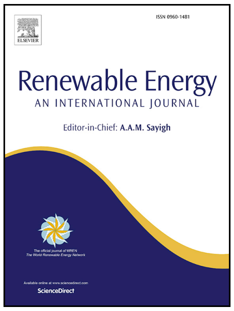

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Enhancing climate resilience of vulnerable women in the Global South through power sharing in DC microgrids

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Abstract

Many women of remote communities in the Global South (GS) are highly vulnerable to natural disasters caused by climate change, due to their low adaptive capability. Inclusion of gender considerations has been emphasized in national adaptation plans and initiatives aimed at reducing vulnerability. However, the potential of low-cost electricity-based solutions in promoting climate change adaptation is largely unexplored. In countries of the GS, remote communities have adopted stand-alone solar home systems, which are often inefficient and require significant investments for upgrading. In this work, a model of an off-grid DC microgrid with distributed generation and storage is proposed, allowing individual households to obtain extra energy through neighborhood-level prosumer power sharing. The benefits of power sharing are evaluated through the development of a mixed-integer linear program using load requirements based on the World Bank's Multi-Tier Framework for household energy access. The results show that households with prosumer power sharing can access more than 60% extra energy compared to their stand-alone status with up to 34% reduction in Levelized Cost of Energy. Access to additional energy can allow vulnerable households to access energy services in the household to potentially improve climate change adaptation opportunities in agriculture, livelihood and educational sectors, among others.

Keywords – Global South; climate change; adaptation; off-grid electrification; energy access; gender; Multi-tier Framework.

1 Introduction

Climate change poses a continuous threat to global ecosystems [1], economies, and human well-being, demanding urgent global action. Climate change is not gender-neutral and disproportionately affects women, particularly in the Global South [2]. Women in these regions often face greater vulnerability [3] due to socioeconomic factors[4], cultural norms[5], and limited access to resources [4] and decision-making processes [6]. Recent disasters in the Global South highlight the specific challenges women face in the context of climate change. For example, in the aftermath of Cyclone Idai in Mozambique, women faced increased risks of violence, loss of livelihoods, and limited access to healthcare and sanitation [7]. Similarly, during droughts in parts of Africa, women are often responsible for securing water and food for their families, placing additional burdens on them during times of disaster [8]. These disasters highlight the urgent need to address climate change and support adaptation efforts in the Global South (GS). Adaptation refers to the "process of adjustment to actual or expected climate and its effects", to reduce vulnerability and increase resilience of individuals and communities to climate change and its impacts [9].

Many developing and least developed countries (LDCs) have submitted their national adaptation plans to the United Nations Framework Convention on Climate Change (UNFCCC) [10]. Despite the emphasis on gender inclusion, most policy recommendations outlined in the reviewed documents are applicable at a national scale, lacking sufficient consideration for localized and context-specific scenarios which cater to the distinct needs of diverse communities, especially focusing on gender. To effectively address climate change, adaptation measures should account for gender-specific challenges, in order to improve women's living conditions and foster improved development prospects for future generations [11], [12]. As of 2023, 760 million people, mostly residing in countries of the GS lack access to electricity and the number is projected to remain high despite governments' electrification efforts [13]. Hence, this paper considers simple adaptation measures, tailored for women with the most basic access to energy services and appliances.

Access to electricity has significant potential to enhance sustainable development [14] and socioeconomic conditions of people in off-grid regions by enabling access to education, healthcare, and economic opportunities [15], [16], [17]. For example, in rural areas of developing countries, electrification projects have led to improved healthcare services through the availability of refrigeration for vaccines and medical equipment [16], as well as increased productivity and income generation using electric-powered machinery and lighting for extended working hours [17]. Electricity-led information and communication technologies (ICTs) enable access to online education and e-commerce platforms, thereby allowing communities to take independent actions in response to the changing climate. Electrification has positively been associated with women's empowerment in the GS [18], for example, through alleviation of time poverty, improved maternal health and changed social norms [19] [20].

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To track the role of last-mile electrification efforts in promoting climate change adaptation, a context-specific definition of electricity access is needed. In this paper, the World Bank's Multi-Tier Framework (MTF) [21] is used as also described in the authors' earlier work [22]. The use of individual Solar Home Systems (SHS) is widespread among off-grid households in the GS [23], which typically have access to Tier 1-2 energy services. SHSs waste up to 50% of the generated energy, due to limited energy usage and storage assets [24]. In addition, these would need significant investments to move up the electrification ladder through individual solutions. Interconnecting SHSs to form decentralized microgrids with power sharing can improve energy access at lower costs [25] with lower losses [26] compared to large centralized deployments. The technical feasibility of peer-to-peer (P2P) power sharing scenarios in DC microgrids with distributed generation and storage has been established in the authors' previous work [27]. A prosumer microgrid with P2P energy sharing was deployed and tested in a controlled pilot environment in an off-grid village in South Punjab, Pakistan [28]. The context-specific prerequisites for microgrid deployment were also identified for the selected site.

In this paper, a bottom-up approach is proposed, where each household has access to individual (atomic) units that connect to form a prosumer microgrid to allow peer-to-peer power sharing. For increased affordability, household users can gain access to excess energy services without additional costs along with the option to expand their systems as and when needed. This inherent flexibility in the system allows evaluating technical options to match the local needs/context [29]. To calculate the excess energy provision potential of a prosumer microgrid, a mixed-integer linear program (MILP) is formulated to model the interconnected SHS scenario with four houses. According to the authors' review of the literature, optimized utilization of energy in off-grid decentralized DC microgrids has not received much attention. Using the MILP developed in this paper, it is shown that the unused energy generation potential of SHSs can be exploited to promote households to higher tiers of energy access, potentially allowing women to use additional energy services which in turn could provide them with climate change adaptation opportunities like increasing awareness and information about climate change and related disasters, improved healthcare and education and access to clean drinking water.

The rest of this paper is arranged as follows: Section 2 presents the review of the literature and highlights the research gaps; Section 3 describes the system modelling and problem formulation; Section 4 gives the results for interconnected SHS system tested for two cases; Section 5 presents gender-specific climate adaptation measures enabled through increased access to energy and Section 6 provides the conclusions.

Symbols used

$S_{PV}(n)$	Nameplate capacity of the solar panel of house ***n.***
$I(t)$	Solar irradiance at time ***t.***
$\varphi(n,t)$	incorporates solar irradiance (a constant depending upon geographical location), PV module efficiency and temperature coefficient.
$P_{PV}(n,t)$	Solar panel output of house ***n*** at time ***t.***
$P_B(n,t)$	State of charge (SOC) of the battery of house ***n*** at time ***t***.
$P_L(n,t)$	The load demand of house ***n*** at time ***t.***
$P_{PL}(n,m,t)$	Flow of power from solar PV module of house ***n*** to the load of house ***m*** at time ***t.***
$P_{BCH}(n,m,t)$	Flow of power from solar PV module of house ***n*** to the battery of house ***m*** at time ***t.***
$P_{BDIS}(n,m,t)$	Flow of power from battery of house ***n*** to the load of house ***m*** at time ***t.***
$u_c(n,t)$	Binary integer variable to control if battery is being charged.
$u_d(n,t)$	Binary integer variable to control if battery is being discharged.
$P_{BR}(n)$	Charging/discharging (c-rate) rate of the battery of house ***n.***
DOD	Battery depth of discharge.
$\eta_{MPPT}(n,t)$	Decision variable to control the curtailment percentage of solar PV panels of house ***n*** at time ***t***.
$\eta_{BCH}(n)$	Battery charging efficiency.
$\eta_{BDIS}(n)$	Battery discharging efficiency.
η_{dist}	2-d symmetric matrix of distribution efficiency between house ***n*** and house ***m.*** For ***m*** = ***n,*** $\eta_{dist} = 1$.

2 Literature review

2.1 The Multi-Tier Framework (MTF) for measuring access to energy

The limitations of simplistic binary definitions of electricity access, which solely focus on the presence or absence of infrastructure, are well-recognized [21]. Such definitions overlook important factors such as the energy generation technology, energy consumption patterns, and the affordability and reliability of the electricity supply. The World Bank's Energy Sector Management Assistance Program (ESMAP) introduced a technology and fuel-neutral multi-tier approach in 2015. This method seeks to evaluate household electricity access as a continuous spectrum of improvement, considering various attributes of the supply that influence users' experiences, specifically concentrating on services like lighting, entertainment, communication, space cooling/heating, refrigeration, mechanical loads, product heating, and cooking. An analysis of measurement methodologies on energy access which takes a gender perspective claims that MTF is suited to the analysis of gender differences as it includes data gathering to understand various common disparities in outcomes and benefits, including differences based on gender [30].

The MTF for assessing household access to electricity is built upon seven key attributes, including supply capacity, availability, reliability, and affordability. These attributes collectively gauge the user's experience by assessing the utility of the electricity supply and, consequently, the usability of electricity services. The classification of overall access is divided into different tiers, ranging from Tier 0 (indicating no access to electricity) to Tier 5 (the highest level of electricity access). It is important to note that the allocation of tiers can vary across different contexts and countries, contingent upon the availability of survey data. The World Bank drafted energy access diagnostic reports for various African countries with low electrification rates based on outcomes of the MTF surveys. These reports use results of surveys to modify the MTF for assessing access to energy across these countries. To develop a generalized scheme for countries in the GS, this paper utilizes the first two attributes of the MTF in this paper, shown in Table 1. This analysis can be easily replicated to include the remaining attributes, which may be weighed in depending upon the context and data availability.

Table 1. Multi-tier Matrix for Measuring Household Access [21]

			Tier 0	**Tier 1**	**Tier 2**	**Tier 3**	**Tier 4**	**Tier 5**
Attributes	1. Capacity	Capacity (W)	< 3	3 - 49	50 - 199	200 – 799	800 – 1999	> 2000
		Daily Energy (Wh)	< 12	12 – 200	200 - 1000	1000 - 3400	3400 - 8200	8200
	2. Availability (Duration) of Daily Supply	Hours per day (h)	< 4	≥ 4	≥ 4	≥ 8	≥ 16	≥ 23
		Hours per Evening (h)	< 1	≥ 1	≥ 2	≥ 3	≥ 4	≥ 4

2.2 Optimized power sharing in distributed microgrids

Optimal P2P energy-trading in decentralized off-grid DC microgrids has been less widely studied compared to its on-grid counterpart [31], [32]. Nasir et al. compare efficiency and cost of energy for various architectures of low-cost microgrids [33]. They conclude that DC microgrids with decentralized generation and storage result in the lowest size and operational cost of the overall system. Decentralized architectures also exhibit lower distribution losses compared to centralized microgrids [26]. Improved energy utilization of excess energy in a microgrid can power shared loads for productive and communal uses [34]. It is challenging to operate a DC microgrid with distributed generation and storage equipment according to varying load requirements. Optimization techniques for P2P trading aim to schedule energy storage or sharing under system constraints and increasing the economic benefits for all peers. In a solar-based DC microgrid, solar modules, batteries and loads are all connected to a DC bus, with different DC voltage levels within and outside households. Energy Management Systems (EMS) and control strategies for the microgrid must then consider accurate system modeling, system stability, uncertainties, mismatch between load and generation, bidirectional power flow and power losses [35]. EMSs need to deal with multiple uncertainties, such as economic, technical or climatic, using scenario analysis, probabilistic analysis, or sensitivity analysis.[36]. In addition, control schemes may have their own imperfections, such as inaccuracy, chattering and slow dynamic response. [37].

The main objectives of optimization problems include maximizing system reliability (LLP, LPSP, etc.), efficiency and lifetime of components or minimizing system losses [38]. Thirunavukkarasu et al. [31] carried out a review of 555 research articles on optimization techniques for energy management in microgrids. Optimization techniques used in EMSs are grouped into four broad categories [31], that include forecasting, economic dispatch, demand management and unit commitment. The review in [31] indicates that MILP techniques are widely used to solve the energy management problem in microgrids. Multi-agent (MAS) and meta-heuristic algorithm-based approaches are more effective in distributed scenarios.

2.3 Impacts of climate change on vulnerable women

With changing climate, the frequency of droughts and floods increases. Droughts bring about water scarcity, which is in turn the root cause of many of the adverse socioeconomic impacts on women. In many cases, men migrate away from a drought-stricken area to work in the nearby towns or cities, leaving women behind, with limited opportunities to earn a livelihood [11, 39, 40]. According to a report by UN Women in 2018 [41], women are responsible for collecting water in 80% of the households lacking access to water on the premises. They have to travel long distances by foot [11], [42], sometimes in extreme heat [43]. The increased workload of the women leaves behind less time for educational [40] and income generation activities [44] .

Floods, on the other hand, lead to water stagnation, propelling the spread of diseases such as malaria. Evidence from the literature suggests that marginalized young women are most acutely affected by malaria. In addition, pregnant women are four times more likely than other adults to be attacked by symptomatic malaria than other adults [44].

Extreme temperatures, changing weather patterns and the altered rain cycle for example in the Badin district (southern Pakistan) [43] cause discomfort among women while carrying out their domestic chores. The increased heat stress in rural Pakistan negatively affects the on-farm and off-farm activities of women [45], which include crop protection, post-harvest activities and livestock and poultry management. Despite their active role in these sectors, social, economic and cultural restrictions limit women's role in the overall agricultural development of the country, making them marginalized and more vulnerable to the damage caused by climate-based hazards. Moreover, during extreme events when assets and cultivable land are lost, the burden on women increases due to their household responsibilities and greater vulnerability. The girls' education is disrupted and early marriages are prevalent to reduce the responsibility of protection of daughters [45].

2.4 Climate change adaptation in a gendered context

Climate change adaptation is needed in addition to mitigation strategies to fight the impacts of slow or sudden-onset natural disasters. Adaptation involves adjusting to current or expected climate effects [46], aiming to reduce vulnerability and enhance resilience [9], encompassing long-term changes and adjustments in ecological, economic, and social systems [47]. It is noteworthy that climate adaptation strategies differ between men and women. These distinctions stem from societal gender barriers rather than individual preferences [48]. An individual's decision-making in climate change adaptation is influenced by their societal roles, sociocultural norms, financial and information resources [39]. These factors vary across genders and neglecting gender-specific challenges may further increase the vulnerability of marginalized groups, diminishing the effectiveness of adaptation efforts [49].

Numerous examples show how vulnerable women have adapted to climate change and its effects. In Mexico, Bolivia, Nepal and Bangladesh, women have gained enhanced roles in agrobiodiversity and food and nutrition through home gardening [49]. They practice crop shifting, use more resistant seed varieties and change plantation and cropping patterns as a means of adaptation to the changing temperatures and uncertain rainfall patterns [42], [45],[48]. In the flood-prone Indus basin in Pakistan, women play the dominant role in flood-preparation [45]. They preserve food and seeds for future use and gather and store grains, fuel and dry vegetables and fruits for use during times of stress.

Women may also be supported through adaptation and capacity building interventions of local/regional governments, and agencies. The introduction of labor and time-saving technologies such as those for irrigation, cooking and agro-processing facilitate household and productive tasks for women. For example, Le Partenaria, an NGO introduced economical and ecologically friendly biodiesel energy solution to a group of 700 women fish-processors in Senegal, saving time spent in collecting wood, successfully increasing the revenue from fish farming [49]. In Bangladesh, post-cyclone Aila in 2009 [40] many men left the area for employment in nearby towns and cities. Women could not work outside the home due to the social tensions within the community and opted for small-scale handicraft work within homes through assistance of local NGOs. The NGOs provided the sewing materials and exported the final products to USA [40]. NGOs also helped to install water filtration plants and pond sand filters (PSF) for the provision of clean water for drinking and cooking. UNDP, UNICEF and similar organizations provided school textbooks, uniforms and helped to build temporary education centers to combat absenteeism in the aftermath of the cyclone.

Access to the latest information helps in capacity-building of women [39]. For example, capacity building interventions in Nepal enhanced precautionary savings and household preparedness towards floods through gender-sensitive trainings and extension services. Household savings for flood preparedness were highest in households having access to radio, remittances from out-migrated men and livestock ownership. The importance of financial literacy and inclusion for enhancing the adaptive capacity of women, especially in migrant-sending households has been emphasized time and again in the literature [39, 50].

2.5 Research gaps and the proposed scheme

A critical analysis of the literature on microgrids highlights a research gap in developing optimization techniques for EMSs for off-grid (islanded) and distributed DC microgrids. The literature on climate change adaptation reveals a gap in connecting climate change adaptation for women with access to energy, despite evidence suggesting energy-dependent adaptation strategies. National and regional climate change policies often devise energy and capital-intensive solutions, instead of focusing on small-scale, localized solutions for rural women. Therefore, it is needed to consolidate energy access with climate adaptation for women and to consider the gender aspect at each stage of electrification interventions. For example, an analysis of survey datasets from 25000 households across seven countries in the GS shows a positive association between improvement in women's conditions and household energy access [18]. In addition, the literature highlights the role of financial inclusion and gender equality in promoting sustainability of solar microgrids, focusing on enterprise and community uses of energy [51],[52], [53]. However, examples of an assessment of how increased energy access is related to women's adaptability in the GS are missing, a gap addressed in this work.

With millions of SHSs already installed in the remote communities of GS [23, 54], this paper proposes that scalable DC microgrids can also be formed by interconnecting or incorporating these, to improve energy access at negligible additional costs, through sharing of excess energy. This enables houses to achieve higher level of energy access compared to their stand-alone status [55]. The authors have already demonstrated the feasibility of prosumer power sharing in a decentralized microgrid system in an off-grid village in South Punjab, Pakistan [28]. A framework for calculating optimized sizes for components in an off-grid stand-alone SHS is also proposed with the objective of minimizing the loss of power supply probability (LPSP) and levelized cost of energy (LCOE) [24]. In this paper, a model is proposed to leverage the existing SHS resources of rural households by interconnecting them to harness excess energy through neighborhood-level power sharing. The interconnected SHS system is modelled through a MILP and stochastic load profiles based on the MTF are used to explore if power sharing in this interconnected SHS system can unlock enough energy to provide additional adaptation opportunities for women. The benefits of prosumer power sharing are examined in terms of tier enhancement for SHS owners, allowing women to gain additional electricity services, with minimal additional investment.

3 System model and mathematical formulation

In this section, prosumer behavior in an interconnected system of existing SHSs is examined. Each SHS can share energy with multiple other houses, based on excess/deficit of energy. At each time slot, a central controller ensures maximum extraction of solar PV potential by fulfilling the unmet load demand of all houses and charging their batteries until either they are full or excess generation is not available. The system model for a case with four houses is shown in Fig. 1. In this case, all houses can share power with all others, in a sequential fashion. However, this modelling can be used for alternate topologies with a given number of interconnections for each house.

The model deals separately with the source of power (PV or battery) in each house to calculate system losses from the model. In a practical system, these flows are lumped, and energy is only exchanged among batteries. Fig. 2 shows the power flows within and among the houses, along with the notation used.

3.1 Problem Formulation

3.1.1 Objective function

The objective is to maximize energy utilization, which is the difference between generated and consumed energy as shown in (1). $\eta_{MPPT}(n, t)$ controls the generation of power from solar PV panels of house *'n'* during each time slot *'t'*, i.e. it determines the amount of curtailment from each PV panel.

$$\min \sum_{n=1}^{N} \sum_{t=1}^{T} \{\eta_{MPPT} P_{PV}(n,t) - \sum_{m=1}^{N} \frac{P_{BDIS}(n,m,t)}{\eta_{BDIS}(n)\eta_{dist}(n,m)} + \frac{P_{PL}(n,m,t)}{\eta_{dist}(n,m)}\} \quad (1)$$

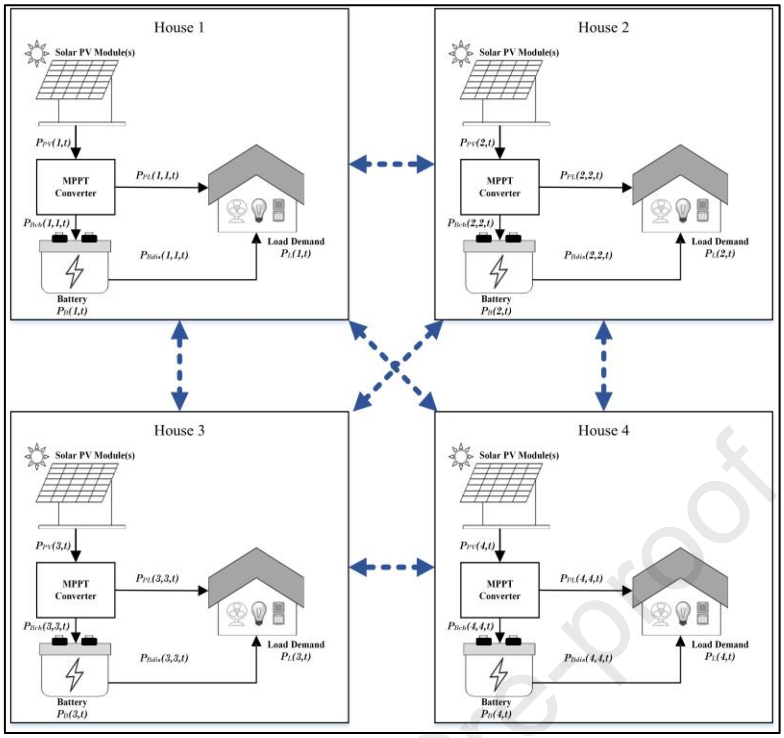

Fig. 1. Interconnected SHS System with bidirectional power sharing

3.1.2 Constraints

3.1.2.1 Solar PV modules

The output of the solar PV modules of house *'n'* at time *'t'* is dependent upon $S_{PV}(n)$, which is the solar PV module rating in Wp as shown in (2). $\varphi(n,t)$ incorporates solar irradiance (a constant depending upon geographical location), PV module efficiency and temperature coefficient.

$$P_{\mathrm{PV}}(n,t) = \varphi(n,t).S_{PV}(n) \qquad \forall t \in [1,T], \forall n \in [1,N] \qquad (2)$$

3.1.2.2 Batteries

The limits for input and output power of the battery are shown in (3)-(6). $u_c(n,t)$ is a binary integer variable, indicating whether power flows into or out of the battery at a particular time slot. P_{BR} is the maximum allowable power flowing into/out of the battery, depending upon its C-rate.

$$\sum_{m=1}^{N} P_{\mathrm{BCH}}(m,n,t) \geq 0 \qquad \forall t \in [1,T], \forall n \in [1,N] \qquad (3)$$

$$\sum_{m=1}^{N} P_{\mathrm{BDIS}}(n,m,t) \geq 0 \qquad \forall t \in [1,T], \forall n \in [1,N] \qquad (4)$$

$$\sum_{m=1}^{N} P_{\mathrm{BCH}}(m,n,t) \leq u_c(n,t).P_{BR}(n,t) \qquad \forall t \in [1,T], \forall n \in [1,N] \qquad (5)$$

$$\sum_{m=1}^{N} P_{\mathrm{BDIS}}(n,m,t) \leq u_c(n,t).P_{BR}(n,t) \qquad \forall t \in [1,T], \forall n \in [1,N] \qquad (6)$$

$$u_{\mathrm{c}}(n,t) \geq 0 \qquad \forall t \in [1,T], \ \forall n \in [1,N] \tag{7}$$

$$u_{\mathrm{c}}(n,t) \leq 1 \qquad \forall t \in [1,T], \ \forall n \in [1,N] \tag{8}$$

$$u_{\mathrm{d}}(n,t) \geq 0 \qquad \forall t \in [1,T], \ \forall n \in [1,N] \tag{9}$$

$$u_{\mathrm{d}}(n;\ t) \leq 1 \qquad \forall t \in [1,T], \ \forall n \in [1,N] \tag{10}$$

$$u_{\mathrm{c}}(n,t) + u_{\mathrm{d}}(n,t) \leq 1 \qquad \forall t \in [1,T], \ \forall n \in [1,N] \tag{11}$$

The power remaining in the battery at a particular time slot $P_{\mathrm{B}}(n,t)$, is an indicative of its state of charge (SOC). At the end of each time slot, $P_{\mathrm{B}}(n,t)$ is calculated according to (14), by adding the power input from all households and subtracting the power output to all households during the preceding time slot. Note that (11) ensures at least one of these quantities is zero for a particular battery at time *t*.

$$P_{\mathrm{B}}(n,t) \geq P_{\mathrm{BMAX}}(n).(1-DOD) \qquad \forall t \in [1,T], \ \forall n \in [1,N] \tag{12}$$

$$\mathrm{P}_{\mathrm{B}}(n,t) \leq P_{\mathrm{BMAX}}(n) \qquad \forall t \in [1,T], \ \forall n \in [1,N] \tag{13}$$

$$P_{\mathrm{B}}(n,t+1) = P_{\mathrm{B}}(n,t) + \sum\nolimits_{\mathrm{m=1}}^{\mathrm{N}} \left\{ P_{\mathrm{BCH}}(m,n,t) - \frac{P_{BDIS}(n,m,t)}{\eta_{BDIS}(n).\eta_{dist}(n,m)} \right\} \qquad \forall t \in [1,T], \ \forall n \in [1,N] \tag{14}$$

3.1.2.3 System balance equations

The load demand at each house '*m*' during time slot '*t*' is fulfilled using the PV generation and discharging the battery storage of every house '*n*' (1 to *N* in ascending order). The flow of power is depicted in Fig. 2. and mathematically represented by (15).

$$\sum\nolimits_{m=1}^{N} \left(P_{PL}(m,n,t) + P_{BDIS}(m,n,t) \right) \leq P_L(n,t) \qquad \forall t \in [1,T], \ \forall n \in [1,N] \tag{15}$$

The sum of power flowing to the loads and the power stored into the batteries of all houses must be less than or equal the generated power at each house during time 't' as shown in (16).

$$\sum_{m=1}^{N} \left(P_{PL}(n,m,t) + \frac{P_{BCH}(n,m,t)}{\eta_{BCH}(n)} \right) \leq \eta_{MPPT}(n,t).P_{PV}(n,t) \qquad \forall t \in [1,T], \ \forall n \in [1,N] \tag{16}$$

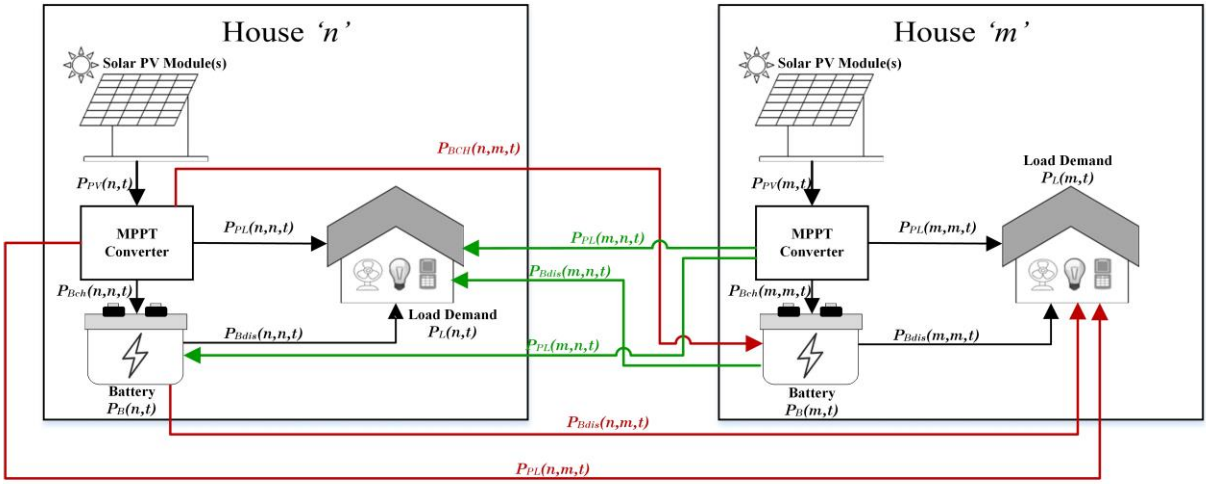

Fig.2. Power exchange between two SHSs

Loss of Power Supply Probability (LPSP) condition: ϵ is the limit of reliability (LPSP) expected by the entire system. As shown in (17), LPSP is the ratio of unmet energy (difference between energy demand and energy supplied by the system) to the total energy demand over the entire time period, T.

$$\frac{\sum_{t=1}^{T} \sum_{n=1}^{N} [P_L(n,t) - \sum_{m=1}^{N} (P_{PL}(n,m,t) + P_{BDIS}(n,m,t))]}{\sum_{t=1}^{T} \sum_{n=1}^{N} P_L(n,t)} < \epsilon \qquad (17)$$

3.2 Methods and datasets

3.2.1 Datasets used

The problem formulated in the preceding section is a mixed-integer linear program (MILP). In this work, a solar generation profile for a typical semi-arid region in the GS is used and modified stochastic load demand profiles are adapted from [56].

3.2.2 Using excess energy to power additional loads

For evaluation of power sharing in the interconnected SHS microgrid depicted in Fig. 1, all SHSs are identically sized and have comparable load demands. Theis microgrid homogeneity prevents the full exploitation of the energy generation capacity of the solar PV panels even with power sharing. To combat this, constant power loads are added to each household at fixed times of the day, to absorb the excess energy generated by the solar panels. The constant power flexible load, P_{FL} is added for 4 hours (hours 11-14) each day, corresponding to the peak sunshine hours of the system location. A real-time EMS can decide the exact value of loads on a day- or hour-ahead basis, depending on the exact system states. For this work, an average of the unused energy from each SHS is used, divided over 4 hours, as shown in (18).

$$P_{FL}(n) = \frac{24 * \sum_{t=1}^{T} \left(\left(1 - \eta_{MPPT}(n,t)\right) * P_{PV}(n,t) \right)}{T * 4} \qquad (18)$$

3.2.3 Context-specific sustainability and policy considerations

To increase the affordability of energy services, in this paper a bottom-up approach is proposed where households can not only gain access to additional energy services without additional costs but may also expand their systems without substantial investment. From a sustainability perspective, careful examination of context-specific social, financial and technical factors is needed [57]. In this regard, the affordability of household appliances for vulnerable women is an important issue together with women’s intrahousehold bargaining process and ability to negotiate the purchase of useful appliances to them. However, the proposed model in this paper removes the initial barrier of upfront cost of the system, making it feasible for households to use appliances later, due to their improved access to energy. In conjunction with the application of this model, the implementation and operation of microgrids in rural communities is an iterative process [58] following a multifaceted approach which combines gender-specific financial support and incentivization policies, community engagement, capacity-building programs aimed at promoting gender equity and inclusiveness, and collaboration across various stakeholders. At the national level, as governments review and update policies to encourage private sector participation and address grid versus off-grid issues, sustainable microgrid operations, especially in remote rural areas, stand to advance significantly [15]. Successful regulation can promote the integration of RES and distributed generation (DG) into traditional grids, enhancing energy security and cost-effectiveness. Consistent regulatory frameworks are crucial for providing security to investors and developers, and approaches may vary by region; for example, Tanzania and India may favor private entrepreneurship [8], while Kenya might prefer government-financed microgrids [8]. In this paper, the focus lies on extra power provision potential unlocked through prosumer power sharing, which alleviates the substantially bigger challenge of high upfront costs of solar installations.

4 Results

4.1 Case 1: Tier 1 households moving to Tier 2

For the first case, the connected households shown in the model in Fig. 1 belong to MTF Tier 1 for household energy consumption. Each house is equipped with a solar PV panel of 120Wp, a 30Ah battery and has an average daily consumption of 140Wh/day. The houses are allowed to share power, and the optimized energy flows are determined by solving the MILP outlined in Section 3. The LPSP of each household is maintained under 10%. The results show that with power sharing, the four houses shown in the model in Fig.1 can gain access to an additional 90Wh per day in addition to their existing load demand (as shown in Fig. 3) using the same solar panels and batteries. The LPSP of these houses remains the same, but the LCOE decreases from 38 cents/kWh to 25cents/kWh. Using this additional energy, households can run their existing appliances for longer periods of time and even run additional appliances such as TV, computer and printer. Fig. 4 shows the improvement in daily energy, maximum peak power and the LCOE along with highlighting the provision of additional energy services for the houses sharing power.

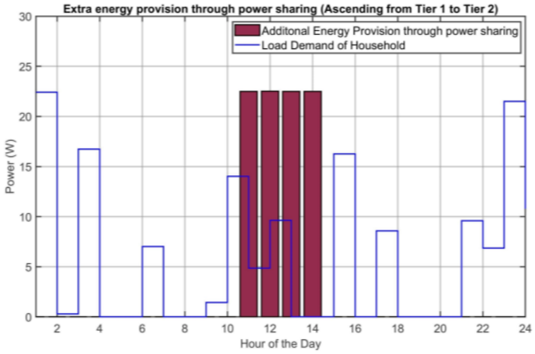

Fig. 3. Extra energy provision for Tier 1 Household

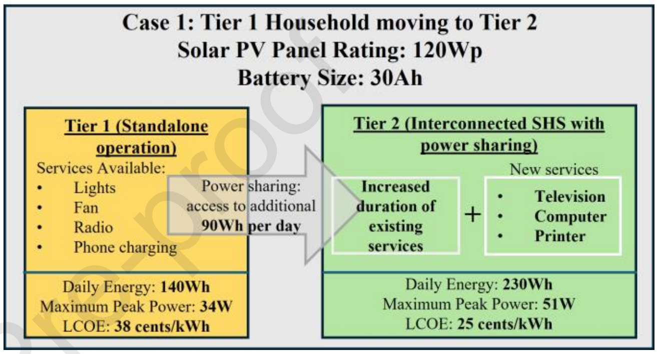

Fig. 4. Benefits of Power Sharing for Tier 1 Household

4.2 Case 2: Tier 2 households moving to Tier 3

In the second case, the households belong to MTF Tier 2, with an average energy consumption of 650Wh/day. Each house is equipped with a solar PV panel of 460Wp and a battery of 100Ah. Through power sharing, these households are able to access an additional 400Wh per day (as shown in Fig. 5) compared to their stand-alone operation. At the same LPSP, the LCOE decreases from 29 cents/kWh to 19cents/kWh. The households can use this energy to run their existing appliances for longer periods of time or run additional appliances as shown in Fig. 6.

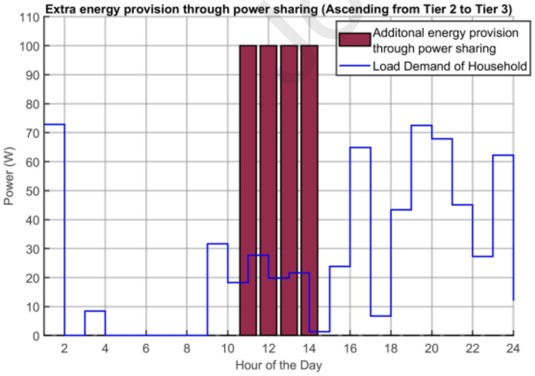

Fig. 5. Extra energy provision for Tier 2 Household

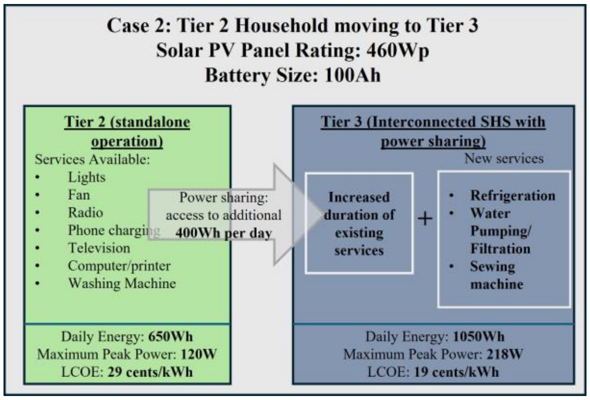

Fig. 6. Benefits of Power Sharing for Tier 2 Household

5 Using additional energy to enable climate change adaptation tools for vulnerable women

Women play a pivotal role in preparing for and responding to climate-related hazards and disasters. Climate adaptation and energy access initiatives must consider local gender-sensitive services to ensure equal benefits for both genders [12]. Since energy needs of climate change adaptation have not received enough attention in the literature and policy frameworks, in this paper, simple adaptation measures are proposed for vulnerable women, available using energy services at the lower tiers of household energy access in the affected communities. The role of energy devices in facilitating gender-specific adaptation measures is examined across various sectors including agriculture, livestock, education, and health. Household energy access Tiers 1-2 can efficiently power improved lights, fans, ICT devices such as phones, computers, and TVs. Surveys conducted in communities of the GS reveal that women have aspirations for labor and time-saving technologies [12], improved lighting inside homes, and expressed a desire to pursue education [53]. Improved lighting inside homes has been linked to better well-being of women, whereas street lighting can promote safe water collection for women without water on their premises [59]. The use of ICTs may support women farmers in the agriculture sector by providing essential information about seed varieties, crop shifting [45], [48], for obtaining forecasts and warnings about impending disasters [42]. Likewise, literature on gender and energy identifies the challenge of time poverty among vulnerable women [60],[49],[61]. Energy-efficient electric appliances can streamline household chores allowing for free time, helping to improve women's health and create avenues for improved livelihoods and educational opportunities [20], [49], [60]. However, it is important to note that the use of additional energy services by women depends on their intrahousehold bargaining power and agency. Electrification interventions and new technologies alone may not eradicate the sociocultural factors that lead to discrimination against women [62], unless awareness campaigns and energy justice policies are implemented.

In Table 2, adaptation measures are identified for vulnerable households, in particular for women in various sectors and propose energy-based services and household energy access tiers that may facilitate them.

Table 2. Energy services leading to climate change adaptation measures for vulnerable households

Sector	**Adaptation Measures (Identified from Literature)**	**Proposed Electricity Services to enable Adaptation Measures**	**Minimum tier of household energy access required for each Service**
Agriculture	Home gardening [49]	Use of ICTs to gain information and alerts	1-2
	New seed varieties [42], [45], [48]		
	Crop shifting [42], [45], [48], [40]		
Water Supply	Water for irrigation	Water Pumping/Filtration	3
	Water for drinking		
	Water filtration		
Disaster preparedness	Food storage [45]	Refrigeration	3
	Knowledge systems [42]	Use of ICTs	1-2
	Warning systems [42]		
	Precautionary Savings [39]		
	Selling livestock/handicraft products	Microfinance (Mobile Phones)	1-2
Labor and time-saving technologies [20] [49] [60]	Water for domestic needs	Household Water pumping	3
	Household chores Care provision	Washing Machine	2-3
		Food Processor	3
		Household appliances	3
	Care provision	Information about diseases, reproductive health etc. (ICTs)	1-2
Financial	Financial inclusion [39] [50]	Microfinancing services using mobile phones	1-2
	Handicraft making [40]	Sewing machines	3
		Solar Iron	3
		Indoor Lighting	1-2
		Microfinancing (mobile phones)	1-2
		Marketing/connecting to sellers (ICTs + Mobile Phones)	1-2
	Ensure access to technical and vocational training [63]	Use of ICTs	1-2
		Lighting	1-2
		Sewing machines	3
		Space Cooling (fan)	1-2
		Water pumping	3
Education	Resuming education after disasters [64]	Lighting	1-2
		Space cooling	2-3
		Computers	3
	Improved health of young girls	Water pumping and lights for sanitation	3
	Combat absenteeism of female students [45]	All services that reduce household chores for young girls	Up to tier 3

6 Conclusion

In this paper, a MILP-based model of an interconnected-SHS system is developed to evaluate excess energy provision potential of a prosumer microgrid. Results show that with optimized consumption, households can acquire up to 60% additional energy compared to their stand-alone status, with a 34% reduction in Levelized Cost of Energy (LCOE). In cases of women-headed households or in absence of other challenges to their energy access and use, optimized energy usage could translate into power availability for longer time duration and use of additional appliances (if economically viable), potentially enhancing climate change adaptation opportunities through water pumping and household/productive device usage [59]. To enhance the short-term sustainability and affordability of this approach, simple adaptation measures available to women in the agriculture, livelihood and educational sectors are mentioned, among others.

This research provides a framework for improved energy service usage in off-grid settings, emphasizing how it can lead to potential positive impacts on women's climate change adaptation. Future research can extend the application of the proposed framework to various geographic and socioeconomic contexts within the GS to assess how electrification interventions impact women's adaptation strategies in diverse settings. A comparative analysis can reveal region-specific challenges and opportunities, thereby refining strategies and technologies for more effective electrification efforts. Further work should focus on providing guidelines to incorporate localized energy solutions in gender-inclusive policymaking. By identifying tier-wise energy needs for various adaptation measures, policymakers can tailor their energy planning to meet specific requirements in different sectors and localized contexts. This targeted approach can optimize resource allocation and ensure that energy solutions align with the unique needs of communities and their most vulnerable members.

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Declaration of interests

☒ 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.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: