline the importance of adopting a broader approach to ensure the desired outcome and impact, in the long run, focusing not only on the technical aspects of energy provision but also on the societal perspective assisting the rural mode of living. The study showed that proposed intervention alone could not be responsible for an acceptable energy solution if not cohesive with rural needs. In particular, it was found that the design intervention for its successful implementation needs to be considered at more comprehensive systemic scale.
- ❖ The study also takes account of Matlab-simulation to realize the rural energy scenarios (developed from the study of the localized photovoltaic ecosystem) in real-time. From the simulation, it was observed that pulse charging outperforms to continuous charging. Moreover, discrete storage architecture is found more reliable compared to the use of a single large battery in a conventional system. Keeping in view simulation results and design parameters, hardware for the adaptive off-grid photovoltaic system is realized and tested. In the hardware development, discrete smart storage (i.e., the battery gets conveniently swapped) considered for advance usability and human factors.

- ❖ The intervention of proposed off-grid photovoltaic design resulted in non-monetary PUE benefits, witnessed to be a critical feature of rural engagement. Furthermore, such non-monetary benefits showed promising scope for the sustenance of off-grid photovoltaic applications promoting community vitality. For monetary benefits, research showed that the design intervention encouraged local energy exchange by facilitating add-on income benefits due to mobile and solar lamp charging.
- ❖ This study reported that non-monetary benefits did not sustain any immediate results. The benefits, as mentioned above, found indirectly persuading monetary benefits due to abetted social cohesion between participants.

## 5.2 Key Contributions of Present Study

This interdisciplinary research makes a novel knowledge contribution to the fields of (a) product design and (b) energy studies. The main contributions of this research are as follows:

- ❖ This study brings understanding about productive usage of photovoltaic energy (PUE) from a product design intervention perspective to the best of researcher knowledge such an attempt has not investigated before. The present research familiarizes, to the domain of product design and energy studies, a perspective to understand the usage of energy concerning localized peer to peer exchange and rural enterprise work productivity. In general, this research brings attention to the productive use of energy through design intervention perspective as an object of research inquiry.
- ❖ The present study majorly contributes towards enabling diversity in local energy exchange to help to address rural householder's limited ability to pay in cash. It is stressed as one of the impediments for the growth of off-grid energy systems (Chaurey et al., 2012; Palit & Bandyopadhyay, 2015; Podes, 2010; Urmea, Harries, & Schlapfer, 2009), as the householders can legitimately use the other types of returns in case of cash scarcity.

### Advantage of Multiplicity in Local Energy Exchange

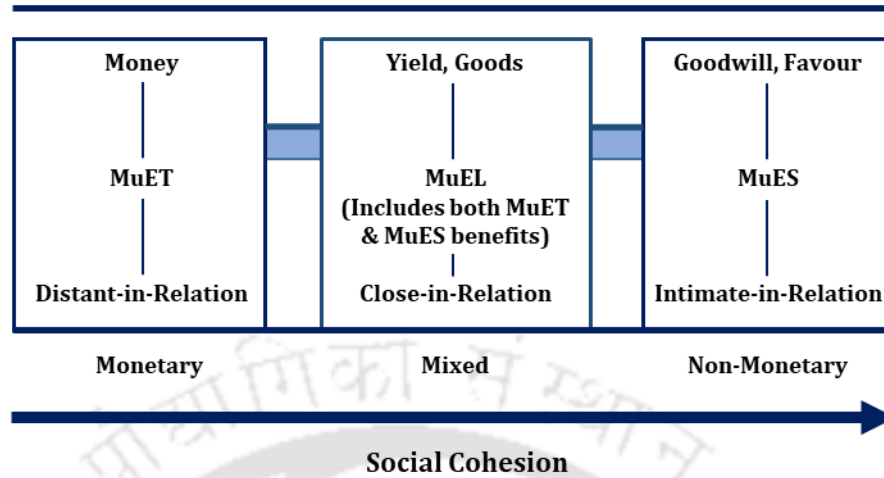


Fig 5.2 Schematic representation for energy exchange continuum as witnessed during intervention of proposed design in localized context of north-east India. The social cohesion improved as continuum emerged from monetary towards non-monetary energy exchange.

This research enabled a people-centered off-grid intervention by making energy exchange more receptive to the social, cultural, and economic spheres in a rural setting (fig 5.2).

- ❖ This study proposes a novel method to supplement product design, by making use of an innovative combination of research tools incorporating MCDM Fuzzy TOPSIS for system architecture and concept design evaluation, MATLAB@Simulink for design optimization, OWAS, SUS and Technology Adoption Model for human factors and usability evaluation. Theory of Change framework implemented for design intervention impact assessment.
- ❖ This study proposes the design recommendations. These recommendations can assist product designers in having an appropriate understanding of the small-scale off-grid photovoltaic intervention and provides the necessary support for concerning interventions to disseminate and sustain in a localized rural context.
- ❖ In context to the exploration of peer-to-peer energy returns, this study contributed towards the social classification of peer-to-peer energy exchange in the non-commercial sphere of energy.

- ❖ The present study contributes to enlarge the scope of photovoltaics driven product design for a design researcher, and showcase that societal evidence are critical for the efficacy of design intervention in the context as mentioned above.

### 5.3 Design Recommendation

The following design recommendations resulted from the present study.

- ❖ This study recommends to energy researchers and practitioners that in context to design and development of the photovoltaic intervention, enabling diversity in peer-to-peer exchange for an off-grid energy system supports societal relevance, and found critical for dissemination and sustainability of the off-grid photovoltaic intervention to rural grassroots. This study facilitates a holistic and critical understanding of how intervention outcomes are deeply embedded in and have implications for social context. The above facilitated the practicability of design intervention in the regional context. In conclusion, a recommendation for design scholars and energy researchers is to work towards convergence of the fields of design and energy, as it specified a prospective scope.
- ❖ Research indicated that the observed evidence supports the assumption that discrete design for the off-grid photovoltaic system resulted in a positive impact on the rural lifestyle. The proposed intervention resulted in core benefits like MuES and MuEI, and are found significant for rural engagement as it evoked diversity in energy returns. Considering the resulted benefits of multiplicity-in-exchange, the study recommends discretization should be considered for design and development of a small-scale off-grid photovoltaic system in the rural settings.
- ❖ Design intervention for the SPVHS was based on certain assumptions. The study witnessed that some of the crucial assumptions on the field were not there while designing the product. Concerning the above, design consideration for rural social-structure assisted in comprehending assumptions for the types of observed energy exchange due to practicing of intervention. It indicated that not only design and development but also design implementation needs to ensure the efficacy of assumptions. Else, the impact of design intervention will be less because of the non-validity of assumptions.

## 5.4 Limitations of Study and Future Scope

Despite enormous and sincere efforts to achieve the best results out of it, there are always some concerns, which restrict the results. The limitations of research can be explored for future investigation.

- ❖ The sample size was moderate for the study due to the limitation of funds available, the time required, and accessibility to the remote area and the users. Further, it could be possible to extend similar research in other relevant energy-poor states for viable testing of the proposed off-grid photovoltaic home system.
- ❖ There exists adequate research scope for the development of design methods or tools that can support energy designers or practitioners to gain quick insights into the multiplicity of energy exchange and its correlation to social cohesion or the rural engagement. Besides, the above will help to measure the impact of design intervention in rural off-grid energy settings.
- ❖ This study reported the significance of introducing a socially grounded, user-centered, and bottom-up approach for the design development of a decentralized energy system and should consider non-monetary and monetary benefits to facilitate energy access. It provides further scope to assist policy-formulation in mitigating regional challenges for dissemination of small-scale photovoltaic applications.



## Appendices



## Appendix 1

### Questionnaire for the Feasibility Study of SHS Design and Development

(Adopted and modified from Barman et al., 2017)

**Dear Respondent,** the purpose of this study is to understand the need for a design and development initiative for the solar home system in the local context of rural North East India, Kindly spare few minutes to go through the questionnaire and fill it accordingly. **Please be assured that your feedback will be kept strictly confidential and will be used for academic research purpose only.**

1. Name and Age

2. Gender:

3. Occupation:

4. Village:

5. Census / Pin code:

6. Block:

7. District / State:

8. No of family members:

9. Approximate family Income / month (In Rs)

10. Do you have electricity connection in your house?

Yes  No

11. If yes, then for how long you use electricity /day?

..... Approximate Hrs

12. Do you own any Solar Product?

Yes  No

13. Do you think solar photovoltaic energy is a feasible option when compared with other renewables like wind, biogas, and micro-hydro?

Yes  No  Maybe

14. If yes, do you prefer a small scale photovoltaic application like home system over large scale applications like a solar microgrid from a utilitarian perspective?

Yes  No  Maybe

15. Do you think solar photovoltaics based design intervention has the potential to assist the local economy, lifestyle?

Yes  No  Maybe

16. Do you prefer an incentive based photovoltaic home system?

Yes  No  Maybe

17. Why did you feel the need for a photovoltaic home system?

a. Grid is not connected

b. Electricity provided through the grid is for a minimal period

c. Others

18. Is there any improvement in livelihood due to the presence of SHS in your house?

.....

19. If solar electricity is available, then for what purpose you like to use it as an alternative?

.....

20. What are the electrical appliances currently being used in your house?

.....

21. Technical Specification of the System

- a) Details of Battery (Type/Rating).....
- b) Details of Luminaire (Type/Rating).....
- c) Details of PV Module (Type/Rating).....
- d) Details of Charge Controller (Rating).....

22. Current Operational Status

- a) Operational
- b) Partial operation with minor faults
- c) Partial operation with major faults
- d) Not working   
(Reasons for not working)

23. Duration of operation of SHS per day (hours)?

.....

24. Connected household load

- a) Lamp (numbers/rating)
- b) TV (numbers/rating)
- c) Mobile charging (numbers/rating)
- d) Any others

25. Do you think the present SHS can meet your electricity needs?

- Yes  No  Maybe

26. What devices do you think can run on solar/, or you wish to acquire in the future?

.....

27. Do you feel the need for a grid connection? If yes, why and if no, why?

.....

28. What are the various faults experienced by you in the system?

.....

29. The period required for rectification of each fault

.....

30. Has the local technician readily available?

- Yes  No

31. Annual expenses on maintenance of the system, and what are the faults on which the expenditures made?

.....

32. Rate the following between 1-5 for existing SHS, 1=lowest, 5=highest

	Highly Dissatisfied (1)	Dissatisfied (2)	Neutral (3)	Satisfied (4)	Highly Satisfied (5)
Portability					
Maintenance					
Affordability					
Functionality					
User Satisfaction					

33. What, according to you, are drawbacks/advantages of existing solar product/s?

Questions	User Statement	Interpretation	Importance
Typical Uses			
Likes			
Dislikes			
Suggested Improvements			

34. Any other comments or suggestions for further improvement?

Place  
Sign and Date

Respondent ID

## Appendix 2a

### Sizing of Solar PV System for Energy Scenario 1

#### Battery Bank Sizing

Total Energy / Day = 700 Wh

System Voltage = 12V

Depth of Discharge = 50

Autonomy Days = 0

Battery Type = \* Valve Regulated Lead Acid (VRLA) Maintenance Free

Battery Capacity Required =  $700 / 0.5 \times 12 = 116.66 \sim 120$  Ah

Number of Batteries in Series =  $12/12 = 1$

Actual Battery Capacity = 120 Ah

Standard Battery Capacity =  $120 / 60$  Ah

Number of Batteries in Series =  $12/12 = 1$

Number of Batteries in Parallel =  $120/120 = 1$

Number of Batteries in Parallel =  $120/60 = 2$

Total Batteries Required =  $2 \times 1 = 2$

\* 120 Ah of Required Capacity is Split into two Batteries of 60 Ah considering difficulties related to maintenance of Batteries in Remote, Rural Geographies.

#### Battery Bank Specification

2 @ 60 Ah, 12V, C10, Valve Regulated Lead Acid (VRLA) Maintenance Free, Parallel Connected

#### Solar Photovoltaic Module / Array Sizing

Total Load Energy = 700 Wh

$\eta_{\text{Cable+Controller+Battery}} = 85\%$

Energy Required from SPV Array =  $700 / 0.85 = 823.53 \sim 825$  Wh

Number of Sunshine Hours available in North East India = 4.5 Hrs / Day

SPV Required Wattage =  $825 / 4.5 = 183.34 \sim 185$  Wp

Standard SPVM Capacity = 100 Wp, 200 Wp 12 V

Number of Panel Required in Series =  $12/12 = 1$

Number of Panel Required in Parallel =  $185/100 = 1.85 \sim 2$  or

Number of Panel Required in Parallel =  $185/200 = 0.92 \sim 1$

Number of Panel Required in Parallel =  $185/200 = 0.92 \sim 1$

1 @ 200 Wp, 12V, Polycrystalline Module

#### SPVM Fixed Mount Tilt Angle

SPVM Tilt Angle  $\beta$  Depends upon Latitude  $\phi$  of the Place

Guwahati Latitude  $\phi = 26.14^\circ$  N

Fixed Mount Tilt Angle  $\beta = \phi - 5^\circ = 26.14 - 5 = 21.14 \sim 21^\circ$  Facing South

## MPPT Charge Controller

Total Wattage = 110

System Voltage = 12 V

Maximum Current =  $110 / 12 = 9.16 \sim 10$  A

## MPPT Charge Controller Specification

10 Amp, 12 V

## DC Wiring, Fuse & Junction Box

Max DC Wattage =  $2 \times 100 = 200$  W

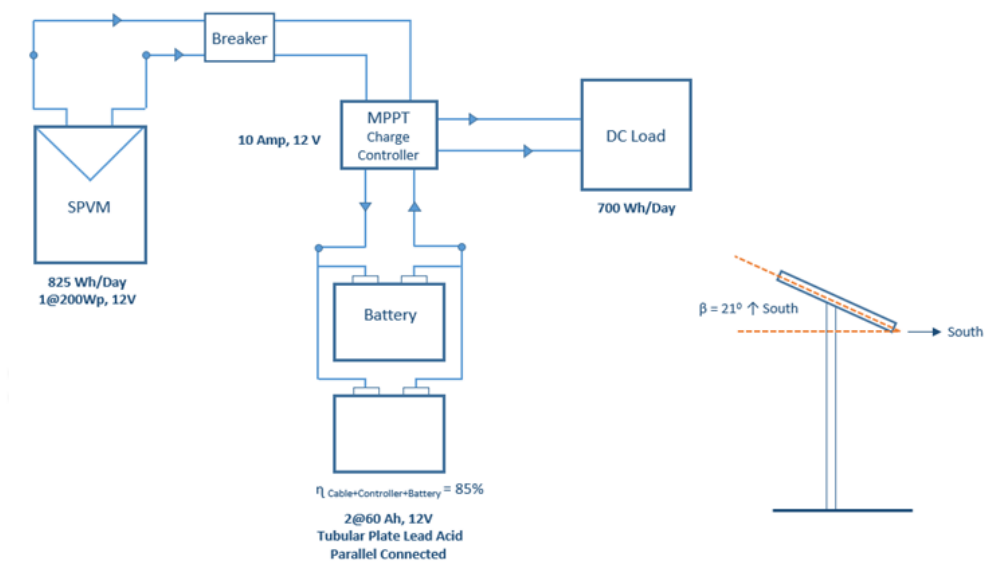
DC System Voltage = 12 V

Max DC Current =  $200 / 12 = 16.67 \sim 17$  A

## Specification

12V, 17 A

## Wiring Diagram



Wiring Diagram for Energy Scenario 1 (Source: Author Compilation)

## Design Specification 1

SPVM

1@200Wp, 12V

SPVM Fixed Mount Tilt Angle

$\beta = 21^\circ$   $\uparrow$  South

Battery

2@60 Ah, 12V, Tubular Plate Lead Acid, Parallel Connected

MPPT Charge Controller

10 A, 12 V

## Appendix 2b

### Sizing of Solar PV System for Energy Scenario 2

#### Battery Bank Sizing

Total Energy / Day = 300 Wh

System Voltage = 12V

Depth of Discharge = 50

Autonomy Days = 0

Battery Type = \* Valve Regulated Lead Acid (VRLA) Maintenance Free

Battery Capacity Required =  $300 / 0.5 \times 12 = 50$  Ah

Lead Acid Battery Efficiency = 85% =  $50 / 0.85 = 58.82 = 60$  Ah

Actual Battery Capacity = 60 Ah

Standard Battery Capacity = 60 or 30 Ah

Number of Batteries in Series =  $12 / 12 = 1$

Number of Batteries in Parallel =  $60 / 30 = 2$

Total Batteries Required =  $2 \times 1 = 2$

\* 60 Ah of Required Capacity is Split into two Batteries of 30 Ah considering difficulties related to maintenance Batteries in Remote, Rural Geographies.

#### Battery Bank Specification

2 @ 30 Ah, 12V, C10, Sealed Maintenance Free, Parallel Connected

#### Solar Photovoltaic Module / Array Sizing

Total Load Energy = 300 Wh

$\eta_{\text{Cable+Controller+Battery}} = 85\%$

Energy Required from SPV Array =  $300 / 0.85 = 352.94 \sim 355$  Wh

Number of Sunshine Hours available in North East India = 4.5 Hrs / Day

SPV Required Wattage =  $355 / 4.5 = 78.88 \sim 80$  Wp

Standard SPVM Capacity = 80 Wp 12 V

Number of Panel Required in Series =  $12 / 12 = 1$

Number of Panel Required in Parallel =  $80 / 80 = 1$

1 @ 80 Wp, 12V Polycrystalline Module

#### SPVM Fixed Mount Tilt Angle

SPVM Tilt Angle  $\beta$  Depends upon Latitude  $\phi$  of the Place

Guwahati Latitude  $\phi = 26.14^\circ$  N

Fixed Mount Tilt Angle  $\beta = \phi - 5^\circ = 26.14 - 5 = 21.14 \sim 21^\circ$  Facing South

#### MPPT Charge Controller

Total Wattage = 50

System Voltage = 12 V

Maximum Current =  $50 / 12 = 4.1 \sim 5$  A

#### MPPT Charge Controller Specification

5 Amp, 12 V

DC Wiring, Fuse & Junction Box

Max DC Wattage =  $1 \times 80 = 80 \text{ W}$

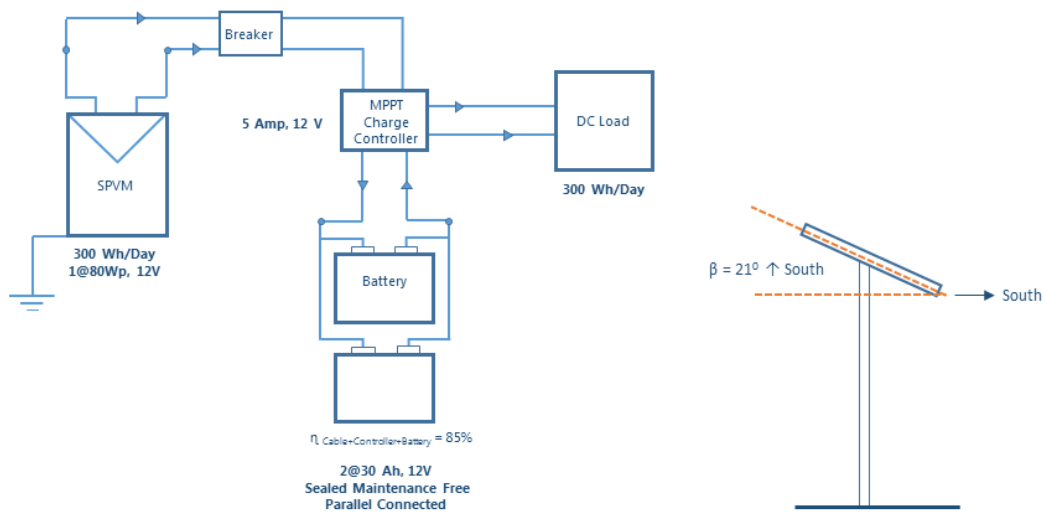
DC System Voltage = 12 V

Max DC Current =  $80 / 12 = 6.66 \sim 7 \text{ A}$

Specification

12V, 7 A

Wiring Diagram



Wiring Diagram for Energy Scenario 2 (Source: Author Compilation)

### Design Specification 2

SPVM

1@80Wp, 12V

SPVM Fixed Mount Tilt Angle

$\beta = 21^\circ \uparrow$  South

Battery

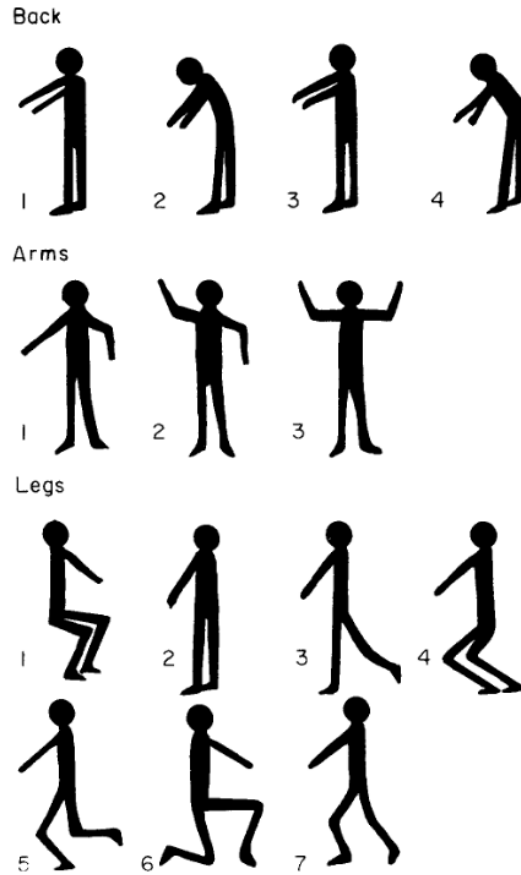
2@30 Ah, 12V, Sealed Maintenance Free

MPPT Charge Controller

5 A, 12 V

## Appendix 3

### Details of Ovako Working Posture Analysis System



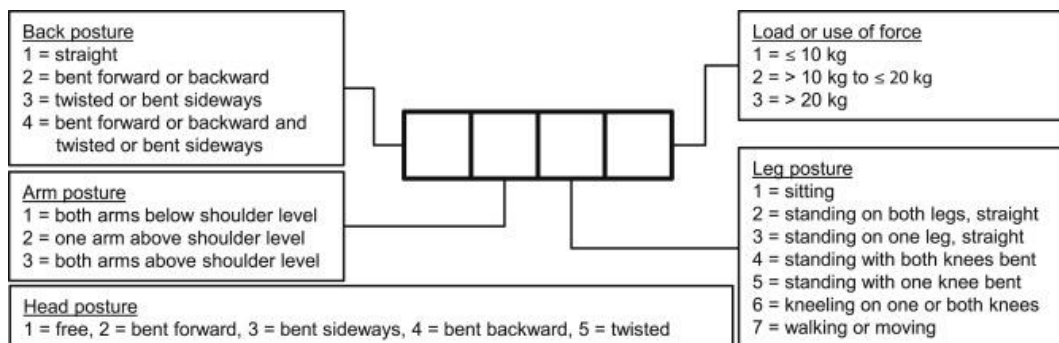
OWAS codes for different body parts  
(Adopted from Mattilda and Vilkki, 1998)

Back code: 1, straight; 2, bent; 3, twisted; 4, bent and twisted

Arms code: 1, both below shoulder level; 2, one above shoulder level; 3, both above shoulder level

Legs code: 1, sitting; 2, both straight; 3, one straight; 4, both bent; 5, one bent; 6, kneeling; 7, walking

Load effort code: 1,  $\leq 10$  kg; 2,  $\leq 20$  kg; 3,  $\geq 30$  kg



(Adopted from Brandl, C., Mertens, A., & Schlick, C. M. (2017))

### Details of Ovako Working Posture Analysis System

Action level category and load risk for evaluation of working postures (Adopted from Mattilda and Vilkki, 1998)		
Category	Description	Posture
Action Category 1	Work postures usually considered with no particular harmful effect on the musculoskeletal system. No actions are needed to change work postures	Good Posture
Action Category 2	Work postures have some harmful effects on the musculoskeletal system. Light stress, no immediate action is necessary, but changes should be considered in future planning	Somewhat Good Posture
Action Category 3	Work postures have a distinctly harmful effect on the musculoskeletal system. The working methods involved should be changed as soon as possible	Poor Posture
Action Category 4	Work postures with an extremely harmful effect on the musculoskeletal system. Immediate solutions should be found to change these postures	Very Poor Posture



## Appendix 4

### Questionnaire for the Study of Photovoltaic System Usability

(Adopted and modified from Bangor, Kortum & Miller, 2008; Lewis, 2018)

Dear Respondent, the purpose of this study is to study the system usability and perceived human factors aspects of the off-grid photovoltaic system. Kindly spare a few minutes to go through the questionnaire and fill it accordingly. **Please be assured that feedback is kept strictly confidential and used only for academic research purposes.**

1	Name of the Respondent / ID (Gender and Age)	
2	Dist. / Village / Block	

System Usability Scale						
Rate the following;		1	2	3	4	5
		1 = Strongly Disagree , 5 = Strongly Agree				
1a	I think I would like to use this product frequently	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
1b	I found the system unnecessarily complex	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
1c	I thought the product was easy to use	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
1d	I think that I would need the support of a technical person to be able to use this product	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
1e	I found that the various functions in this system were well-integrated	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
1f	I thought that there was too much inconsistency in this product	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
1g	I would imagine that most people would learn to use this product very quickly	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
1h	I found the product very awkward to use	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
1i	I felt very confident using the product	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
1j	I needed to learn many things before I could get going with this product	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Perceived Human factors						
Rate the following;		1	2	3	4	5
		1 = Strongly Disagree , 5 = Strongly Agree				
2a	Exposure of system to potential dangers while in use (electrical, chemical, physical, etc.)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
2b	Potential of system while use in unsafe conditions	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
2c	The system requires less effort to accomplish a task (carrying of the storage module, installation of the system, etc.)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
2d	Perceived comfort for workspace improved, due to the intervention of the photovoltaic system	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
2e	Perceived comfort facilitated work productivity	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

## Appendix 5

### Questionnaire for the Study of System Technology Adoption

(Adopted and modified from Sauro, Lewis, Sauro, & Lewis, 2012)

Dear Respondent, the purpose of this study is to study the aspects of technology adoption for an off-grid photovoltaic system. Kindly spare a few minutes to go through the questionnaire and fill it accordingly. **Please be assured that feedback is kept strictly confidential and used only for academic research purposes.**

1	Name of the Respondent / ID (Gender and Age)	
2	Dist. / Village / Block	

1.2 Technology Adoption Model		1	2	3	4	5
Rate the following;						
		1 = Strongly Disagree , 5 = Strongly Agree				
	<b>Intention to Use</b>					
1a	Assuming I have access to the system, I intend to use it	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
1b	Given that I have access to the system, I predict that I would use it	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
	<b>Perceived Usefulness</b>					
1c	Using the system improves my performance in the job	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
1d	Using the system in my job increases my productivity	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
1e	Using the system enhances my effectiveness in my job	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
1f	I find the system to be useful in my job	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
	<b>Perceived ease of use</b>					
1g	My interaction with the system is clear and understandable	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
1h	Interacting with the system does not require a lot of my mental effort	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
1i	I find the system to be easy to use	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
1j	I find it easy to get the system to do what I want it to do	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

## Appendix 6

Part A Logframe matrix depicts research goal, objectives, level, criteria, sub-level and assumptions for proposed design evaluation

Goal	Objective	Level	Criteria	Sub-Level	Description	Assumptions
Facilitating access to decentralized solar energy with productive use benefits through proposed SPVHS design intervention, coherent with rural lifestyle	Proposed Design intervention would result in household enterprise productivity benefits	Outcome	Effectiveness	Outcome 1.1	Multitasking for indoor/outdoor rural activities ; Use for various indoor and outdoor rural activities	Proposed design is appropriate and specific to rural lifestyle conditions
				Outcome 1.2	Mutual energy exchange benefits among rural household ; 1 Social Connectedness 2 In-kind exchange	Access to decentralized power will provide flexibility to perform location specific multiple tasks facilitating work productivity
		Outcome 1.3	To Improve household enterprise productivity; (in reference to) 1 Handloom weaved mekala chadder 2 Handmade incense sticks	Time for livelihood activities should be within operable time of battery		
	Proposed Design intervention would result in additional - income benefits	Outcome	Effectiveness	Outcome 1.4a	Mutual energy trading benefits related to charging ; 1 Charging Mobile Phone 2 Charging Solar Lamp	Improved production is less time intensive
				Outcome 1.4b	Mutual Energy Trading Benefits related to Lending ; 1 Module lending to neighbours 2 Module lending to local vegetable, fruit and fish vendors	Mutual energy sharing will provide scope to promote social connectedness between households Non-monetary exchange will help growing local energy network in rural scenario of north-east Battery module will come back to same facility for charging People are capable and willing to pay to receive energy trading benefits
						Improvement in household income materialise and benefit household / community members

Part B of Logframe matrix depicts indicators, measure and questionnaire for proposed design evaluation

Indicators	Measure	Questionnaire
1 Frequency of activities performed/day	Scale	Q1.1.1 Do you think that proposed design has given you flexibility to perform indoor and outdoor multiple activities Y/N
2 Type of activities performed	Scale	Q1.1.2 If yes, then how many times you think such activities were performed in a day or a week ? Q1.1.3 What was the nature of activities performed using proposed design ?
1 Perceived improvement in social relation	Scale	Q1.2.1 Does your neighbour have ever asked you to lend them storage module ? Y/N
2 Number of goods exchanged/day or week		Q1.2.2 Did you receive any favours for lending storage module ? Y/N
3 Number of times storage module lentended / day or week		Q1.2.3 How many times storage module is lentended per day or per week ?
4 Number of hrs module lentended / day or week		Q1.2.4 What was the nature of such transactions ? Monetary Non-Monetary
5 Social Connectedness		Q1.2.5 On average, for how long (in hrs) storage module is taken eachtime ?
1 Work hrs/day	Q1.2.6a	Rate your relationship with your neighbour before start of such exchange
2 Number of units produced /day or / week (depending on nature of product)	Q1.2.6b	Rate your relationship with your neighbour after start of such exchange
3 Overall Income Earned		
1 Frequency of devices charged / day	Scale	Q1.3.1 Proposed design has improved household scale work productivity
2 Amount charged / device / category		Q1.3.2 What is cost of production per piece of mekala chadder ? / What is the cost of production per incense stick ?
3 Income (1x2)		Q1.3.3 How much time you took to produce one unit ?
		Q1.3.4 How many units of mekala chadder are produced per week ?
1 Frequency of lending	Scale	Q1.3.5 How many units of incense sticks are produced per day ? / How many units of incense sticks are produced per hour ?
2 Number of hrs storage module lentended / day or week on monetary basis		Q1.4.1.1 Proposed design has improved the scope of mutual energy trading benefits due to charging
3 Per hour charges		Q1.4.1.2 How many devices were charged in a day ?
4 Income (1x2x3)		Q1.4.1.3 What is the amount charged per mobile charging ?
		Q1.4.1.4 What is the amount charged per solar-lamp charging ?
		Q1.4.1.5 What is the amount you charged per battery-bank ?
		Q1.4.2.1 Proposed design has improved the scope of mutual energy trading benefits due to lending
	Scale	Q1.4.2.1 What is the frequency of lending storage module ?
		Q1.4.2.2 After how long modules are returned back per transaction ?
		Q1.4.2.3 On what basis you charged amount for lentended storage module ?
		Q1.4.2.4 1. Per transaction basis 2. Per Hour basis 3. Per Day basis 4. Others
		Q1.4.2.4 What is the amount you charged per lending transaction ?

## Appendix 7

### Questionnaire for the Study of Efficacy of the Design Intervention

(Adopted and modified from Barman et al., 2017)

Dear Respondent, the purpose of this study is to study the efficacy of the off-grid photovoltaic system. Kindly spare a few minutes to go through the questionnaire and fill it accordingly. **Please be assured that feedback is kept strictly confidential and used only for academic research purposes.**

1a	Name of the Respondent / ID	
1b	Gender and Age	
1c	Dist. / Village / Block	
1d	Current Monthly Income	<ul style="list-style-type: none"> <li>a. Below Rs 2,500</li> <li>b. Rs 2,501 - 5000</li> <li>c. Rs 5,001 - 7,500</li> <li>d. 7,501 - 10,000</li> <li>e. &gt; Rs 10,000</li> </ul>
1e	Monthly expenditure on fuel or electricity (Candle/Kerosene/ Electricity/others)	<ul style="list-style-type: none"> <li>a. Fuel</li> <li>b. Electricity</li> </ul>
1f	Which option is better for lighting (based on his/her perception of interaction with other villages having grid)?	<ul style="list-style-type: none"> <li>a. Solar lighting</li> <li>b. Grid</li> </ul> Reason for Preference
1g	Income activities in the family	<ul style="list-style-type: none"> <li>a. Agriculture</li> <li>b. Govt job</li> <li>c. Self Employed</li> <li>d. Un-Employed</li> <li>e. Others</li> </ul>

#### 1.1 Work Productivity Benefits

2a	Product Category	
2b	What is the cost of production/unit (In Rupees)	
2c	How much time did it take to produce / unit (in hrs)?	
2d	How many units are produced / hour or week?	
2e	Has the photovoltaic system improved the work hrs if Yes, please mention tentative time	
2f	Does the presence of an off-grid photovoltaic system facilitate productivity due to workspace comfort, if any, then please describe?	

## 1.2 Energy Trading Benefits

Mutual Energy Trading due to Lending		Yes (whichever applicable)	No (whichever applicable)	Freq. (whichever applicable)	Others (whichever applicable)
4a	Did you lend a module on a monetary basis?				
4b	If yes, then how many times storage modules rented in a day on a monetary basis				
4c	Did the receiver willingly pay the lending amount?				
4d	Did the receiver capable of paying the lending amount?				
4e	What is the mode of the lending storage module	Per Unit basis		Total Time Consumed	
4f	What is the amount charged per lending?				Rs
4g	On average, after how long the storage module returned back				hrs

Mutual Energy Trading due to Charging		Yes (whichever applicable)	No (whichever applicable)	Freq. (whichever applicable)	Others (whichever applicable)
3a	Did people charged their mobile phones or solar lamps using SPVHS				
3b	How many devices charged per day				
3c	Did the receiver willingly pay the charged amount?				
3d	Did the receiver capable of paying the charged amount?				
3e	What is the amount charged per mobile charging				Rs
3f	What is the amount charged per solar lamp charging				Rs

## 1.3 Energy Sharing Benefits

Non-Concrete Mutual Energy Exchange		Yes (whichever applicable)	No (whichever applicable)	Freq. (whichever applicable)	Others (whichever applicable)
5a	Did you lend the storage module to the neighbor?				
5b	How many times storage module lends in a day or week on a non-monetary basis.				
5c	Did you receive any favors for such a transaction, if yes, please describe?				
5c	On average, for how long the storage module is taken by neighbor every time.				hrs
5e	Do you feel improvement in the relationship with neighbors due to mutual energy sharing?				

## Appendix 8

### Work Productivity;

#### 1. Handwoven Mekhla Independent Sample

Variable	Kolmogorov Sig Value
PCPU	0.01
PTPU	0.02
UPW	0.01
PEW	0.03
EEW	0.01

\* For data to normally distributed  $p \geq 0.05$

PCPU Production cost per unit (Rs)  
PTPU Production time per unit per week (hrs)  
UPW Units produced per week (Value)  
PEM Profit earned per month (Rs)  
EEW Extended evening working hrs (hrs)

#### 2. Handmade Incense Sticks Independent Sample

Variable	Kolmogorov Sig Value
PCPU	0.01
PTPU	0.01
UPD	0.01
PEM	0.03
EEW	0.02

\* For data to normally distributed  $p \geq 0.05$

PCPU Production cost per unit (Rs)  
PTPU Production time per unit (hrs)  
UPD Units produced per day (Value)  
PEM Profit earned per month (Rs)  
EEW Extended evening working hrs (hrs)

### Mutual Energy Trading Exchange;

#### 3. Mutual Energy Exchange Independent Sample

Variable	Kolmogorov Sig Value
FMC	0.02
FSLC	0.01
ACMP	0.01
ACSL	0.01
IEMC	0.04
IESLC	0.01
OEM	0.05

\* For data to normally distributed  $p \geq 0.05$

FMC Frequency of mobile charging per day  
FSLC Frequency of solar lamp charging per day  
ACMP Amount charged per mobile phone for charging  
ACSL Amount charged per solar lamp for charging  
IEMC Income earned from mobile charging per day  
IESLC Income earned from solar lamp charging per day  
OEM Overall earning per month

## Appendix 9



অসম শক্তি উন্নয়ন অভিকৰণ  
ASSAM ENERGY DEVELOPMENT AGENCY  
(Under Science & Technology Department, Govt. of Assam)  
Bigyan Bhawan, Near IDBI Building, G.S. Road, Guwahati -781005  
☎ 0361-2450147, 2450646, Fax: 0361-2464617 e-mail: assamrenewable@gmail.com

No. AEDA/409/2014/ 2513

Date: 24/09/18

To,

✓ Sri Brajesh Dhiman  
Research Scholar  
Dept. of Design  
Indian Institute of Technology, Guwahati  
Guwahati-781039

**Sub: Design of prototype for Modular Solar Home System-Letter of Appreciation.**  
Ref: AEDA Sanction No. AEDA/409/2014/13/612 dtd. 14.06.17

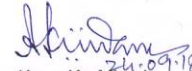
Dear Sir,

Assam Energy Development Agency would like to express its sincere appreciation for success achieved by New Design of the Modular Solar Home System duly funded by AEDA. The response on the proposed Design Prototype was positive with respect to fulfilling rural needs and was able to perform under challenging environmental conditions for solar energy.

During field-testing for over nine months in villages of Sonitpur district as well as Majuli, trials of Proposed Design Prototype Indicated Positive Social Impact by facilitating Rural Livelihood Opportunities. The new design of the Modular Solar Home System has shown significant improvement for rate of acceptance by rural user and indicated a positive response in dissemination of solar technology to rural grassroots.

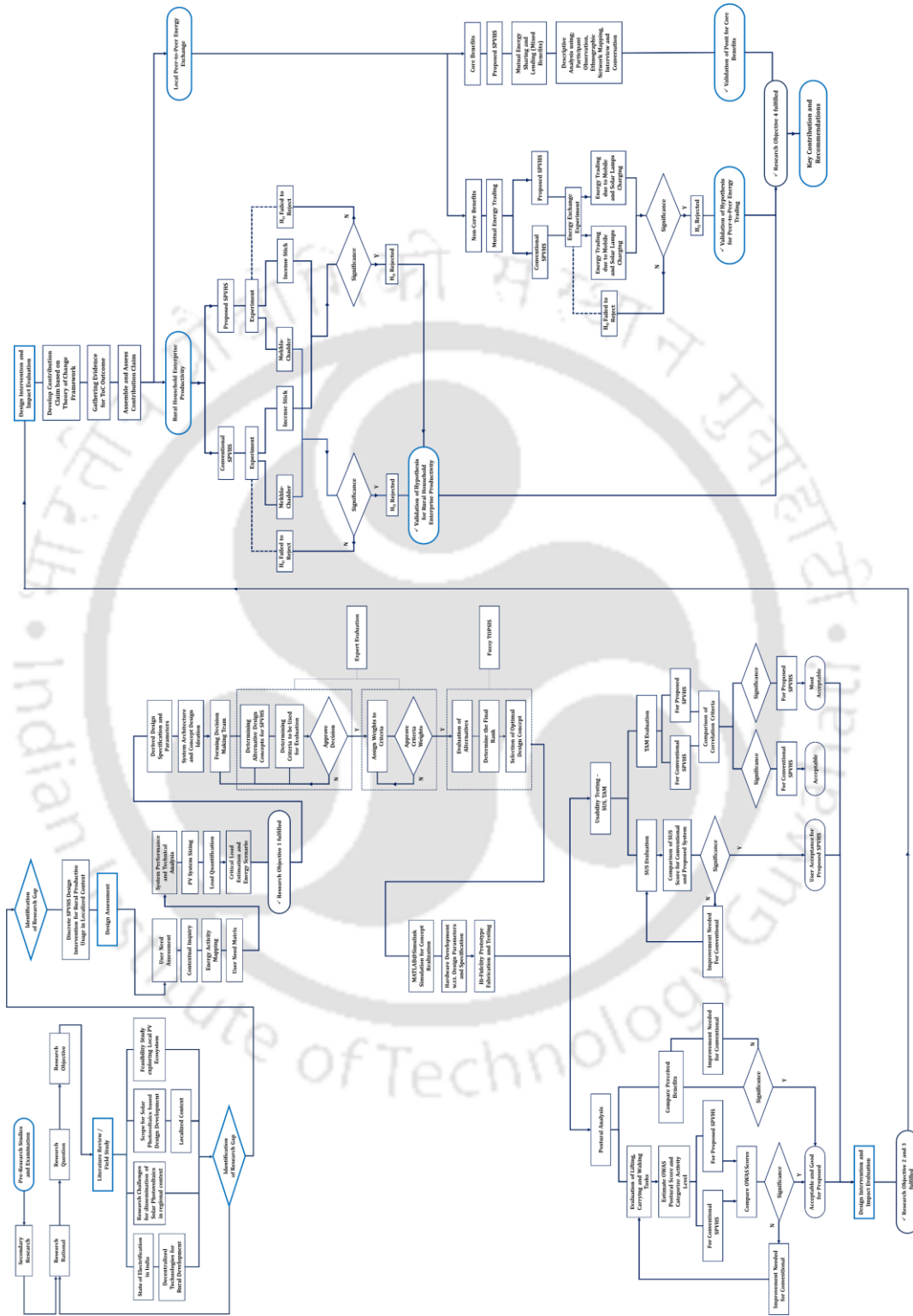
AEDA wish you success to his on-going Doctoral research work and for future endeavor.

Yours faithfully

  
(Arup Kr. Misra)  
24.09.18  
Director, AEDA



# Appendix 10



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## List of Publications

- ❖ Dhiman, B., Chaudhury, M. K., Deb, S. K., & Chakrabarti, D. (2017, January). Micro solar energy systems: product design intervention facilitating sustainable development for rural North East India. In International Conference on Research into Design (pp. 117-125). Springer, Singapore.
- ❖ Dhiman, B., Chaudhury, M. K., Mahapatra, S., & Chakrabarti, D. (2019). Socially Constructed Design in the Context of Small-Scale Solar Photovoltaic Home System. In Research into Design for a Connected World (pp. 391-401). Springer, Singapore.
- ❖ Dhiman, B., Rituraj, G., Chaudhury, M. K., & Chakrabarti, D. (2019). Design Optimization Tool for Development of Solar Photovoltaic System in Rural Household Context. In Research into Design for a Connected World (pp. 255-264). Springer, Singapore.
- ❖ Dhiman, B., Rituraj, G., Kumar, T., Bhalla, K., & Chakrabarti, D. (2019). Study of Small Scale Photovoltaic Applications in Rural Indian Household Context. IoP Journal of Physics Conference Proceedings. Scopus Index ISI Web of Science, Switzerland.
- ❖ Mishra, V., Dhiman, B., Kumar, T., Bhalla, K., & Sivakumar, S. (2019). Design and Development of Khadi-Kart: A Web based application for rejuvenating the Handloom Industry in India. IEEE Global Humanitarian Technology Conference (GHTC). Seattle, US.
- ❖ Conclave Poster, Case study of an off-grid photovoltaic home system : Opportunities in social perspective for rural communities in northeast India, IIT Guwahati Research Conclave 2016, Dhiman, B., & Chakrabarti, D.

# Micro Solar Energy Systems: Product Design Intervention Facilitating Sustainable Development for Rural North East India

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**Abstract.** Energy Access is one of the prime concerns, particularly for the development of North-Eastern India. Though this region is a hub of natural resources, yet it is deprived of easy access to commercial energy including, energy for domestic and other small scale applications. Complete Rural Electrification may not be possible in this part of the country through a conventional grid due to its remote geographical locations, dispersed population density, and the high cost of extending transmission lines. This creates an imbalance leading to the lack of basic amenities and thereby economic backwardness for the northeast region persists. In this regard, decentralized energy solutions become part of the development of local self-reliance. In general, this paper aims to demonstrate possible benefits of a product design intervention for Micro Solar Energy Systems and Micro Enterprise, upscaling rural livelihood.

**Keywords:** Micro Solar Energy System • Product Design • Sustainable Development • Decentralized Energy • Rural North East India.

# Socially Constructed Design in Context of Small Scale Solar Photovoltaic Home System

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**Abstract.** Societal relevance plays an essential role in the dissemination of solar photovoltaic home system design in the rural context, as it syndicates economic benefits for livelihood improvement along with social and environmental advantage. For socially responsible design, it must cradle design that apprehends and bring positive social change. Furthermore, the socially constructed design facilitates the progress of a rural community in the broader context such as up-scaling the rural livelihood, generating micro-enterprise opportunities. Energy-Poverty is one of the main concerns, especially for the development of northeastern states of India. This creates a disparity, leading to economic backwardness of the region. In this regard, socially constructed energy solutions may emerge as an integral part of growth and development. The noticeable benefits due to the adoption of small-scale solar photovoltaics home system in the social context of rural northeast India studied in this paper. During the field study, it is observed that such approach could overcome present challenges like lack of involvement of local stakeholders and lack of employment-related opportunities necessary to facilitate the diffusion of solar photovoltaics home system to rural household. As a result, socially constructed energy solutions can become a part of the rural development promoting local self-reliance. Besides, this may facilitate dissemination of renewable energy technologies along with socio-economic development of the rural community in the region.

**Keywords:** Solar Photovoltaic Home System • Socially Constructed Design • Productive Use of Energy • Technology Dissemination • Decentralized Technology

# Design Optimization Tool for Development of Solar Photovoltaic System in Rural Household Context

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**Abstract.** In India, there are about 263 million people do not have access to electricity (IEA, World Energy Outlook 2015). Many rural parts either are not connected with the grid or are served with an irregular power supply. In such cases, a dependable source is required to avail the electricity primarily for lighting purpose. Solar photovoltaic home system (SPVHS) may provide a solution to compensate electricity for households where the national grid does not reach or the population density is too sparse to build a mini-grid. SPVHS becomes the most reliable and dependable option to provide electricity. Generally, in most of the rural areas, people are using the unverified quality solar PV home systems, which are less reliable and have an unpredictable lifespan. Although, such a system is lower in cost due to the poor configuration, which results in repeated malfunction and frequent failure of components. This makes it more expensive or unsustainable in the long run and causes user dissatisfaction. Considering the scenario above, a design optimization tool (DOT) can be conceptualized to create an opportunity, which can play a prominent role in improving the reliability of SPVHS. This paper presents the concept of a design optimization tool for the small-scale solar photovoltaic home system along with its user interface. Such a tool would provide a level of confidence to the user or a service provider and establish the dependability of solar PV technology in remote areas. Various aspects of tool development, including electrical design and usability, are studied in context to remote villages of Assam. The conceptualized tool focuses on system configuration, system size, and tilt of PV-module. Moreover, the graphical user interface of DOT can facilitate self-designing of such system by average rural users. To fulfill energy demand by considering affordability and reliability of design when taken up as a whole, the proposed tool would ensure optimal design selection based on the user requirement.

**Keywords:** Solar Photovoltaic Home System • Design Optimization Tool • Decentralized Energy • Technology Dissemination • Rural Application

# 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 fulfill 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.



