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# Towards equitable and inclusive energy systems for remote off-grid communities: A socio-technical assessment of solar power for village Helario in Tharparkar, Pakistan

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ABSTRACT

Universal access to clean electricity (SDG7) in remote areas of the rural South remains a key challenge for economic growth, and has particular implications for equitable, inclusive and sustainable development. In Pakistan, techno-economic constraints in grid expansion for last-mile users, combined with the country's high solar energy potential make off-grid solar energy generation a viable solution, provided its technological, social and economic implications are well-understood in terms of actual energy demands and designed for equitable distribution. This paper presents a socio-technical feasibility assessment for designing equitable and inclusive off-grid solar systems using the case-study of Helario village in Tharparkar, Pakistan, with a key focus on gender-specific benefits. A mixed-methods approach is used to conduct a baseline field assessment of existing energy sources, community needs, women's access and energy use, affordability, future energy aspirations and social acceptability of renewable energy technologies. Results indicate gendered differences in mobility, education, everyday practices and income that have socio-economic implications, whereby women can benefit more from electrification, particularly when electricity is interlinked with access to clean water. Results are used to model, simulate and optimise a solar-battery mini-grid system for tiered and equitable energy access using CLOVER. Analysis shows that a system designed with a 10-year lifetime provides the lowest levelised cost of electricity and minimum emissions intensity, emphasising the need for long-term energy system planning. This paper serves as a demonstration for policymakers, project developers and rural communities for designing more equitable and inclusive energy systems with clear gendered implications for sustainable future access.

## Introduction

Access to clean, modern, and sustainable energy is amongst the United Nation's Sustainable Development Goals (SDG7) and is crucial for economic growth, social prosperity, and poverty reduction. Global SDG7 tracking [1] reveals that the current rate of energy progress remains inadequate to achieve 2030 targets, with an estimated 675 million people still without access to electricity and 2.3 billion without access to clean cooking. The share of renewables in total final energy consumption remains below 20 %, falling below the target of 33–38 % by 2030, while major economic challenges like macroeconomic uncertainties, high levels of inflation, debt distress and lack of financing continue to impede progress on SDG7 globally. In Pakistan, universal access to clean energy remains a critical challenge, with about 56 million people (~26

*Abbreviations:* AEDB, alternative energy development board; AREPs, alternative and renewable energy projects; ARE, alternative and renewable energy; ARET, alternative and renewable energy technologies; GHG, greenhouse gases; IPPs, independent power producers; LCOE, levelised cost of electricity; NEPRA, national electric power regulatory authority; PV, photovoltaic; RO, reverse osmosis; RE, renewable energy; SDGs, sustainable development goals; SME, small and medium-sized enterprises; SHS, solar home systems.

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% of the population) still lacking basic access to electricity [1]. Pakistan's rural off-grid population (approximately 11 million people) [2] presents particular challenges to electrification due to wide dispersion of small clusters of communities, rendering it economically unfeasible for the government to extend utility supply.

For many such regions, decentralised Renewable Energy (RE) systems can provide a sustainable and technically viable alternative to conventional centralised energy generation prone to inefficiencies and economic constraints [3]. Smaller scale grids have been shown to provide reliable and cost-effective electricity access in remote locations [4–6], while also leading to greater democratisation, agency and community empowerment [7]. However, such systems are still relatively new and face sustainable design and operation challenges limiting their application [3,8]. Although the benefits of rural electrification through mini-grids are generally acknowledged, these are often not based on empirical evidence, specifically socio-economic impacts on communities [9]. Configuring energy systems on estimates of present demand and predicted future scenarios often lead to significant discrepancies between estimated and actual energy consumption [10] and costing [11]. Lack of reliable on-site energy-use data hinders the successful implementation of RE projects [8,12]. Recent research also highlights the need for qualitative evaluation and enquiry in addition to quantitative assessment for a holistic approach [13–15] and energy system modelling [16,17]. One way to address current gaps and constraints in RE projects is through comprehensive case-studies that provide better understanding of localised socio-economic characteristics and differential energy needs. Whilst the situated impact of particular case-studies may be different from that observed elsewhere, the findings can provide useful lessons to overcome barriers, contribute to the theoretical framing underlying RE design and improve decision-making [11], thus informing the broader field of renewable and sustainable energy.

Most research in Pakistan on renewable and solar energy is based on technical feasibility on national scale (e.g. 2,11–13,18–20), while limited focus is given to socio-economic dimensions [21,22], and impacts on local communities. Previous studies have shown that for an energy system to be sustainable, in addition to its technical feasibility, the services it provides must be socially acceptable [8,9] and economically sustainable, i.e. ensure affordability for local residents and promote economic development, particularly focusing on socio-economic disparities in relation to class, income and gender. Recent studies highlight significant disparities in accessing energy and its associated benefits, especially for vulnerable groups like impoverished women [24,25]. Focus on equitable and inclusive distribution in energy transitions is crucial to address challenges of poverty and inequality, and to foster holistic community resilience through sustainable development.

To address these gaps, this paper provides an equitable and inclusive socio-technical assessment of solar energy mini-grids in off-grid communities of Pakistan through the case-study of village Helario in Tharparkar. It aims to investigate the present and potential future community energy demands with a particular focus on different affordability and gendered considerations. Based on this assessment, an off-grid solar system is modelled for optimal performance to meet the community's electricity needs under a range of potential temporal and tiered access scenarios, with a clear understanding of the socio-economic impacts. The findings of this paper provide key recommendations and suggestions to inform equitable future design of decentralised RE projects in Pakistan.

## Literature review

### *The case for decentralised renewable energy in Pakistan*

Pakistan ranks as the eighth most affected country by climate change [26], with an energy mix dominated by oil and gas (76 % of primary energy supply) [27] that further exacerbates its climate vulnerability. Renewable electricity makes up only 8.8 % of the total primary energy supply and roughly 24 % of total electricity generated [28]. The country faces extreme challenges of planning, upscaling, and infrastructure development, specifically for energy security. Centralised control of electricity generation and distribution as the prevailing governance model forms a major obstacle in the sector's growth and development. Hence, in spite of massive investment in the generation sector over recent years, electricity consumers continue to face issues of expensive, unreliable, and inferior quality supply and overbilling [28]. Whilst energy policy reforms of the past two decades have proved successful in unbundling the vertically integrated electric utility stream and attracting private investment, the sector still faces financial instability due to high costs of supply and poor performance with extremely high transmission and distribution losses (up to 15.5 % in 2018–19) [28]. Vast improvements and reform are required to improve energy performance, reliability, accountability, and transparency.

Under the National SDG framework, Pakistan has set an RE target of achieving 20 % of its installed power capacity from solar and wind by 2025 and 30 % by 2030 [29]. However, progress has been slow under significant challenges. According to the National Electric Power Regulatory Authority (NEPRA) [28], during FY2022, the total electricity generated through solar, connected with the national grid, was recorded at 1022 GWh. Further, six solar power projects of 430 MW cumulative capacity were operational under independent private investment through the Alternative Energy Development Board (AEDB). However, until recently,[1] decentralised solar micro/mini-grid projects have been almost completely absent from the energy landscape [30], due to critical roadblocks including lack of regulatory policy and technical expertise [2].

The recent Alternative and Renewable Energy (ARE) Policy 2020 [29] claims to focus on improving energy security, affordability, and availability for all. Its main goal is the induction of power plants on open competitive bidding for lowest tariff and technology transfer. This will be achieved by enabling private sector investment and participation in on-grid and off-grid AREPs (Alternative and Renewable Energy Projects) through technological solutions such as RE forecasting capabilities, hybrid AREP solutions and distributed generation. The policy also highlights the need for support to local ARET manufacturing, human resource development and RE training and skill development. Although the policy formulation at the national level remains largely focused on independent power producers (IPPs) for improved capacity, there is also consideration of decentralised electricity systems. The progressive technological advancements and cost efficiencies in AREs demonstrate the government's recognition of the potential that decentralised and distributed mini/micro grid, off-grid, localised energy systems and business-to-business solutions offer [29]. If implemented successfully, the policy can help Pakistan transition to a sustainable energy future. Empirical, research-based evidence, as provided in this paper, can play a significant role in successful policy implementation.

### *Socio-economic impacts of remote off-grid solar energy*

In most literature, socioeconomic impacts of RE are predominantly estimated at the national level, with limited studies undertaken at sub-national, city or community level [4], overlooking specific regional and local differences. For decentralised RE, studies show that such projects centre on complex multi-dimensional processes requiring the assessment of multiple technical, as well as environmental, economic and social indicators [31,32]. According to [3], key economic attributes for evaluation should include initial investment, operation and

[1] The German Development Bank (KfW) and Pakistan Poverty Alleviation Fund (PPAF) set up solar energy mini-grids projects with a total capacity of 500 kW in remote areas of Karak, Swabi, and Lakki Marwat districts of KPK in 2013, completed in 2018. https://tribune.com.pk/story/1760582/power-off-grid-areas-solar-mini-grids-set-two-districts-k-p

maintenance (O&M) costs, payback period and service life cycle. Juanpera et al. [33] further advocate including a socio-institutional dimension, including consideration of acceptable tariffs and technologies, along with institutional alignment of system design with national strategies and goals.

According to [8], the social sustainability of decentralised RE projects rests on the perspectives of end-users and the wider community, and should include factors like health and education, power, and gender structures. Numerous studies [24,34,35] highlight the links between gender, energy access and women's socio-economic empowerment. Whilst gendered disparities in access to energy are evident from the literature, women are also shown to significantly benefit from rural energy projects [25]. For this, community participation and involvement must be central to energy system design [36].

User experience of decentralised solar home systems in rural India [37] showed that satisfaction and procurement of additional solar power were influenced by factors like income, level of education, duration of solar use, time of day for the power supply, and financial support for procurement. Insufficient investment and lack of technical personnel were also identified as barriers to RE penetration in remote islands in Japan [5]. In Bangladesh [12], whilst remote island residents were able to benefit from solar energy systems, user dissatisfaction was associated with high costing, high rate of light and controller replacement, system irregularity during monsoon, and lack of knowledge regarding disposal of expired components. For some users, the high costing meant taking up extra hours of work to ensure continued use of the system, resulting in extra financial burden. Blair et al. [36] developed a framework for synchronising RE technology, local resources and community needs through a participatory ground-up approach. Emphasising cultural, perceived and resource values of electricity services was seen to improve their uptake and long-term sustenance. This and other studies (e.g., Krumdieck and Hamm [38]) show that participatory frameworks that allow community co-design are better able to account for trade-offs between resource and cultural values, leading to more ecologically conscious and equitable energy decisions with long-term paybacks.

A study of rural electrification in Brazilian Amazon [39] showed that the level of electricity supply had a significant impact on the uptake of productive uses of energy and income generation. Smaller solar projects (like standalone solar home systems (SHS)), whilst reducing the use of conventional energy sources (e.g., candles, wood etc.), were unable to eliminate their use completely. Similar results are evidenced in other studies [40,41] that advocate for micro/mini-grids instead of SHS, as well as battery storage [42] for more socio-economically empowering solutions. However, care must be taken in designing suitable tariffs as some rural electrification projects in Indonesia [e.g., 23] were unsuccessful in recovering cost of production and achieving financial viability. Further, lack of local on-site technical expertise and skills made it difficult to ensure adequate system maintenance. In addition, the study showed that due to certain socio-cultural practices, electrification did not result in a significant shift from fuelwood to electricity for cooking as the former was readily available at little or no cost. This highlights the importance of local contextual factors in designing off-grid solutions. In the Philippines [4], RE interventions were found to have positive socio-economic impacts on access to education, information, health services, and perceived safety, whereas a weaker impact was found on income generation. Further, significant differences were identified in electricity usage patterns based on household incomes. These examples show the need for moving beyond a binary approach to energy by designing systems that account for multi-tier and multi-dimensional access to energy [43,44].

Most RE studies in Pakistan focus on the national scale and explore the technical feasibility and policy shortfalls in relation to decentralised systems. Case-studies are limited and rarely focus on RE's socio-economic dimensions. Of this limited research, Qureshi et al. [45] investigate solar PV adoption in an urban case-study in Pakistan, highlighting key constraints like high costs, absence of adequate government financial support, and shortage of reliable vendors and technicians. Khan and Latif [46] identified high initial costing, lack of community knowledge and awareness, lack of technical expertise and inadequate policy as critical barriers to Pakistan's solar energy proliferation. Similarly, Mirza et al. [22] suggest developing innovative financing programs for RE technologies for greater market penetration, as well as developing techniques for estimating local externalities such as pollution reduction, increased local employment, and economic development.

These studies clearly show the need for decentralised RE projects to be developed in close connection with the local institutional, infrastructural, and geographical contexts, as their success hinges on socio-economic factors and cultural values. In addition, they show that a one-size-fits-all solution for RE system development will not necessarily work and system modelling must be informed by community needs and constraints [47]. Further, energy systems must be designed in an equitable and inclusive manner to cater to different energy needs and groups. This paper seeks to address these gaps through a demonstration project that focuses on different levels of electricity access to account for affordability and gendered considerations, and investigates the socio-technical feasibility of a decentralised off-grid solar PV system design for Helario village in Tharparkar.

## Methodology and materials

The project on which this paper is based was designed to frame an integrated development approach towards achieving SDG11 (sustainable communities), SDG7 (affordable and clean energy access) and SDG5 (gender equality) in remote off-grid communities in Pakistan, with a focus on techno-socio-economic assessment of renewable solar energy systems.

### *Case-study*

Helario is a remote off-grid village in the Tharparkar district of Sindh province (Fig. 1 and Fig. 2). With a tropical desert climate, Tharparkar suffers extreme heat during summer days, reaching temperatures of 45–48 °C, while nights are cooler, and an average temperature of 20 °C in winters [48]. The Thar desert is regarded as the only fertile desert in the world with rain-fed agriculture as the main livelihood. However, increasing frequency and severity of droughts in recent decades has resulted in reduced agricultural yield, leading to increased poverty, food insecurity and water scarcity [49]. The human development index rating is lowest for the district and according to the UNDP [50], 87 % of Tharparkar's population lives below the poverty line.

Helario is located 24 km from Mithi city, the nearest electrified town. The village has a population of roughly 2000, with nearly equal division between Muslims and Hindus. Houses are generally made of mud with thatch roofs and, more recently, clay bricks along unpaved streets. In addition to housing, there are two primary schools for boys and one secondary school, along with three girls' primary schools, but no girls' high school. There are also two religious buildings: a Hindu temple in the village centre and a mosque on the eastern end, and three community centres. The village presents a good case study as there are currently no electricity or telecommunication services.[2]

Women constitute roughly 46.5 % of the rural population of Tharparkar District.[3] The literacy rate is below 20 %, which drops to about 7

[2] Recently, a telecommunication tower has been installed a few kilometres northeast of the village, and 4G network services are hoped to be made available soon. A few houses have been using WLL (Wireless local loop) Telephone since 2004-05, which requires a small antenna installation. Mobile phones are used by the adolescent boys, who travel to some nearby mounds (higher altitude) where they can sometimes get access.

[3] http://www.pakinformation.com/population/tharparkar.html

**Fig. 1.** A view from Helario village in Tharparkar. (Source: author).

**Fig. 2.** Aerial map of village Helario. (Source: Google maps).

% for girls [51]. In addition to the lack of education, lack of proper health services and inadequate facilities result in malnutrition and high mortality rates. Female health workers or trained birth attendants are not available in 69 % of the villages [51]. Women often work long hours, participating in crop cultivation, livestock management, dairy production, forestry, in addition to completing household chores including food preparation, fetching water and fuel, caring for children and the elderly [51].

*Methods*

The study used a socio-technical methodology and mixed-methods approach for data collection. The complete project design with various phases is illustrated in Fig. 3. Phase 1 included a detailed baseline energy assessment, including a questionnaire survey (Appendix A) with 373 households out of a total of 400 (93 % sampling size) and qualitative enquiry using focus groups, informal interviews and field observations. Data included community and household demographics (for the purposes of identifying the range of income/affordability and differences between women and men, for example), energy sources and community energy needs, in addition to future energy aspirations and social acceptability for renewable energy technologies. Special attention was given to women's energy access and use in activities like cooking and household chores, child-rearing, safe means of travel and

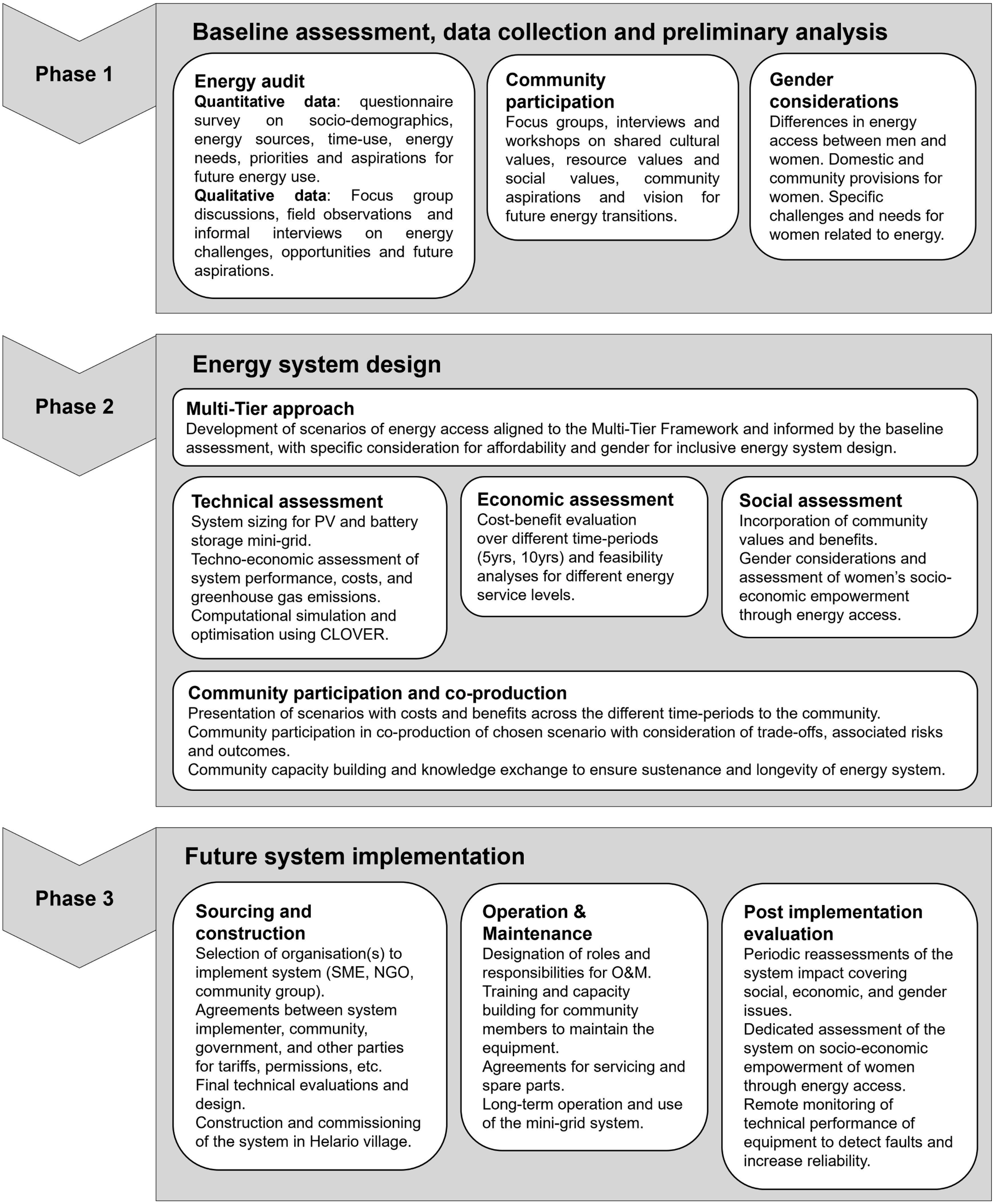


**Fig. 3.** Helario village RE electrification project design and phases.

communication, access to community facilities and productive uses of energy to understand pathways for their socio-economic empowerment. In addition, community participation was ensured to determine the shared values and vision for future energy transitions, with opportunities for engagement and dialogue to ensure equitable and inclusive development, in addition to community capacity-building and knowledge exchange (Phase 1 and 2).

The baseline energy assessment was used to model, simulate, and optimise the configuration of a solar-battery mini-grid system to power the community and meet its various energy needs, in Phase 2. Energy modelling was done using CLOVER, an open-source energy system software for community-scale rural electrification design [52,53]. The software takes user-defined inputs for electricity service demands, electricity generation and storage source(s) available to a community, and data on the cost, performance, and environmental impact of system components.[4] It can simulate electricity systems at an hourly resolution over a specified time-period and, by considering many potential combinations of technology capacities, identify an optimum system based on user-defined constraints and goals. Software outputs include costs and emissions per unit of electricity, reliability of the system, and total cost and emissions of the system over its lifetime etc.

Using the stochastic load modelling framework in CLOVER, different demand scenarios with different electricity loads were developed, shown in Table 1, drawing on the Multi-Tier Framework (MTF) of energy access [44]. The MTF overcomes the limitations of a binary approach to assessing energy needs by defining multiple tiers (in quality and quantity) of access to energy services for households, community needs and productive uses. Previous studies [e.g., 39,53] that have used a tiered or levelled approach to energy service provision demonstrate its usefulness in better aligning energy supply with community needs, aspirations and priorities- providing a more equitable and inclusive design. However, some studies [43,56] critique the MTF's universalising approach, advocating for empirically-grounded categorisation of access in line with situated needs. Hence, adapting the MTF using data from the questionnaire surveys, observations and focus groups, five scenarios were developed interlinked with the community's various socio-economic requirements (including gendered considerations, discussed further in Section 4.4). These scenarios represent:

- (1) The present situation and (1a) with the integration of the RO plant, in line with Tier 1–2 of the Multi-Tier Framework.
- (2) A future situation with these loads plus increased electricity demand from refrigeration and ICT, aligned with Tier 1–2.
- (3) The above, with additional domestic appliances to reduce the burden of household chores, particularly for women, aligned to Tier 3.
- (4) An aspirational situation with all the above loads, plus electricity for productive uses by small enterprises, community centres, and street lighting in the village, aligned to Tier 4.

A summary of the ownership statistics and typical usage durations is available in Appendix B. Systems or devices which could reduce drudgery without requiring electricity, for example passive drying systems or water-saving innovations, are not considered as non-electrical appliances are beyond the scope of this paper and its methodology. These could be considered in future work as alternatives or additions to the scenarios included here in pursuit of similar goals.

Sustainable mini-grid systems were modelled in CLOVER to identify the optimum combination of solar and storage capacity to meet community needs. For our modelling, we defined the optimum system as one able to supply electricity at least 95 % of the time at the lowest levelised cost of electricity (LCOE, $/kWh), which aligns with the goal of SDG7 to provide affordable, reliable, and clean access to energy. Some battery storage is therefore included in all scenarios, and is backed by previous studies [42] which show that energy storage has a positive effect on RE project success. Costs were calculated using a discount rate of 10 % and divided into capital expenditure (such as upfront equipment costs) and ongoing or yearly costs (such as for maintenance).

We optimised the mini-grid systems over two time-periods, five years and ten years, to evaluate the potential financial and technical impacts of shorter- and longer-term planning. This allows for a scenario-based sensitivity analysis given the unknown future lifetime of the potential system. A five-year period could be reflective of a relatively short-term project which could, e.g., be representative of private-sector delivery aiming to recoup its investment within that timeframe, or the duration of an NGO-led project. It could also represent the lower bounds of the lifetimes of certain components, such as batteries. A ten-year period, meanwhile, offers an insight into aspirational longer-term planning which could represent successful project delivery which meets the needs of the community further into the future.

## Results

### *Household characteristics*

Survey data of the 373 households showed that the total population of Helario village is just over 1950, including 55 % adults and 45 % children (under 18). The gender distribution was found to be 54 % male and 46 % female. A typical household is made up of five occupants: three adults and two children, with a median and mean age of 20 and 24 respectively, with 75 % of the population under 33.

The average monthly income was about **PKR15,000 (USD 66.49)**. The median and mean salary for women is less than half of that of men, as shown in Table 2.

Most villagers had a primary- or secondary-level education (74 %), while only 6 % had a graduate degree (primarily men) and 4 % had acquired a training apprenticeship (primarily women). As shown in Table 3, women have a lower education level compared to men, with around 60 % of women with an education between nursery and primary level while 80 % of men have an education between nursery and secondary level.

The occupation or income source for adults is reported in Table 4.

On average, female children study at home 1.74 h per day while male children study at home 2.02 h per day, i.e., 16 % more. The most used lighting source to study was indicated on average to be candles (46.4 % of households) and firewood (22.3 % of households).

In terms of housing construction, most houses (74 %) were built with burnt bricks and mortar with concrete roofs (Figs. 4–7) and approx. 70 % of households had a (non-flush) toilet inside.

### *Household current energy access and use*

Table 5 provides a breakdown of the key energy sources currently used for various domestic purposes in households. As the table shows, common primary fuels available are manure and firewood. Small-scale renewable solar lanterns, torches and batteries are also used but are only available for purchase or charging from outside the village. On average, household monthly cost for energy was found to be **PKR796 (USD3.53),** which amounted to **4.3 %** of average household income.

For lighting, candles and firewood were indicated as the primary sources by 74.3 % and 65.7 % of the households, respectively. On average, 64.9 % households indicated getting 3–4 h of artificial lighting per day, 19 % indicated getting 5–6 h of artificial lighting per day, while only 8.8 % indicated getting 7–8 h of artificial lighting per day. Interestingly, the evening lighting was reported to be used mostly on average for cooking (95.7 % of households), studying (66 % of households), and safety reasons (56.6 % of households). Also, 34 % of households indicated that the availability of lighting is limited mostly because of lack of

[4] Further information about the operation of the CLOVER model is available from [54]

**Table 1**
Demand scenarios for the community.

| Demand type | Scenarios Description | 1 HH Tier 1–2 (4 h electricity). | 1a HH Tier 1–2 (4 h electricity- with min 2 evening hours). | 2 HH Tier 3 (8 h electricity) | 3 HH Tier 4 (8–16 h electricity) | 4 HH Tier 4 + Productive Engagements + Community Facilities |
|---|---|---|---|---|---|---|
| Domestic | Lights | ✔ | ✔ | ✔ | ✔ | ✔ |
| | Phone charger | ✔ | ✔ | ✔ | ✔ | ✔ |
| | TV/radio | ✔ | ✔ | ✔ | ✔ | ✔ |
| | Fan | ✔ | ✔ | ✔ | ✔ | ✔ |
| | ICT (Computers/ internet access) | | | ✔ | ✔ | ✔ |
| | Refrigeration | | | ✔ | ✔ | ✔ |
| Water availability | RO Plant | | ✔ | ✔ | ✔ | ✔ |
| Domestic plus | Domestic appliances to reduce drudgery and time spent by women on chores (e.g. electric pressure cookers[5], washing machine, mixer grinders etc.) | | | | ✔ | ✔ |
| Productive engagement | SMEs (e.g. sewing machines) | | | | | ✔ |
| Community facilities | Streetlights | | | | | ✔ |
| | Electricity/water in public buildings (schools, religious buildings, vocational centre for women) | | | | | ✔ |

[5]Keeping in line with the survey analyses which showed women's preferences for traditional cookstoves and social values of familiar cooking practices, along with previous research [23,57] which shows that modern cookstoves (e.g., solar cookstoves) are often unsuited to cultural practices, we did not overly emphasise new cooking technologies. Nevertheless, clean cooking options and specific technologies will be discussed with the community residents in project Phase 3 co-design.

**Table 2**
Salary [PKR] distribution in Helario village.

| Gender | Min | 25 % Quantile | Median | 75 % Quantile | Max | Mean |
|---|---|---|---|---|---|---|
| ALL | 600 | 7125 | 10,000 | 20,000 | 300,000 | 15,157 |
| Male | 1000 | 8000 | 10,000 | 20,000 | 300,000 | 15,702 |
| Female | 1000 | 2850 | 5000 | 7750 | 30,000 | 6863 |

**Table 3**
Education level in Helario village.

| Gender | E1 | E2 | E3 | E4 | E5 | E6 | E7 | E8 | E9 |
|---|---|---|---|---|---|---|---|---|---|
| Total | 9 % | 24 % | 14 % | 36 % | 8 % | 6 % | 0 % | 0 % | 4 % |
| Male | 7 % | 19 % | 13 % | 41 % | 10 % | 8 % | 0 % | 0 % | 2 % |
| Female | 12 % | 33 % | 16 % | 28 % | 3 % | 2 % | 0 % | 0 % | 7 % |

Legend: E1 Nursery, E2 Primary (1–5), E3 Secondary (6–8), E4 Matric (9–10), E5 Intermediate (FA/FSc), E6 BA/BSc, E7 MA/MSc and above, E8 Vocational training, E9 Apprenticeship.

**Fig. 4.** Old houses made from mud with thatch roof.

**Table 4**
Occupation of residents in Helario village.

| Occupation | Total | Male | Female |
|---|---|---|---|
| Farmer | 3 % | 3 % | 3 % |
| Labourer | 23 % | 32 % | 3 % |
| Small Business - Owner | 1 % | 2 % | 0 % |
| Small Business - Worker | 2 % | 3 % | 1 % |
| Government employee | 10 % | 14 % | 1 % |
| Housewife | 7 % | — | 21 % |
| Student | 46 % | 37 % | 65 % |
| Unemployed | 2 % | 3 % | 1 % |
| Invalid | 0 % | 1 % | 0 % |
| Retired | 1 % | 2 % | 0 % |
| N/A | 4 % | 3 % | 5 % |

**Fig. 5.** Village temple.

cash to pay for it.

For cooking, 84 % households indicated using firewood as the primary fuel for cooking. 17.2 % households indicated spending **3–6 h** collecting fuel, while 66.5 % spent 6–8 h or more. Collection is done predominantly in the morning, from 08:00–11:00 (74.8 % of households). Further, 95.4 % households primarily used a self-made cookstove, mostly located inside the house (89.3 % of households) without any air extractor or chimney (Figs. 8 and 9). It was therefore unsurprising that respiratory issues were the major health issue

**Fig. 6.** Newer houses built with burnt bricks and concrete roofs.

**Fig. 7.** A typical street in the village.

**Table 5**
Breakdown of typical energy sources used in Helario village.

| Energy source | Households using this energy source (%) | Supply Location* |
|---|---|---|
| Firewood | 96.2 | 2 |
| Candles | 67.3 | 3 |
| Manure (Biomass) | 66.8 | 1 |
| Cell phone ** | 51.5 | 1 |
| Batteries | 50.1 | 3 |
| Sticks/ leaves/ grass | 24.9 | 1 |
| Solar Lantern | 9.9 | 1 |
| Battery charger | 9.4 | 3 |
| Solar Home System (11+ Wp) | 5.1 | 1 |
| Cooking gas (cylinder) | 2.4 | 3 |
| Diesel for Generator | 1.3 | 2 |
| Natural gas | 0.8 | 3 |
| Charcoal | 0.5 | 2 |
| Kerosene | 0.5 | 2 |

* 1: Within village or less than 30 mins; 2: 2–5 km or 31 mins-1 hour; 3: 5–10 km or 1–2 h; 4: More than 10 km or more than 2 h.
** Cell phones are used as a source of lighting, from their integrated torches, and the "supply location" refers to cell phone charging.

(indicated by 71 % of the respondents) faced in relation to cooking. The baseline assessment also showed that cooking is primarily a female activity **(98 %[5])**, with an average of **3.3 h** spent on cooking daily.

[5] The remaining 2% represented missing information, while none of the respondents indicated that cooking was done by men.

**Fig. 8.** Mud cookstove with wood residue.

**Fig. 9.** Mud cookstove showing smoke residue on the wall.

**Table 6**
Appliances used in Helario village, per day.

| Item | Total Units | Hour per Unit | Total Hour |
|---|---|---|---|
| Candles | 743 | 3 | 2280 |
| Fixed Lights | 502 | 5 | 2556 |
| Mobile phone charger | 184 | 5 | 931 |
| Torches | 152 | 3 | 512 |
| Fan | 45 | 7 | 321 |
| Solar lamps | 41 | 5 | 185 |
| Sewing machine | 24 | 3 | 65 |
| Water pump | 6 | 24 | 144 |
| Kerosene lamps | 1 | 5 | 5 |

Crucially, in terms of the most important features for a cooking system, the respondents indicated their requirements for: (i) a traditional/ familiar stove aligned with women's cooking habits; (ii) that saved fuel; (iii) and that generated less smoke.

Typical appliances available in households are listed in Table 6, including the total number and hours of use for different appliances. This is also used to calculate the average time allocated for each item in a given day (hour/item). It is apparent from the data that energy is primarily consumed for lighting and mobile charging, aligning with MTF tier 1 distribution.

Data was also collected to investigate energy access in relation to household dynamics, with some significant results presented in Table 7. As the data suggests, contrary to common conceptions, firewood collection was predominantly carried out by males (93 %) in the case-study village, whereas manure/biomass collection was predominantly done by females (76 %). The reason for this is that socio-cultural norms often constrain women's movement beyond the village. Since manure is collected from households within the village, women and girls mainly undertake its collection.

It was estimated that 50 % households use batteries while only 9 % owned a battery charger. Crucially, only 5 % households currently had a solar home system and only 10 % used solar lanterns. Most households (50 %) get their batteries charged monthly, while 9 % get them charged on a fortnightly basis. Importantly, the average distance travelled for charging was approx. 27 km. On average, households spent **PKR440 (USD1.95)** monthly on charging of batteries.

### *Predicting household electricity demand*

In addition to current energy access, data was also collected on user satisfaction as well as future needs and aspirations for electricity use. Overall, **32 %** of respondents believed they had very bad or bad access to energy sources. The major reason noted for this was a lack of cash for payment. The villagers are keen to get better access to electricity, however, for the majority (66 %), it does not matter what the source of this electricity is (whether grid-connection, mini/micro-grid or renewables).

On the community level, access to communal electric facilities is minimal, due to lack of larger-scale electricity sources. Only 0.8 % households indicated having streetlighting available. 10 % owned a personal vehicle/transport facility, while another 20 % had access through borrowing from neighbours and family/friends. Due to lack of communal electricity services, households indicated sharing, for example, mobile chargers (21 %) and income-generating appliances (e.g., sewing machines, 39 %) with others in the village.

Table 8 gives a summary of the respondents' future needs and aspirations for electricity use. Overall, respondents highlighted their need for longer supply hours (92 %) and more cost-efficient means of energy supply (90 %). Further, durability/reliability (71 %), urgency of need (48 %), and portability (40 %) were indicated as the three most important considerations in energy purchasing decisions.

Data was also collected on women's specific energy access and needs.

**Table 7**
Energy access in relation to household dynamics.

| | |
|---|---|
| Who is the primary collector of firewood/ sticks? | **Adult male:77 %**<br>Adult female: 3 %<br>Child male: 16 %<br>Child female: 3 % |
| Who is the primary collector of manure/biomass? | Adult male:12 %<br>**Adult female: 63 %**<br>Child male: 12 %<br>Child female: 13 % |
| How often do you get (any) batteries charged from outside the village? | Weekly: 8 %<br>Fortnightly: 20 %<br>**Monthly: 67 %**<br>Every few months: 4 % |
| What is energy (e.g. lighting) in your home usually used for? (Multiple selections possible) | **Cooking[7]: 96 %**<br>Cleaning: 9 %<br>**Studying[8]: 66 %**<br>Socialising: 5 %<br>Recreation: 3 %<br>Working: 18 %<br>**Safety/Security: 57 %**<br>Moving around easily: 37 % |
| What lighting source is specifically used for studying? | **Candles: 47 %**<br>Keronese: 3 %<br>Solar lamp: 21 %<br>Firewood: 29 % |

[7] 93 % of households reported that they use manure or mud as fuel for cooking.
[8] From the survey, the average study length per day is 2 h, with a minimum of 1 hour and a maximum of 7 h.

**Table 8**
Respondents' future aspirations for electricity use.

| Appliance | 1st | 2nd | 3rd | TOT |
|---|---|---|---|---|
| Electric lighting | 87 % | 2 % | 1 % | 90 % |
| Phone charger | 1 % | 72 % | 3 % | 77 % |
| Fan | 2 % | 4 % | 65 % | 71 % |
| Electric iron | 2 % | 8 % | 3 % | 13 % |
| Water pump | 0 % | 4 % | 4 % | 8 % |
| Cooking appliances | 0 % | 1 % | 7 % | 8 % |
| Television | 1 % | 5 % | 1 % | 6 % |

Of the **63.5 %** households with access to mobile phones, only **19.8 %** indicated that women in the household had access to mobile phones. Women contributed to income-generation in **19.5 %** households, mostly through undertaking sewing and embroidery work. Financial decision-making was predominantly done by men **(87 %),** with only two households **(0.5 %)** indicating it was done by both men and women. On the other hand, women mostly take decisions on cooking and food preparation (93 %) and childcaring (83 %). The only assets that women directly own are jewellery while men own houses, land, and liquidity. At the community level, most women (65 %) had access to primary education and a health centre, while **29 %** indicated having access to a religious centre/building and **22 %** indicated having access to a community market. Most women **(88 %)** felt safe travelling alone or in the company of other women within or near the village during daytime, while only **3 %** felt safe leaving their homes at night.

Data analysis showed that most women spent their mornings in various household chores, including cooking, cleaning, dish washing, milking, in addition to sewing and embroidery work, whereas evenings were mostly spent in embroidering/sewing, or fetching/storing water. Data shows that if more free time was made available, women wanted to spend that time in sewing/embroidery work, as a means for income generation. In addition, women were asked to rate their first three choices from a list of possible options (Table 9) in terms of availing various activities if given the opportunity. Analysis showed that getting an education was the first priority for the majority of women (42 %), followed by financial asset ownership (25 %). In addition, vocational training and appliances to ease household chores and income-generation were indicated as the second or third priority by most women. They highlighted that a lack of suitable income sources, opportunities for education and rising inflation were key constraints in improving their situation. These results are significant in designing energy systems to ensure that women's needs are given due consideration.

Whilst the questionnaire survey included standard energy audit questions on electricity needs and demands, it was only through our field analyses, focus groups and informal discussions that the critical gender-energy-water nexus became apparent. Community residents indicated that collection of drinking water was the most challenging issue currently faced by women, involving the greatest drudgery. Erratic rainfall and lack of proper water storage in the area mean that groundwater becomes the only sustainable source of water; however, the supply is increasingly brackish,[6] and the depth of the water table is falling [46]. The adverse effects of these conditions on women are corroborated by previous studies [51], which show that women have to travel longer distances and allocate more time in collecting water. A 34 kW Reverse Osmosis (RO) plant was installed in the village in 2010 for water purification with a capacity of 7500 gallons/hour. Run on a diesel-powered generator, this was one amongst 600+ similar RO plant installations carried out across Tharparkar. However, due to mismanagement and corruption, diesel fuel supply was discontinued to the village about two years ago. This, together with lack of proper

[6] Recent water quality assessments in Helario village near the RO plant reveal Total Dissolved Solids (TDS) of 5040 mg/l. Data obtained from USAID Water Centre MUET, Jamshoro.

**Table 9**
Women preferences for additional activities in Helario village.

| If women had the opportunity, which of the following three would you be likely to choose. (3 selection possible) | Choice 1st | 2nd | 3rd |
|---|---|---|---|
| Education | 42 % | 1 % | 1 % |
| Vocational training | 4 % | 28 % | 2 % |
| Means for income-generation/ Self-earning | 3 % | 10 % | 7 % |
| Travel and Mobility/ Safe transportation facilities | 1 % | 2 % | 2 % |
| Financial asset ownership | 25 % | 3 % | 1 % |
| Property/Land ownership | 1 % | 1 % | 2 % |
| Recreational facilities (TV, Radio) | 1 % | 3 % | 4 % |
| Personal mobile phone | 1 % | 2 % | 2 % |
| Community-based facilities (gathering spaces, green spaces, recreational spaces) | 0 % | 6 % | 8 % |
| Appliances to ease household chores like cooking, washing, cleaning etc | 2 % | 25 % | 13 % |
| Appliances to ease income-generation (e.g. electric sewing machine) | 4 % | 2 % | 40 % |
| Improved housing facilities (better structure, more space, electricity, water, toilets, etc.) | 0 % | 0 % | 1 % |

maintenance and management resulted in the plant being shut down in 2020. Discussions with women indicated that drawing water has become more difficult over time. Focus groups with women revealed that improvements in energy and water procurement could help free up time for other productive work, relaxation or for taking care of children, highlighting the significance of the gender-energy-water nexus that otherwise remained invisible.

*Energy system modelling: sizing and impacts*

Based on the findings, five electricity usage scenarios were developed to represent the present and potential future needs of the Helario community, with a key focus on improving affordability and gendered access to energy. In line with the present needs of the community, Scenarios 1 and 1a both include domestic access to basic electricity services such as lighting, phone charging, fans, and televisions, with the inclusion of electricity for improved water access in 1a that would particularly benefit women with the addition of an RO plant; this broadly aligns with Tier 2 access to electricity under the Multi-Tier Framework [44]. In Scenario 2, households additionally have access to refrigerators and ICT (such as computers and internet access), and have longer access to electricity throughout the day, aligned with Tier 3. In Scenario 3, households also have access to domestic appliances, such as electric pressure cookers, washing machines or mixer/grinders etc., designed to reduce the drudgery of household chores which predominantly affect women. In Scenario 4, demand from SMEs (representing loads such as sewing machines, cottage industries, small shops or other modest productive uses) are also included in line with women's needs for future energy demand and aspirations for economic empowerment through income generation. Furthermore, aligned with the results of the field visits and survey, community lighting is included for public areas and shared facilities such as schools and community centres. The increased electricity services in Scenarios 3 and 4 reflect the results of the survey for greater socio-economic opportunities (e.g., in education and skills development) and community participation, especially for women, and to reduce the time spent on household chores. With the exception of Scenario 1, the community electricity demand includes the RO plant that is currently inoperable but could be connected to a future mini-grid system, reflecting the need for improved water access from the focus groups and surveys. Scenario 1a and 1b have average community energy demands of 100.1 kWh/day and 135.5 kWh/day respectively, Scenario 2 has an average of 176.7 kWh/day, whilst the higher-tier Scenarios 3 and 4 have much higher community demands of 595.7 kWh/day and 644.7 kWh/day. In this way, different energy tiers in multiple combinations can be used to accommodate corresponding differences in affordability of different households, as highlighted in previous work [43].

The results of the energy system modelling with solar PV and battery storage are shown in Tables 10 and 11. Y5 Scenario represents the predicted capacity and impacts of the energy system for a five-year period, and Y10 Scenario represents the same for a ten-year period. In the Y5 Scenario, the sizing of the PV and storage capacity needed for the community remains relatively similar without (Scenario 1) and with (Scenario 1a) the RO plant; only minor differences in financial and environmental impacts are found and result from the larger PV capacity and inverter. This is a result of running the RO plant during the day, when solar generation is greatest, to avoid larger storage requirements and to utilise solar energy that might otherwise have been dumped due to overgeneration. This is reflected in the differences in the percentage of demand being met by storage.

Scenario 2 requires larger PV and storage capacities to accommodate the increased demand from additional domestic appliances, particularly for refrigeration. This results in higher impacts, noticeably for the costs which are **35–60 %** higher than Scenarios 1 and 1a. This larger system relies slightly more on storage to provide electricity because of refrigeration loads during the night and so the levelised cost of electricity (LCOE) and greenhouse gas (GHG) emissions intensity are between those of Scenarios 1 and 1a, despite the higher electricity demand which might have provided economies of scale.

Scenarios 3 and 4 have greatly increased electricity demands and, as a result, require much larger PV and storage capacities to meet the needs of the Helario community. Interestingly, the lowest-cost system configuration for Scenario 3 requires slightly more PV but less storage than Scenario 4 as a result of the different compositions of demand varying in relative magnitude throughout the day. The total system costs are around three times higher than for Scenario 2 but provide more than three times the electricity: while the larger upfront costs may be a barrier to deployment, the lower LCOEs would provide more affordable power on a per-unit basis, assuming the modelled demand is actualised.

## Discussion

Several techno-economic effects come into play when considering a ten-year period: the system modelling shows a higher initial capacity of battery storage to counteract the effects of degradation and to maintain the desired reliability levels throughout; higher overall O&M costs due to the longer lifetime; and lower per-unit impacts of electricity, as a result of similar equipment capacities being used for twice as long. The initial capital costs are around just 5 % higher for the energy systems

**Table 10**
Y5 Scenario: The capacities and impacts of optimised solar and storage mini-grid systems for each scenario, considered over a five-year period.

| Scenario | Unit | 1 | 1a | 2 | 3 | 4 |
|---|---|---|---|---|---|---|
| **PV size** | kWp | 30 | 40 | 55 | 225 | 210 |
| **Storage size** | kWh | 160 | 160 | 230 | 535 | 645 |
| **Demand met by storage** | % | 64 % | 48 % | 54 % | 38 % | 41 % |
| **Cost** | Capital ($) | 63,889 | 74,742 | 103,063 | 311,675 | 329,880 |
| | O&M ($) | 9308 | 9626 | 12,888 | 30,430 | 34,329 |
| | Total ($) | 73,197 | 84,368 | 115,951 | 342,105 | 364,209 |
| **LCOE** | $/kWh | 0.500 | 0.430 | 0.453 | 0.397 | 0.386 |
| **GHGs** | kgCO2 | 75,498 | 130,871 | 129,822 | 469,383 | 459,004 |
| **Emissions intensity** | gCO2/kWh | 411 | 383 | 404 | 434 | 388 |

**Table 11**
Y10 Scenario: The capacities and impacts of optimised solar and storage mini-grid systems for each scenario, considered over a ten-year period.

| Scenario | Unit | 1 | 1a | 2 | 3 | 4 |
|---|---|---|---|---|---|---|
| **PV size** | kWp | 30 | 40 | 55 | 200 | 210 |
| **Storage size** | kWh | 170 | 170 | 245 | 590 | 670 |
| **Demand met by storage** | % | 64 % | 47 % | 54 % | 39 % | 41 % |
| **Cost** | Capital ($) | 67,049 | 78,780 | 108,424 | 312,540 | 340,964 |
| | O&M ($) | 15,733 | 16,248 | 21,858 | 51,582 | 57,256 |
| | Total ($) | 82,782 | 95,028 | 130,282 | 364,122 | 398,220 |
| **LCOE** | $/kWh | 0.349 | 0.298 | 0.313 | 0.260 | 0.261 |
| **GHGs** | kgCO2 | 134,737 | 102,368 | 192,674 | 453,578 | 484,340 |
| **Emissions intensity** | gCO2/kWh | 225 | 207 | 218 | 209 | 206 |

with ten-year lifetimes compared to its five-year equivalents. This suggests that if sufficient funds were raised for the five-year design, then it would be reasonable to incur the relatively small additional costs to install the ten-year system. Although O&M costs are higher, these remain constant throughout the system's lifetime (albeit subject to discount rates in the modelling calculations) and so if electricity is paid for with the same regularity throughout, then this may not be an issue.

The percentage of energy supplied by storage is only slightly different owing to variations in solar generation and random fluctuations in demand. It is important to note that all suggested scenarios offer carbon emissions intensities lower than that of the national grid network; for the ten-year period, this becomes **less than half** of current emissions. Finally, over ten years the LCOE is around 30 % lower for each scenario, and the emissions intensity is around **45 % lower**, compared to the five-year analogues.

In terms of the economic feasibility, larger systems under Scenarios 3 and 4, operating for longer time periods, offer the lowest LCOEs (Fig. 10) which could be passed onto the Helario community as the lowest tariffs. If possible, the largest system in Scenario 4 including the RO plant, improved domestic electricity access, power for SMEs, and community lighting should be selected for implementation owing to the community priorities raised in the survey and focus groups. This is further compounded by the added socio-economic impacts resulting from electricity access: greater productive opportunities with increased participation in income-generation by women will not only serve to improve households' economic status and affordability but can also lead to women's economic empowerment. Here, the link between women's economic contribution and the continued sustenance of the energy system is key. Our analyses showed that not only would women benefit more from the RE system due to their household responsibilities, but also in undertaking the dual responsibilities of care work and agricultural activities as men migrate in pursuit of education or income. Putting women in management and agentive roles in off-grid communities has proved beneficial for RE projects, for example as seen in the "light a million lives" project of the Buksh Foundation.[7] In addition, studies show that the physical drudgery of hauling water from wells and other laborious household chores can also be accompanied with emotional labour for women [58]. Freed evening time (for example by running the RO and collecting water more efficiently during daytime) can then be used by women in either economic engagements, or in rest and spending time with children- a priority indicated in the surveys- leading to their psychological empowerment [34]. Similarly, community lighting would improve mobility and communication, specifically benefitting women through improved safety and social capital [59]. Having said this, caution must be taken in making direct causal links between electricity access and women's economic empowerment due to the presence of significant structural barriers [34,35,57]. Further, as previous research indicates [36], care must be taken in evaluating trade-offs between socio-economic impact and increased electricity demands (for example in the use of washing machines that may also be water intensive). Moreover, whilst alternative low-energy appliances can be integrated with renewable energy systems to improve cost efficiency, care must also be taken that such technologies are both culturally-sensitive and socially-relevant, especially for cooking practices [23,57].

The average monthly energy usage per household across the entire community ranges from 7.6 to 10.2 kWh (Scenarios 1 and 1a) to 13.3 kWh (Scenario 2) and 44.6–48.4 kWh (Scenarios 3 and 4). Under the ten-year tariffs, these equate to monthly costs of USD 2.64–3.03, USD 4.15, and USD 11.60–12.62 respectively. Compared to the current average monthly expenditure on energy (USD 3.53), Scenarios 1, 1a and 2 could offer a relatively affordable improvement on present levels of energy access. Scenarios 3 and 4, meanwhile, would require a significant increase in expenditure which could be met through increased income from productive uses of electricity, and can be justified by the overall improvement to the socio-economic conditions brought about through electricity access, as previous studies indicate [5,40,41]. In practice, higher-usage households and businesses would pay more for their above-average electricity consumption and so lower-income households might still be able to afford access under Scenarios 3 and 4; this could also be supported via tiered pricing tariffs to cross-subsidise less affluent households to ensure a more inclusive system design. Monthly electricity costs are higher for the five-year tariffs for all scenarios owing to the higher LCOEs, and further highlighting the affordability benefits of longer-term system designs.

Caution must be taken when considering a ten-year or indeed longer timeframe as many factors could mean that the system becomes inoperable over time. Technical faults, a lack of buy-in from the community, lower electricity demand than expected, equipment degradation, vandalism, or unforeseen factors could cause the system to fail (and, indeed, within the first five years of operation). Mini-grid developers must be aware of these risks when implementing the electricity system as they could undermine both the long-term benefits to the community and the overall sustainability of any project.

All benefits of the ten-year systems are contingent on the high initial capital costs being raised at the start of a project. It is also dependant on the reliability of the system in meeting community demands for the entire operational period as, if faults or other issues result in system downtime or inoperability, customers may no longer pay their tariffs and the system would not be able to recoup its costs. Furthermore, whilst we account for degradation of the batteries over the investigation periods, it may be necessary to replace the batteries owing to the relatively harsh environment. This would incur additional costs that need to be incorporated into the tariff structure, a contingency fund, or other financial instrument to ensure that the system remains operational in the long term. In addition to the directly incurred O&M costs, system viability and durability depends on the availability of local technical expertise. This will incur labour costs, as well as costs for training and skills development currently unavailable on site. As our field visits revealed, lack of local technical expertise was a key barrier in the long-term operation of the existing RO plant. This means that system longevity necessarily depends on training and education of local citizens, especially women left behind as men migrate under economic necessities, who directly benefit from the project and so have a stake in

[7] For more details: https://news.un.org/en/audio/2016/03/610042

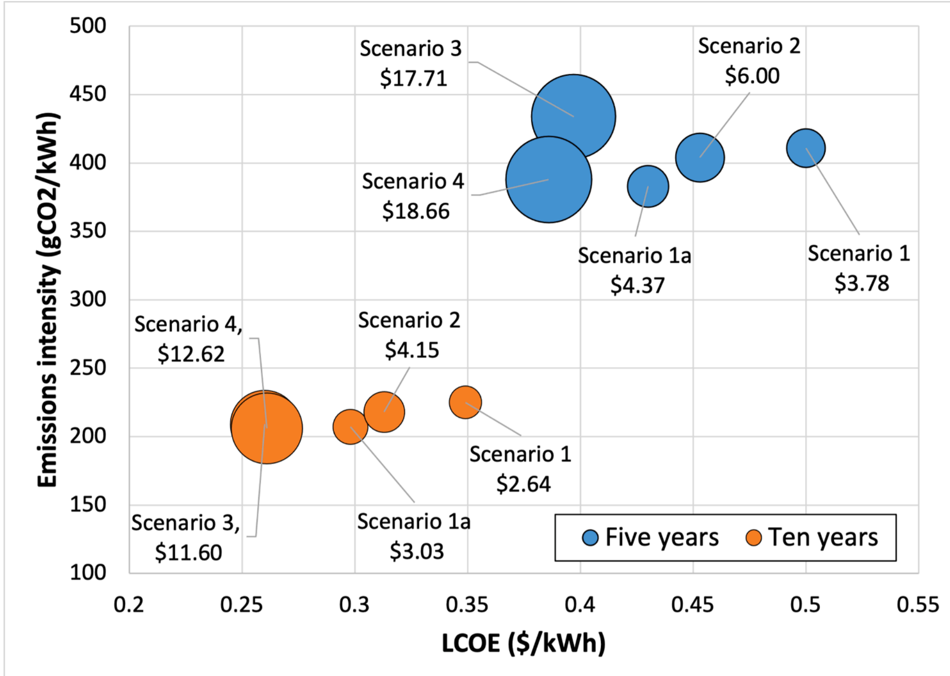


**Fig. 10.** The LCOE and emissions intensities of each of the scenarios under lifetimes of five years (blue) and ten years (orange). The area of the circles is proportionate to the average monthly expenditure on electricity (the product of the LCOE and electricity usage) across the community.

its successful operation. A socio-technical, inclusive and participatory approach is therefore essential to ensure project success in Phase 3 [36, 38].

In assessing the socio-economic implications of electricity access for women, our analysis reveals that in the present case, women would incur the most benefit from rural electrification. This is not only substantiated by the fact that women currently have less access to essential resources like energy, education, mobility and economic opportunities, they are also responsible for most household chores and care work. Electrification would provide the foremost benefit of access to clean water, in this case through the RO plant, thus reducing the time spent and drudgery faced by women in collecting water. In many hot and arid regions of the South, strong interlinks exist between the gender-energy-water nexus and access to electricity can serve to address the greater need for access to clean water. Secondly, due to the gendered nature of energy use, specifically in domestic settings, improved access to lighting in the evenings would improve women's working conditions through enhanced convenience and reduced drudgery in undertaking domestic chores like cooking and childcaring, while also providing extended working hours for economic opportunities. Further, due to women's limited mobility beyond the village, electrification would ensure that women would have better access to education and public facilities currently unavailable in the village. Electricity access can also substantially improve health services in the village, for example in storing medicines, or providing medical equipment. Currently, in case of any major medical treatment, women have to travel 24 km to the nearest electrified town, under the supervision of men. Further, access to televisions, internet and other communication devices can mean that women have better access to higher education and training inaccessible to them otherwise, which can lead to their socio-economic empowerment. Lack of electricity has also meant limited availability of markets and goods in the village. This has consequences for women, who often rely on their male family members to acquire everyday goods, household items and energy batteries on their visits to the nearby towns. Women, therefore, have limited choice and agency in purchasing decisions. Hence, access to electricity can have knock-on effects in terms of improved welfare and socio-economic development.

## Conclusions

This study presents the first of its kind socio-technical mixed-methods assessment of solar PV in Pakistan with a specific focus on affordability and gendered considerations, and thus serves as a useful demonstration project for future equitable and inclusive renewable energy system design in the region. Using Helario village as a case study, it establishes a replicable methodology for tiered and equitable energy access in Pakistan's rural areas that still lack access to electricity. Through its socio-technical approach, the study contributes to the field of energy systems planning with three key practice/policy recommendations: 1) taking account of socio-economic dimensions of RE along with techno-physical assessments so as to holistically integrate energy transitions into existing socio-cultural fabrics of rural communities, 2) designing for multi-tier and multidimensional access to energy for more inclusive pathways to sustainable development, and 3) understanding the gendered implications of energy access and use for improved energy justice and equity.

Our study shows that modelling renewable energy systems using actual energy-use data, in addition to understanding the complex socio-economic conditions, energy aspirations and future needs of end-users through quantitative *and* qualitative assessments can aid in designing more accurate, efficient and sustainable future energy systems. For example, energy-use data revealed the range of affordability in relation to energy sources, as well as the gendered disparities in access and use of energy (e.g., in productive uses, community spaces and evening lighting etc.). It also provided more accurate understanding of time-of-use (e.g., for domestic versus income-generating activities), energy requirements (e.g., women's preference and cultural values for traditional/familiar cookstoves) and potential for demand response through time-shifting for realistic system design and battery sizing. These results are in line with previous studies [e.g., 38] which demonstrate that scenarios with the highest levels of electricity (up to 24 h) can be unfeasible and impractical for remote rural communities, and may also be deemed undesirable, pointing to the need for better aligning community needs and aspirations in system design. Further, situated knowledge of local energy needs can help reveal unexpected links, such as those between access to energy and water, and their gendered implications. In our case, the gender-energy-water nexus would have remained invisible using purely quantitative metrics or standard energy audits that neglect the interlinks of energy with wider systems. The paper thus illustrates the need for a nexus approach and whole-systems thinking in energy system design.

The project's long-term techno-economic viability depends on the self-reinforcing cycle of the energy system which requires careful consideration. Larger supply systems to meet increased demands necessarily depend on higher incomes expected to be generated from higher productive uses of energy. This also means that energy systems are dependant on the emergence of new income sources as well as income generators- a factor where women can play a crucial role as change agents and ensure system longevity. Whilst previous studies [36,38] show that integrating community values and ensuring their participation is essential, limited attention is given to gender differentials in energy access and women's specific energy needs, such as in productive uses. Our study shows that community values can also be gendered and have differential implications for women's energy-use practices, highlighting their critical role in project design and sizing. Further, as [36] suggest, trade-offs (such as those between resource use versus electricity consumption, comfort and well-being versus higher economic costs) need to be evaluated in a holistic manner. Whilst our study has focused specifically on solar PV generation, previous studies [11,36,38,41] show that often hybrid systems work best, as community residents continue to employ fuel stacking within conventional energy-use patterns. Further scenarios can be developed taking hybrid systems into consideration. Nevertheless, the tiered approach used in the study provides the opportunity to discuss different scenarios in detail with the community, allowing for fuel stacking, hybrid considerations and negotiations in traditional (gendered) practices for different levels of service in Phase 3 of system co-design.

Primary end-user data in energy system modelling can provide critical insights into how a future mini-grid system might perform, but this methodology is naturally limited by its theoretical nature. For example, differences between modelled and real-life energy demands would affect system performance and variations in component costs could have impacts on the resultant LCOE, potentially by around 10 % [53]. However, this is mitigated somewhat in our work through the investigation of a range of scenarios as a first evaluation, with Phase 3 (Fig. 3) focused on project implementation and assessment. Further, our analyses does not account for lifecycle costs such as embodied carbon or disposal of solar waste and batteries, which can pose environmental risks [e.g., 13], and require further research. For this, alternatives to increasing demands through tiered demand response strategies can also be considered [e.g., 55]. Nevertheless, our study shows that equitable and inclusive renewable energy system design is possible through a socio-technical approach that emphasises community participation, actual energy-use data and modelling based around specific service offerings and affordability. Further, a key focus on gendered considerations can result in more equitable outcomes of future energy transitions.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A

Questionnaire survey for household domestic energy use

**Questionnaire Survey**

| | |
|---|---|
| Enumerator name: | Survey number: |
| Housing community: | Date of survey: |
| Time survey started: | Time survey ended: |

*Enumerators are advised to encourage gender parity in overall respondents to survey or aim for a higher proportion of women. The last section on women's practices should preferably be answered by women from the household.*

**Introduction and Survey Objective**

"Hello, my name is ____. We are conducting a survey on behalf of —-. This survey is part of a study aimed to investigate the energy access and use of people living in Helario village in Tharparkar and their future energy needs. This will be used to inform the design of future off-grid microgeneration solutions for the community. We would like to ask you few questions which will take about **30mins**. This survey will ask questions about your personal situation, including your family and finances. All the answers that you provide will be kept anonymous– only members of the survey team will have access to this information. Participation in this study is entirely voluntary. You can stop the interview at any time, ask me to clarify any question, or ask me to repeat something if you don't understand. Please answer the questions as accurately and honestly as possible to ensure accuracy of our study. Note that multiple answers are only applicable when specified in question. Your cooperation is greatly appreciated.

**Do I have your consent to ask the questions? Answer: Yes: ☐ No: ☐**

*Responded signature:* ____________________

*Survey conducted in language:* ____________________

**A. HOUSEHOLD DEMOGRAPHICS**

**Please provide information on who lives in the household, their age, gender, education, occupation and income**.

| | | | | |
|---|---|---|---|---|
| A.1 | Size of House (Footprint in sq.m) | | | |
| A.2 | Estimated height of rooms | | | |
| A.3 | Number of windows | | | |
| A.4 | Number of Bedrooms | | | |
| A.5 | Number of Occupants | Total | Adults | Children (under 18) |
| A.6 | House building structure | ☐ Burnt bricks and mortar with concrete roof<br>☐ Burnt bricks and mortar with wooden roof<br>☐ Burnt bricks and mortar with thatch roof<br>☐ Mud with thatch roof<br>☐ Wooden structure<br>☐ Others (__________) | | |
| A.7 | Is there a toilet inside the house? | **Yes:** ☐ **No:** ☐ | | |

| A.8 | **Name** (only note down initials) | **Relation to respondent** (For example: husband/wife, son/ daughter, father/mother, daughter-in-law, grandchild, cousin, friend, grandmother/ grandfather) | **Age** (Years) | **Gender** (Male, female, Other) | **Education**<br>1 Nursery<br>2 Primary (1–5)<br>3 Upper-primary (6–8)<br>5 Secondary/ Matric (9–10)<br>6 Intermediate (FA/FSc)<br>7 BA/BSc<br>8 MA/MSc and above<br>9 Vocational training<br>10 Apprenticeship<br>11 Other (specify) | **Occupation/ Income source**<br>1 Farmer<br>2 labourer<br>3 Small business/ Retail owner<br>4 Small business/ Retail worker<br>5 Government employee<br>6 Housewife<br>7 Student<br>8 No employment<br>9 Invalid<br>10 Retired<br>11 Other (Specify) | **Location of occupation**<br>1 Inside village: in the home<br>2 Inside village: near home<br>3 Inside village: in the local marketplace<br>4 Outside village: within 2–5 km (30 mins-1 hour)<br>5 Outside village: 5–10 km (1–2 h)<br>6 Outside village: >10 km (more than 2 h) | **Avg monthly income** (PKR) |
|---|---|---|---|---|---|---|---|---|
| 1. | | | | | | | | |
| 2. | | | | | | | | |
| 3. | | | | | | | | |
| 4. | | | | | | | | |
| 5. | | | | | | | | |
| 6. | | | | | | | | |
| 7. | | | | | | | | |
| 8. | | | | | | | | |
| 9. | | | | | | | | |
| 10. | | | | | | | | |
| 11. | | | | | | | | |
| 12. | | | | | | | | |
| 13. | | | | | | | | |
| 14. | | | | | | | | |
| 15. | | | | | | | | |

## B. ENERGY SOURCES AND ACCESS

| Source | | | Tick | Capacity Quantity/ Amount | Cost (PKR) | Per (Specify unit, e.g.: per candle, per litre or per charge of battery) | How often<br>1 Daily<br>2 2–3 times/ week<br>3 Weekly<br>4 2–3 times/ month<br>5 Monthly<br>6 Less than monthly | How long/far<br>1 Within village or less than 30 mins<br>2 2–5 km or 31 mins-1 hour)<br>3 5–10 km or 1–2 h)<br>4 More than 10 km or more than 2 h |
|---|---|---|---|---|---|---|---|---|
| Buy | B.1 | Natural gas | | | | | | |
| | B.2 | Batteries | | | | | | |
| | B.3 | Battery charger | | | | | | |
| | B.4 | Diesel for Generator | | | | | | |
| | B.5 | Charcoal | | | | | | |
| | B.6 | Firewood | | | | | | |
| | B.7 | Kerosene | | | | | | |
| | B.8 | Cooking gas (cylinder) | | | | | | |
| | B.9 | Candles | | | | | | |
| | B.10 | Other (_______) | | | | | | |
| Collect | B.11 | Firewood | | | | | | |
| | B.12 | Manure (Biomass) | | | | | | |
| | B.13 | Sticks/ leaves/ grass | | | | | | |

(*continued on next page*)

(*continued*)

| Source | | | Tick | Capacity Quantity/ Amount | Cost (PKR) | Per (Specify unit, e.g.: per candle, per litre or per charge of battery) | How often 1 Daily 2 2–3 times/ week 3 Weekly 4 2–3 times/ month 5 Monthly 6 Less than monthly | How long/far 1 Within village or less than 30 mins 2 2–5 km or 31 mins-1 hour) 3 5–10 km or 1–2 h) 4 More than 10 km or more than 2 h |
|---|---|---|---|---|---|---|---|---|
| | B.14 | Other (_______) | | | | | | |
| Charge | B.15 | Solar Home System (11+ Wp) | | | | | | |
| | B.16 | Solar Lantern | | | | | | |
| | B.17 | Cell phone | | | | | | |
| | B.18 | Other (_______) | | | | | | |
| B.19 | How much of monthly household income goes into energy sources? | | | | | | | |
| B.20 | Who pays for kerosene/ candles/firewood? | | | | | | | |
| B.21 | Who is the primary collector of firewood/ sticks? | | ☐ Adult male ☐ Adult female<br>☐ Child male ☐ Child female | | | | | |
| B.22 | Who is the primary collector of manure/biomass? | | ☐ Adult male ☐ Adult female<br>☐ Child male ☐ Child female | | | | | |
| B.23 | How often do you get (any) batteries charged from outside the village? | | ☐ Weekly<br>☐ Fortnightly<br>☐ Monthly<br>☐ Every few months<br>☐ Other (________)<br>☐ N/A | | | | | |
| B.24 | Where is the nearest battery charging facility located? | | ________ km away | | | | | |
| B.25 | What is your monthly expenditure on battery charging? | | | | | | | |

| | | | | | |
|---|---|---|---|---|---|
| B.26 | How would you assess the availability of energy sources for your household? | | | | |
| | **Excellent** | **Very Good** | **Good/Satisfactory** | **Bad** | **Very Bad** |
| | 5 | 4 | 3 | 2 | 1 |

| | | |
|---|---|---|
| B.27 | If bad or very bad, why is that the case? | ☐ I don't have sufficient cash for purchase<br>☐ Lack of availability of suitable energy sources to purchase<br>☐ Seasonal availability of fuel<br>☐ Lack of grid electricity/gas supply<br>☐ Others (__________) |
| B.28 | What would you like your primary source of energy to be? | ☐ Grid connection<br>☐ Mini grid or off-grid (decentralised)<br>☐ Renewable energy sources (solar, wind)<br>☐ It doesn't matter to be as long as I get better and more reliable supply<br>☐ Others (__________) |

### Ba. Lighting

| | | |
|---|---|---|
| Ba.1 | What sources of lighting are regularly used in your home? (Multiple selections possible) | ☐ No lighting at home<br>☐ Mobile phone<br>☐ Candles<br>☐ Disposable lanterns<br>☐ Kerosene lamp<br>☐ Solar-powered lights<br>☐ Battery powered lights/torches<br>☐ Firewood<br>☐ Others (____________) |
| Ba.2 | Primary sources of lighting | |
| Ba.3 | How many hours of artificial lighting do you get (per 24 h) on average? | ☐ Nil<br>☐ 1–2 h<br>☐ 3–4 h<br>☐ 4–6 h<br>☐ 6–8 h<br>☐ more than 8 h |

(*continued on next page*)

(*continued*)

| | | |
|---|---|---|
| Ba.4 | How much do you spend on average on lighting? | ________ per month in PKR |
| Ba.5 | What is evening lighting in your home usually used for? (Multiple selections possible) | ☐ Nil<br>☐ Cooking<br>☐ Cleaning and other essential household chores<br>☐ Studying/education<br>☐ Socializing/ Communication<br>☐ Recreation/ leisure time<br>☐ Working from home/Income-generation activities<br>☐ Safety and security purposes<br>☐ Moving around easily at night (including using toilet)<br>☐ Others (_________) |

| | | | | | |
|---|---|---|---|---|---|
| Ba.6 | How would you assess the availability of lighting for your household? | | | | |
| | **Excellent** | **Very Good** | **Good/Satisfactory** | **Bad** | **Very bad** |
| | 5 | 4 | 3 | 2 | 1 |

| | | | |
|---|---|---|---|
| Ba.7 | If bad or very bad, why is that the case? | ☐ I don't have sufficient cash for purchase<br>☐ I don't know where to purchase products/services<br>☐ There is a lack of products/ services available in the village<br>☐ There is a lack of products/ services available in the nearby market<br>☐ Others (_________) | |
| Ba.8 | If excellent or satisfactory, what are the reasons for your satisfaction? | ☐ Good lighting<br>☐ Long lasting<br>☐ Cheap<br>☐ Portable<br>☐ Easily available<br>☐ Others (_________) | |
| Ba.9 | How much would you be willing to pay per month for having access to 8 h of lighting? | ________ per month in PKR | |
| Ba.10 | On average, how many hours per day do your children study, read, or do schoolwork at home? The last time they studied at home, what time of the day did they study? | **Girl child**<br>Hours:<br>Start Time<br>[:]<br>End Time<br>[:] | **Boy child**<br>Hours:<br>Start Time<br>[:]<br>End Time<br>[:] |
| Ba.11 | What lighting source do they use whilst studying? | ☐ Candles<br>☐ Kerosene lamp<br>☐ Solar-powered/ Battery lights/torches<br>☐ Firewood<br>☐ Others (___________)<br>☐ N/A | |

### Bb. Cooking

| | | |
|---|---|---|
| Bb.1 | What do you usually use for food preparation/ cooking? (Multiple selections possible) | ☐ Manure/ mud<br>☐ Gas<br>☐ Electric stove<br>☐ Kerosene<br>☐ Coal<br>☐ Solar stove<br>☐ Firewood<br>☐ Sticks/ leaves/ grass<br>☐ Others (___________) |
| Bb.2 | Primary source(s) of cooking | |
| Bb.3 | How much time is spent in collecting fuel for cooking on a weekly basis? | ☐ Nil<br>☐ 1–2 h<br>☐ 3–6 h<br>☐ 6–8 h<br>☐ 8–12 h<br>☐ more than 12 h |
| Bb.4 | When during the day is the fuel for cooking usually collected? | ☐ Early morning (04:00–08:00)<br>☐ Morning (08:00–11:00)<br>☐ Noon (11:00–13:00)<br>☐ Afternoon (13:00–16:00) |

(*continued on next page*)

(*continued*)

| | | |
|---|---|---|
| | | ☐ Evening (16:00–18:00)<br>☐ Nighttime (18:00 onwards) |
| Bb.5 | Which of the following better describe how your primary cookstove was produced? | ☐ Self-made<br>☐ Unbranded manufactured or artisanal<br>☐ Branded/ manufactured<br>☐ Don't know |
| Bb.6 | Where is your cookstove located? (Select all that apply) | ☐ Inside the house- without extract/chimney<br>☐ Inside the house- with extract/ chimney<br>☐ Outside in the open |
| Bb.7 | Who is primarily responsible for food preparation/ cooking in your house? (indicate gender) | |
| Bb.8 | How many hours per day is spent on cooking? | ____ hours/day |
| Bb.9 | How do you store food? | |
| Bb.10 | Have you ever been injured or faced health issues (coughing/breathing problems, itchy eyes, skin irritation etc.), or witnessed someone else in the village being injured or facing health issues due to cooking fuel use? | ☐ No<br>☐ Yes- Burn<br>☐ Yes- Poisoning<br>☐ Yes- Respiratory issues<br>☐ Yes- Other (_________)<br>☐ Don't know |

| | | | | | |
|---|---|---|---|---|---|
| Bb.11 | How would you assess the availability of cooking fuel for your household? | | | | |
| | **Excellent** | **Very Good** | **Good/Satisfactory** | **Bad** | **Very Bad** |
| | 5 | 4 | 3 | 2 | 1 |

| | | |
|---|---|---|
| Bb.12 | If bad or very bad, why is that the case? | ☐ I don't have sufficient cash for purchase<br>☐ I don't know where to purchase products/services<br>☐ Inconsistent or Seasonal availability of fuel<br>☐ There is a lack of products/ services/ fuel available in the village<br>☐ There is a lack of products/ services/ fuel available in the nearby market<br>☐ Others (__________) |
| Bb.13 | If excellent or satisfactory, what are the reasons for your satisfaction? | ☐ Easy to store<br>☐ Cheap<br>☐ Easily available<br>☐ Easy to use<br>☐ Others (__________) |
| Bb.14 | What does your household usually do if there is not enough fuel for cooking? | ☐ Skip meals<br>☐ Purchase hot food from shop<br>☐ Cook food for less long<br>☐ Skip tea/coffee, hot water preparation<br>☐ Reduce portions<br>☐ Exchange food items for fuel<br>☐ Exchange non-food items for fuel<br>☐ Prepare "fast" cooking food<br>☐ Eat cold meals/don't warm up meals<br>☐ Use heated stoves from other households<br>☐ Borrow money/fuel from other households<br>☐ Only feed some members of the household<br>☐ Others (__________)<br>☐ None of the above |
| Bb.15 | Please rate three features of a cooking system that are most important to you (Multiple selections possible) | **Rate** **Feature**<br>Traditional/familiar stove<br>Suits our cooking habits<br>Save fuel<br>Less smoke<br>Safe to use<br>Fast preparation of food<br>Easy to handle<br>Comfortable size of stove<br>Good taste of food<br>Easy to repair<br>Stove is easily transportable<br>Stove is locally available<br>Stove can be used with different pot sizes<br>Affordable price<br>No preparation of fuel required<br>Other (____________) |

## C. ACCESS TO SERVICES/APPLIANCES

**Please provide information on appliances available in your household and related information**

| | Appliance | Quantity | Total hours of operation per day | Time of use (Hour) | | | | | | | | | | | | | | | | | | | | | | | | Who in the house mostly uses this appliance? |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | **AM** | | | | | | | | | | | | **PM** | | | | | | | | | | | | |
| | | | | 00 | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 | 12 | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 | |
| C.1 | Fixed Lights | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C.2 | Solar lamps | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C.3 | Kerosene lamps | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C.4 | Biomass lamps | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C.5 | Torches | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C.6 | Candles | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C.7 | Other lighting | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C.8 | Cooking appliances | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C.9 | Water pump (manual) | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C.10 | Solar water pump | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C.11 | Mobile phone | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C.12 | Mobile phone charger | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C.13 | WLL Telephone | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C.14 | Fan | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C.15 | Radio | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C.16 | Iron | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C.17 | Sewing machine | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C.18 | Other (________) | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C.19 | Other (________) | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C.20 | Other (________) | | | | | | | | | | | | | | | | | | | | | | | | | | | |

## D. COMMUNITY FACILITIES

## Please provide details of community facilities and community access to various services

| Item | | Type of facility |
|---|---|---|
| D.1 | Which electricity services/goods do you **access** from other HHs?<br>(HH doesn't own itself, but might be able to access from neighbours, relatives, market, etc.) | ☐ Mobile chargers<br>☐ WWL Telephone<br>☐ Solar batteries<br>☐ Income-generation appliances (e.g. sewing machine/ agriculture or farming appliances)<br>☐ Vehicles/ Automobiles<br>☐ Other rechargeable batteries<br>☐ Non-rechargeable batteries<br>☐ Other (____________) |
| D.2 | Which electricity services/goods do you **share** with other HHs?<br>(HH might share ownership with or provide access to other neighbouring houses or relatives, etc.) | ☐ Mobile chargers<br>☐ WWL Telephone<br>☐ Solar batteries<br>☐ Income-generation appliances (e.g. sewing machine/ agriculture or farming appliances)<br>☐ Vehicles/ Automobiles<br>☐ Other rechargeable batteries<br>☐ Non-rechargeable batteries<br>☐ Other (____________) |
| D.3 | Do you have access to your own vehicle/transport facility?<br>If fuel is used, indicate which kind of fuel (petrol, diesel,etc.) | ☐ Yes, my HH owns a ________<br>☐ No |
| D.4 | Do you share any of the following **activities** with other HHs? | ☐ Cooking<br>☐ Clothes Washing<br>☐ Fuel collecting<br>☐ Income-generation activities<br>☐ Other (____________) |
| D.5 | Are there streetlights installed near your house? | ☐ Yes ☐ No |
| D.6 | If yes, how many streetlights are present in your street? | |

## E. FUTURE NEEDS, SATISFACTION AND BEHAVIOURS

| | | | |
|---|---|---|---|
| E.1 | If applicable, which aspects of your energy supply would you like to improve? (3 selection possible; *First, wait for respondents to reply on their own. Provide them with options if they fail to respond or find it difficult to come up with any options by themselves.*) | **Rank** | **Aspect**<br>Longer supply hours<br>More services/appliances I can use<br>Lower cost<br>Less effort/drudgery involved<br>Greater consistency/reliability<br>Less pollution/ health risks from cleaner sources of supply<br>Other (____________) |
| E.2 | If you had an adequate supply of electricity, please rank the top three additional appliances you would like to regularly use<br>(3 selection possible) | **Rank** | **Appliance**<br>Nil<br>Electric lighting<br>Radio<br>Television<br>Electric iron<br>Phone charger<br>Water pump<br>Electric iron<br>Computer<br>Refrigerator<br>Freezer<br>Cooker or other cooking appliances<br>Fan<br>Washing machine<br>Air cooler<br>Air conditioner<br>Electric iron<br>Other (____________) |
| E.3 | Name the three most important things when making a purchasing decision. | ☐ Price<br>☐ Quality<br>☐ Portability<br>☐ Durability/Reliability<br>☐ Design<br>☐ Capacity<br>☐ Size (compact)<br>☐ Ease of use<br>☐ Colour/ Form<br>☐ Urgency of need<br>☐ Others (___________) | |

## F. GENDERED ENERGY: WOMEN'S ENERGY ACCESS AND USE

**Please provide details of women's access to services and activities** ***(Preferable to be answered by women in the house)***
*Was a woman able to answer these question*: ☐ Yes ☐ No

| | | |
|---|---|---|
| F.1 | Do women in the HH contribute to income-generation? | ☐ Yes ☐ No |
| F.2 | If yes, please indicate how? | |
| F.3 | Women in the HH have access to following energy services/ appliances: | ☐ Mobile phones<br>☐ Radio<br>☐ Television<br>☐ School<br>☐ Higher education<br>☐ Transportation<br>☐ Mobility within/outside the village |
| F.4 | Financial (Money-related) decision-making in the HH is mostly taken by: | |
| F.5 | Women in the HH take decisions related to the following: | ☐ Cooking/food preparation<br>☐ Childcaring<br>☐ Schooling<br>☐ Mobility<br>☐ Appliance purchases<br>☐ Purchase of small household goods (daily goods etc.)<br>☐ Purchase of major household goods (larger appliances, furniture, electric supply etc.)<br>☐ Household finances<br>☐ Community-related decisions<br>☐ Decisions related to assets (finances, property, land, inheritance)<br>☐ Life decisions (marriage, occupation, |
| F.6 | Do women in the HH own any assets? | ☐ House/property/land<br>☐ Inheritance<br>☐ Finances<br>☐ Jewellery<br>☐ Other (__________) |
| | Which above listed community-based facilities are available/accessible to women? | ☐ Food storage<br>☐ Water supply/storage<br>☐ School (upto class 8)<br>☐ Higher education institution<br>☐ Health center/ dispensary<br>☐ Hospital/ emergency medical aid<br>☐ Vocational/ training facilities<br>☐ Religious center/ building<br>☐ Transportation facilities<br>☐ Community center<br>☐ Sports/ Physical activity<br>☐ Recreational/ entertainment facilities<br>☐ Public park/green spaces<br>☐ Community-based Solar electricity kiosk<br>☐ Community market/service area<br>☐ Other (___________) |
| F.7 | Can women travel alone or feel safe travelling alone or in the company of other women? | ☐ Within the village<br>☐ Near the village<br>☐ Farther outside the village<br>☐ None of the above |
| F.8 | Do women feel safe going outside their home? | ☐ During daytime<br>☐ At nighttime<br>☐ None of the above |
| F.9 | How do women in the HH mostly spend their time in the morning? | |
| F.10 | How do women in the HH mostly spend their time in the evenings? | |
| F.11 | If women had the opportunity, which of the following three would you be likely to choose. (3 selection possible) | **Rank** **Opportunity**<br>Education<br>Vocational training<br>Means for income-generation/ Self-earning<br>Travel and Mobility/ Safe transportation facilities<br>Financial asset ownership<br>Property/Land ownership<br>Recreational facilities (TV, Radio)<br>Personal mobile phone<br>Community-based facilities (gathering spaces, green spaces, recreational spaces)<br>Appliances to ease household chores like cooking, washing, cleaning etc<br>Appliances to ease income-generation (e.g. electric sewing machine)<br>Improved housing facilities (better structure, more space, electricity, water, toilets, etc.) |
| F.12 | If women had more free time available to them due to ease of HH chores and electricity supply, what would you like to spend that time doing? | |

## Appendix B

Tables A.1 and A.2

**Table A.1**
The cost and GHG emissions of the main system components considered in the techno-economic modelling. Data has been taken from studies of solar mini-grid systems in rural areas of India [52,53,60].

| Input | | Cost ($) | GHG emissions (kgCO2eq) | Unit |
|---|---|---|---|---|
| **Solar** | Panel cost | 400 | 1520 | /kWp |
| | O&M | 8 | – | /kWp per year |
| **Storage** | Battery cost | 250 | 110 | /kWh |
| | O&M | 10 | – | /kWh per year |
| **Systems** | Installation | 100 | – | /kW |
| | Inverter | 200 | 75 | /kW |
| | Balance of systems | 200 | 200 | /kW |
| | Connection | 100 | 10 | /Household |
| | General O&M | 500 | 200 | /Year |

**Table A.2**
The number of appliances of each type in the community, their power usage, and typical hours of usage per appliance per day. Data has been taken from the surveying undertaken in this work and supported by studies of rural communities in India [52,53,60], with additional data from [61–63].

| Electricity service | Power (W) | Number in community | Typical usage (hours per day) |
|---|---|---|---|
| Lights | 3 | 1600 | 4–8 |
| Phone charger | 5 | 800 | 1 |
| TV/radio | 20 | 40 | 2 |
| Fan | 10 | 400 | 6 |
| Laptop/computer | 40 | 20 | 2 |
| Refrigerator | 50 | 20 | 16 |
| Drudgery reducing appliances | 500 | 400 | 2 |
| SMEs | 200 | 20 | 4 |
| RO plant | 17,000 | 1 | 2 |
| Streetlights | 25 | 80 | 9 |
| Community facilities | 500 | 5 | 9 |

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