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Swarm electrification for Raqaypampa: Impact of different battery control setpoints on energy sharing in interconnected solar homes systems

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ABSTRACT

In rural electrification, decentralized systems have proven to bring fast, affordable, and sustainable electricity supply for the last mile of energy access. Especially, solar home systems (SHS) have lately increased in number and impact. Recently, a new concept promises even better utilization of SHS and the potential for higher access to electricity. This concept is found under the name of swarm electrification, also known as interconnected SHS, nanogrids, or decentralized DC systems in rural areas. This paper studies the benefits of such interconnected SHS for a case study in the indigenous rural Highlands of Bolivia, an area called Raqaypampa. Our study emphasizes analyzing the energy sharing setpoints for the decentralized battery control and how the choice of these values influences energy distribution in the community. We draw concepts of energy justice into our discussion to evaluate different combinations of battery state of charge setpoints. Our study finds four types of households in Raqaypampa based on their demand for electricity. The modeled and simulated results of a potential energy sharing through interconnected SHS reveal three outcomes for the households based on the battery state of charge setpoints: Outcome I — Improving households, Outcome II — Depending households, and Outcome III — Deteriorating households. We conclude that a common approach of e.g. minimization of total unmet demand alone will not necessarily lead to just energy distribution, and it is crucial to integrate discussions about justice and community goals into the design process from the beginning.

1. Introduction

1.1. Interconnected solar home systems

In recent years, the adoption of Solar Home System (SHS) has surged, particularly in rural areas where access to traditional grid electricity is limited. These systems have provided a crucial solution for households that previously had no reliable source of power, enabling them to meet basic energy needs and significantly improving their quality of life. The increased deployment of SHS aligns with global efforts to achieve the United Nations Sustainable Development Goals (SDG), specifically SDG 7, which aims to ensure access to affordable, reliable, sustainable, and modern energy for all.

While SHS have made substantial contributions towards rural electrification, there is growing interest in exploring how the interconnection of these systems into a SHS based microgrid can further enhance and expedite energy access. A step-by-step interconnection of SHS is defined as *Swarm Electrification* by Groh et al. [1]. Fig. 1 presents these steps as adapted from Fuchs et al. [2], where the authors focus on analyzing step two in the overall process of swarm electrification. In the present paper, we study the third step, highlighted with yellow background color in Fig. 1.

By creating a network of interconnected SHS, households can share surplus energy, optimize resource utilization, and increase the overall reliability of power supply. This interconnected approach maximizes the efficiency of individual systems and could potentially also foster community resilience and support sustainable development. Including this already while planning SHS deployment is mentioned as an important highlight for the success of the technology by Shyu [3]. In a recent review, Sheridan et al. [4] finds several central themes in contemporary studies on swarm electrification. These themes include the

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Acronyms

b-cha-max	Battery state of charge setpoint for energy sharing - maximum for charging from neighbors
b-dis-min	Battery state of charge setpoint for energy sharing - minimum for discharging to neighbors
EJ	Energy justice
HH	Households
NGO	Non-Governmental Organization
PVGIS	PV Geographical Information System
pvlib	PV library in Python
RAMP	Remote-Areas stochastic Multi-energy load Profiles generator
SDG	Sustainable Development Goals
SHS	Solar Home System
TMY	Typical Meteorological Year

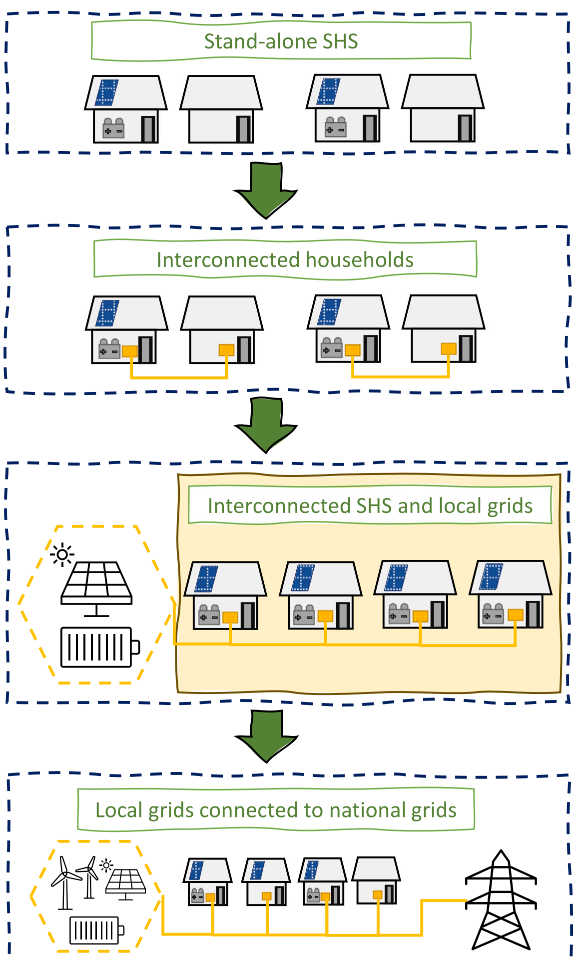

Fig. 1. Swarm electrification - a step-by-step process for rural electrification, where the third step (yellow background color) is focus of this study.

motivating factors and obstacles, financial considerations, structural integrity and stability, control mechanisms, energy sharing markets, and optimization strategies. The review emphasizes the need for additional research in the areas of optimization, stability, and reliability to effectively scale up swarmgrids. Since energy sharing is crucial to swarm electrification, it must be optimized to meet established goals. But what goals to choose, and what factors influence these? Numerous studies propose various control algorithms and rules to enhance energy sharing efficiency and often minimize unmet demand.

1.2. Energy sharing in interconnected SHSs

Opiyo [5] presents energy sharing with 25 and 100 households, showing increasing benefits with size, however, uses a battery model as common battery, not individual batteries, which eliminates the discussion on the individual setpoints for the battery state of charge for energy sharing with their neighbors.

Narayan et al. [6] quantifies the benefits of interconnecting SHS. The authors find that while standalone SHSs can only support electricity access for lower level of demands, a microgrid composed of interconnected SHSs can significantly improve system metrics such as loss of load probability and battery size for higher levels of demands. A rule based energy sharing concept is used with the objective to minimize the total unmet demand. Surplus energy from PV is shared, however, batteries from neighbors do not participate in the energy sharing, which further could have improved the situation.

Narayan et al. [7] presents a decentralized control scheme designed to facilitate power sharing between SHS within a rural DC microgrid. Highlighted are the benefits of a communication-free, state of charge based adaptive droop control. By incorporating a deadband in the droop characteristics of the battery converter, unnecessary battery cycling is minimized. Furthermore, making the droop resistances adaptive to the state of charge levels of the battery ensures that batteries discharge at higher rates when state of charge levels are high and at lower rates when state of charge levels are low.

Richard et al. [8] presents a droop-control algorithm with energy sharing for interconnected nanogrids in Madagascar. Battery state of charge setpoints are defined for battery charge and discharge from the interconnected nanogrids. However, the choice of these setpoints is not analyzed deeper. Further, the nanogrids are initially dimensioned with sufficient capacities to be self-supplied, making it unnecessary to analyze the energy balance benefits of energy sharing, however, stability benefits and lifetime improvements are still valuable advantages of the concept.

Sayed et al. [9] presents a laboratory test of energy sharing between four households with interconnected SHSs, looking into the design of the sharing algorithm including state of charge setpoints for battery sharing. However, the authors do not discuss why the utilized setpoints are chosen and what consequences they have for the optimality and energy sharing between the households.

These studies aim to execute energy sharing using a rule-based approach, enabling a decentralized and communication-free implementation. In the context of rural electrification, such robust technologies are preferred due to the frequent absence of existing communication infrastructure, which would enable more complex optimization methods for distributed energy resources, as presented in [10–15]. These methods often assume perfect foresight of the future, or enable the inclusion of forecasts. However, in our setting, we assume the only values known to the individual controllers, are the actual measured values by that controller (voltages locally and at point of interconnection, and state of charge of battery) which enables a decentralized rule-based approach.

The studies presenting such a rule-based control share a common approach: they either exchange only direct surplus energy from PV panels or, additionally, they exchange energy based on the setpoints of their battery state of charge. However, none analyze the impact of these setpoints on the benefits of energy sharing for communities and individuals. Our paper addresses this gap and discusses the findings based on a real case study in Raqaypampa, in the Bolivian Highlands.

1.3. Community energy as a just and democratic affair

The ways communities deal with energy are not only a matter of getting the right technologies in place, but also of making sure that the cost and benefits of the energy matters are distributed across the community in a way that is justifiable according to the community's own value systems, and in a way that is decided upon in line with the community's structures of self governance. This raises the question of what kind of socio-economic relations the technologies seem to presume or even enforce, and how communities can incorporate the technologies. Addressing such considerations has been central to theorization of Energy justice (EJ). We build on this literature to evaluate and discuss the findings of our energy sharing simulations.

EJ has emerged as a topic across humanities and social sciences over the past decades, building on traditions of general theorizing of justice as well as specific traditions such as environmental justice and, more recently, also decolonial justice. Jenkins et al. [16,17] count as central publications in this tradition, defining EJ as a compound of three central pillars: distributive, procedural and recognition justice. Distributive justice concerns the question of how goods are (re-) distributed, and thus what all need to contribute and are entitled to receive. Procedural justice addresses the question whether collectively binding decisions are made in such a way that all affected and involved persons can meaningfully contribute to the decision making, and whether the possibility to contribute is sufficiently available to all. Recognition justice addresses the question of whether the interests of affected persons have been adequately reflected in the decision process and been taken seriously. Building more on a decolonial tradition, Menton et al. [18], Vermeylen [19] argue that many discussions on EJ too uncritically reproduce Western, modernist conceptions of justice and enforce the underlying individualist epistemologies and overrule local epistemologies. This leads us to see eventually emerging inequities rather as questions to address within local epistemologies, with reference to local conceptions of justice and democracy (or otherwise 'good governance'), rather than as something that is to be resolved straightforwardly by, for example, compensatory payments. We will further address this in Section 5.

1.4. Research questions and contributions

Based on the found research gap and presented ambition we formulate the following research question: Can swarm electrification bring benefits to the electrification scheme of Raqaypampa? To answer this question, we need to dive into two sub-questions:

- How is the access to energy changing (unmet demand) individually and for the community based on different state of charge setpoints for energy sharing?
- What problems of fair energy distribution does swarm electrification pose, and how can these be addressed?

Based on these research questions the major contributions of our study are:

- A detailed real case study with first energy access through solar homes systems and the electricity demand for different sizes and types of households
- A multi-model simulation based analysis of the benefits of energy sharing for the identified households
- A comprehensive study of different battery setpoints in rule-based control schemes, enabling a communication-free energy sharing implementation
- A detailed discussion on the energy justice implications of different setpoint strategies and the benefits for individuals and the whole community

The novelty of our study lies in its approach of calculating all possible outcomes from energy sharing based on varying battery setpoints, followed by a discussion grounded in energy justice principles. This contrasts with the more conventional approach, where a specific goal is set beforehand, and a model is then optimized to achieve that goal.

1.5. Paper outline

From this point the paper sections are the following: In Section 2 we present the theory and methodology for our study, which includes our rule based energy sharing method and some essential understandings of energy justice. Section 3 presents our case study, Raqaypampa, which is located in the Indigenous autonomy area in the Bolivian Highlands. Section 4 presents our results from the simulations of energy sharing with different setpoints for the battery. In Section 5 we discuss these simulation results and assess the findings against core principles of justice, presented in Section 2. Finally, we present our conclusion of the study.

2. Method and theory

The approach undertaken in this study encompasses four principal phases: (1) Data collection, (2) Data simulation and validation, (3) Swarmgrid model, and (4) Evaluation of energy justice. Initial data gathering was accomplished through field visits to Raqaypampa, encompassing both sociological information acquired via surveys, interviews, and observations, and technical data obtained through data loggers and direct measurements. The second phase involves structuring the input data for the swarmgrid model by simulating both the demand and PV generation, followed by validating these simulations with actual measurements. Subsequently, this prepared data is employed to execute the swarmgrid model, aiming to evaluate the advantages of energy sharing within Raqaypampa. Finally, the results from the swarmgrid model are evaluated based on energy justice concepts followed by a critical discussion. This comprehensive methodology is depicted in Fig. 2, with further elaborations provided in the following subsections.

2.1. Data collection

Self-reported data on energy practices was necessary for estimating demand. To collect this information, questionnaires were utilized and administered as surveys during fieldwork in the studied zone. The instrument for data collection was designed to include both closed-ended and open-ended questions, aiming to capture principally the main activities families perform during the day and that require energy. The questionnaires used for this work are shown in Appendix A.

Additionally, this study gathered measured data from data loggers of installed SHS, capturing energy consumption and PV generation. However, due to the limited duration of available measured data, it was used solely for validating the simulated demand and PV generation. It is important to note that the PV generation data may not reflect the full generation potential, as unused PV energy is curtailed in an off-grid system.

2.2. Data simulation and validation

2.2.1. Demand simulation

In the development of the swarmgrid model, it is essential to utilize annual demand time series for Raqaypampa. However, the available measured data only covers a shorter duration and primarily reflects the current consumption with the existing SHS, omitting potential demand in scenarios of increased electricity availability. To bridge this gap, demand profiles are constructed using surveys and the open-source stochastic demand modeling tool, as introduced by Lombardi et al. [20]. This Python-based tool, named the Remote-Areas

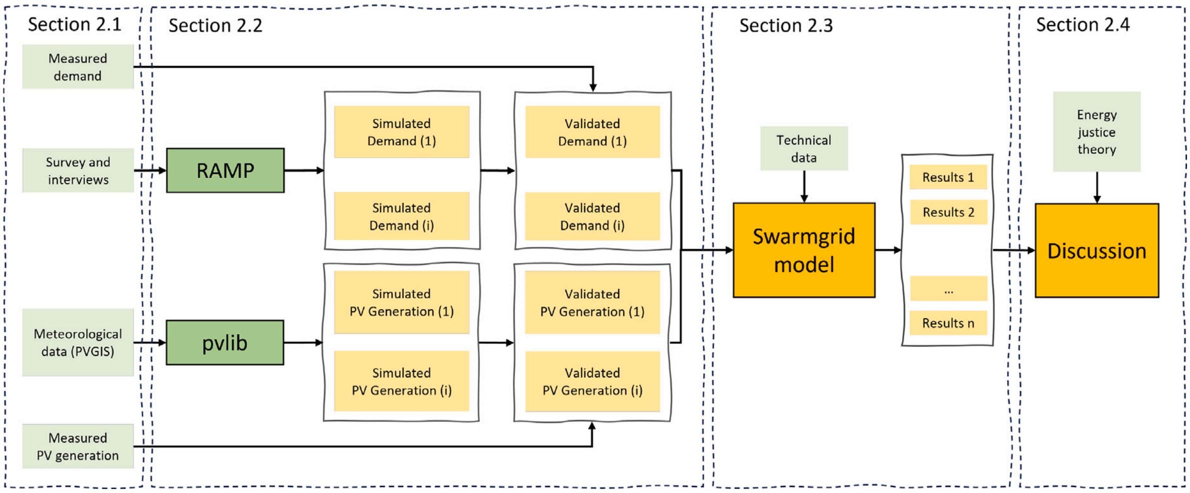

Fig. 2. Methodology comprising data collection, data simulation with RAMP for demand modeling and pvlib for PV generation modeling, validation of simulated data, swarmgrid model and finally evaluation of energy justice based on results from swarmgrid model.

stochastic Multi-energy load Profiles generator (Remote-Areas stochastic Multi-energy load Profiles generator (RAMP)),[1] and specifically version v0.5.1, facilitates the generation of such demand profiles. RAMP is tailored for the typical electricity usage patterns found in rural settings, including households, schools, health centers, and churches. Its versatility allows for adaptation to any rural region or village by customizing input data related to appliances. The model simulates each appliance by setting various parameters, such as power capacity, usage duration, and operational time slots. It also incorporates stochastic elements to produce diverse demand profiles with each execution, offering a comprehensive tool for modeling potential electricity demand in regions with limited access to electricity.

2.2.2. PV generation simulation

The PV power output of the SHS is simulated using the PV library in Python (pvlib), a collaborative open-source project hosted on GitHub.[2] This library is built upon algorithms derived by Holmgren et al. [21]. Various resource datasets are available in pvlib. For this study we utilize the PV Geographical Information System (PVGIS) developed and updated by Huld et al. [22]. This dataset provides solar radiation data derived from geostationary satellites. The dataset offers hourly data, including measures of solar radiation, sun elevation, ambient temperature, and wind speed. To ensure the dataset accurately reflects the specific conditions of our system's location, we select the typical meteorological year data for our site.

2.2.3. Data validation

To validate the simulated demand and PV generation, we compare them with measured data for corresponding periods. A visual comparison is performed, and any discrepancies are analyzed. Based on this analysis, adjustments are made to the simulated data before it is used further in the swarmgrid model.

2.3. Swarmgrid model

In this study, a swarmgrid composed of four households (Fig. 3) is modeled using an energy flow model that calculates the energy exchanges between households at each time step. A time resolution of 10 min is used to most accurately represent the actual demand and PV power in the energy system.

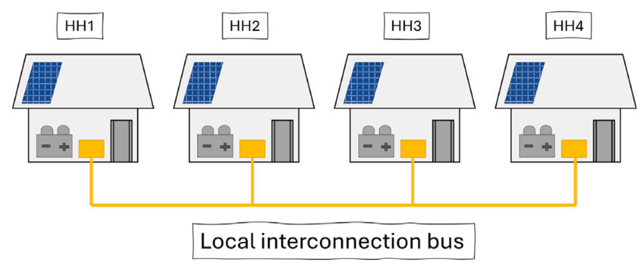

Fig. 3. Local interconnected grid of four households, each with an individual controller (yellow) that controls the energy sharing with the neighbors.

To represent the interactions in a distributed swarmgrid, a simulation model is developed with two primary phases: the Individual dispatch section and the Energy sharing among SHS section, as outlined in Fig. 4.

Initially, the model prioritizes meeting the household's own demand using available PV power and charging the household's battery. The second priority arises when PV energy falls short, such as during rainy periods or nighttime, prompting the battery to fulfill the energy needs. Subsequently, each individual system calculates its surplus energy and lost load for that specific timestep by subtracting demand from generated power or available energy stored in the battery. These values are inputted into the energy sharing segment of the swarmgrid model.

In the energy sharing phase, the collective surplus energy and lost load are evaluated, and the model begins redistributing energy by adding and subtracting energy values for each timestep. The third priority involves addressing the lost load of households with the surplus energy from those with excess, assuming surplus energy surpasses lost load. Should surplus energy remain beyond this distribution, it is directed towards charging batteries below the Battery state of charge setpoint for energy sharing - maximum for charging from neighbors (b-cha-max), a model parameter. A lower set value for this limit restricts batteries from receiving energy during this phase, whereas a higher value promotes receiving additional energy from neighbors in the presence of surplus.

Conversely, if surplus energy is less than the total lost load, the model activates its fourth and final priority action. This entails allocating the remaining surplus energy towards covering lost loads and engaging batteries from households with a state of charge above the Battery state of charge setpoint for energy sharing - minimum for discharging to neighbors (b-dis-min), to cater to the outstanding lost

[1] https://github.com/RAMP-project/RAMP
[2] https://github.com/pvlib/pvlib-python

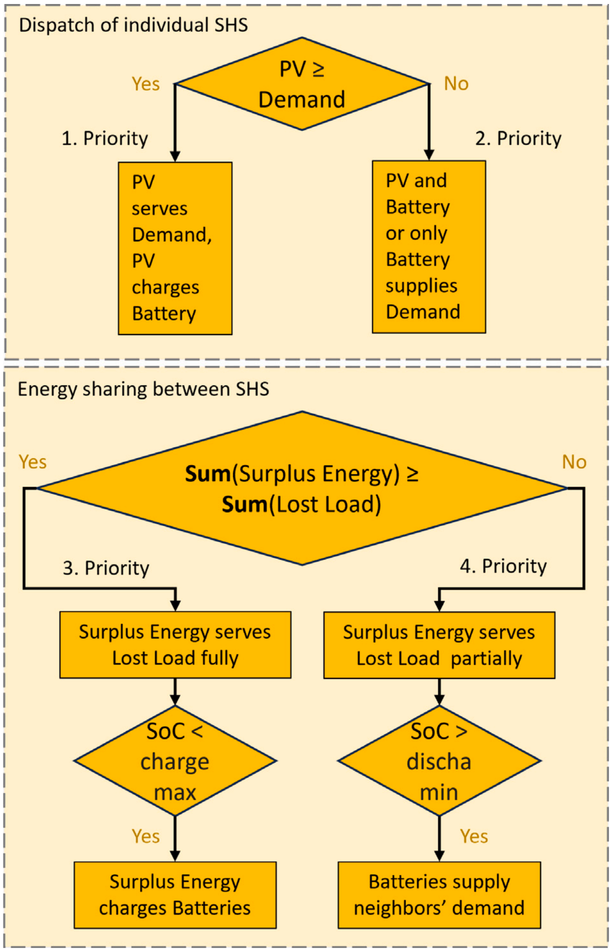

Fig. 4. Flow chart for Swarmgrid model with individual dispatch of SHS and energy sharing between all SHS.

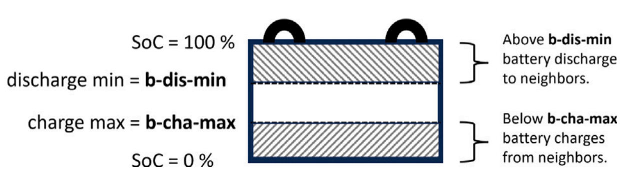

Fig. 5. Visualization of charge max (b-cha-max) and discharge min (b-dis-min).

loads. Setting a low discharge limit enables these batteries to share maximally, while a higher limit results in minimal sharing, preserving energy primarily for the individual household's use. These limits are the same for each household and have to be programmed into the hardware.

This study explores how the setting of charge and discharge limits affects energy sharing within the community. To understand this, simulations are run across all possible combinations of these limits, aiming to identify the key outcomes of energy sharing for further comparison and analysis. Fig. 5 visualizes the setpoints for charge maximum (b-cha-max) regarding charging from neighbors, and discharge minimum (b-dis-min) regarding discharging energy to neighbors.

These limits are parameters that are programmed into the control software for the energy dispatch when interconnecting SHS. The setpoints are usually chosen once when the system is installed, and remain the same for the lifetime of the system. Thus, the correct choice of

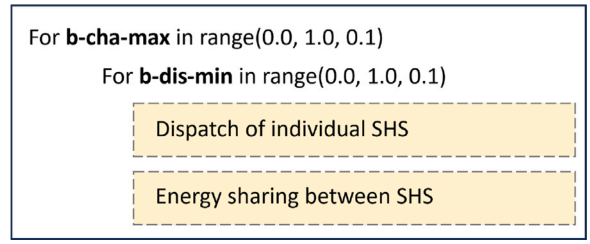

Fig. 6. Code for b-cha-max b-dis-min combinations.

setpoints for b-cha-max and b-dis-min is an important issue to study. Therefore, the algorithm runs through all possible combinations of setpoints and calculates the results and key performance values for one year for each set of b-cha-max and b-dis-min. Fig. 6 illustrates how the algorithm loops through the values of possible combinations. The range for the setpoints is from 0 to 1 representing the percentage of state of charge as a fraction. The loop takes steps in 0.1 resolution to fully capture the behavior of the key performance parameters with all setpoints combinations.

2.4. Evaluation of energy justice

We evaluate the outcomes of the simulation against the notions of energy justice presented in Section 1.3 by means of a thought experiment. Parameters of the household energy practice are thought through with respect to their consequences in light of the broader social and cultural context. These consequences can be sketched comparably solidly, even if the context of use is sketched in general terms. We then translate these consequences into what they would entail for the governance of local communities, and the kind of questions that practices of governance would need to address in the adoption of a technology such as the one we propose in this paper.

3. Case study

The chosen study area is located in Bolivia, within the native indigenous autonomy of Raqaypampa, in the Cochabamba department. Fig. 7 illustrates the administrative boundaries of the territory, as well as the locations of the communities contained within it. The autonomy condition empowers the 43 communities comprising the territory to plan and execute their own social, economic, and political development. This is achieved through direct elections of authorities at all government levels, direct management of resources, and the capacity to legislate, regulate, and implement policies autonomously according to [23].

An electrification initiative is underway in three communities as part of a Research for Development Project, funded by the Belgian institution Académie de recherche et d'enseignement supérieur (ARES). This project involves distributing 100 SHS to families through a co-financing model, where users contribute 20% of the total cost. The process began with informational meetings with community leaders to discuss the project's objectives in collaboration with researchers and Non-Governmental Organization (NGO). The selection of SHS was done collaboratively, with various system options presented to future users and community leaders. During these meetings, the technical and economic features of each option were explained in detail, and the final selection was made through a consensus-driven discussion involving both authorities and community members, taking into account needs and economic possibilities. The SHS characteristics are presented in Table 1.

It features a 20 Wp solar panel paired with a 7 Ah lithium battery. The solar panels should be installed at a tilt of 17 degrees and an azimuth of 63 degrees clockwise from North, facing a Northeast direction,

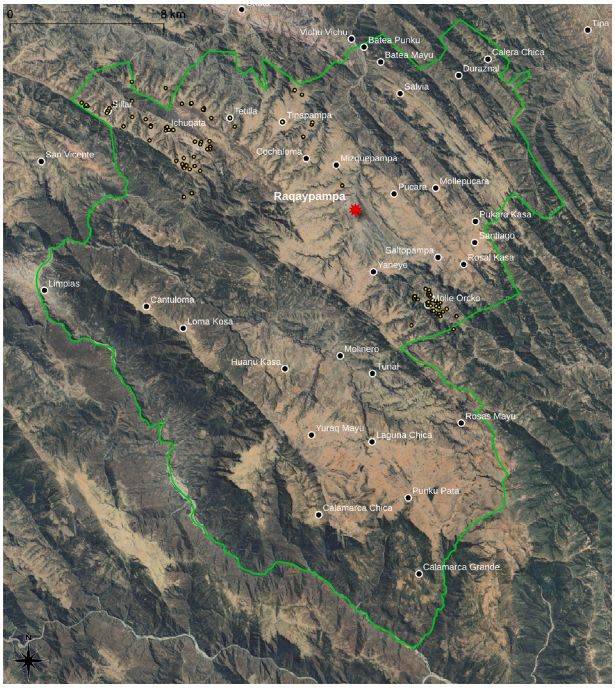

Fig. 7. Raqaypampa Autonomous Territory.

Fig. 8. Household in Raqaypampa equipped with a SHS.

Table 1
Characteristics of the Solar Home System acquired by the families in Raqaypampa.

Component	Characteristics
Solar PV	Polycrystalline 20 Wp, 12 V
Battery	LiFePO4 12.8 V 7000 mAh, 89 Wh
Accessories	1 LED light 2 W, 200 lm SFL 1 LED light 3 W, 200 lm SFL Phone charging set Metal structure Rechargeable radio

as instructed to the users. This system's capacity enables the use of 2 to 3 LED lights, charging of mobile phones and portable radios, powering a small TV, and the option to charge a laptop during daylight hours.

The families owning the SHS primarily generate income from agriculture and livestock farming, producing primarily for self-consumption. Household compositions vary, ranging from single-member families to nuclear and extended families. The lifestyle of people living in the Raqaypampa territory is closely tied to seasonal production cycles. During planting and harvesting seasons, families stay in the region to work on the land. In contrast, during dry seasons, primarily men migrate temporarily to seek alternative income sources, while the rest of the family remains at home. A typical household in Raqaypampa equipped with the SHS is shown in Fig. 8.

Households within the communities are widely dispersed from each other, which favors the implementation of decentralized energy supply systems. These characteristics make this case interesting to study, exploring the potential for innovative rural electrification approaches, such as swarm electrification. In this context, this work focuses on four types of households identified by energy consumption level among the users of the SHS, specifically in the community of Ichuqata, in the Raqaypampa territory.

4. Results

4.1. Data collection

A total of 16 families were surveyed to collect the necessary data for generating load profiles. Based on the gathered data, four types of households were identified and characterized according to their electricity consumption, which is closely linked to family size. Table 2 presents the appliance usage characteristics of these four household types, serving as inputs for RAMP. For each appliance, the following parameters are taken into consideration: the quantity of each appliance type, the nominal power rating (P), the minimum operational duration ($func\_cycle$), the average daily usage time ($func\_time$), the number of usage windows throughout the day, and the specific start and end times of each usage window (SWn/EWn).

The self-reported energy practices of the Households (HH) exhibit variations. Household 1 (HH1) consists of a single individual, typically a senior resident, who uses only lights and occasionally charges a phone when family members visit. In the second scenario (HH2), a nuclear family utilizes phones and radios for information and communication purposes. The third and fourth scenarios (HH3 and HH4) involve larger families of four to six members residing together, needing additional phone charging throughout the day, often due to the presence of multiple phones in the household.

4.2. Data simulation and validation

Fig. 9 illustrates the electricity demand patterns for a typical day and week across the four modeled households types, revealing significant variations in consumption. Notably, the peak demand observed in HH4 is double that of household one, a discrepancy that is particularly evident in the plots representing weekly demand. Additionally, for household type HH1 and HH2 there exists short periods of measured

Table 2
Appliance usage.

User	Appliance	Quantity	P [W]	$func\_cycle$ [min]	$func\_time$ [min]	$SW1$	$EW1$	$SW2$	$EW2$
HH1	LED 1	1	3	60	180	18:00	00:00	–	–
	LED 2	1	2	120	300	00:00	8:00	1080	1440
	Phone charger	1	5	60	180	12:00	00:00	–	–
HH2	LED 1	1	3	60	180	18:00	00:00	–	–
	LED 2	1	2	120	300	00:00	8:00	18:00	00:00
	Phone charger	1	5	60	180	12:00	00:00	–	–
	Radio	1	5	60	120	6:00	12:00	18:00	21:00
HH3	LED 1	1	3	60	180	1080	1440	–	–
	LED 2	1	2	120	300	00:00	8:00	18:00	00:00
	Phone charger	2	5	60	180	12:00	19:00	–	–
	Radio	1	5	60	120	6:00	12:00	18:00	21:60
HH4	LED 1	1	3	60	180	1080	1440	–	–
	LED 2	1	2	120	300	00:00	8:00	18:00	00:00
	LED 3	1	2	120	300	00:00	8:00	18:00	00:00
	Phone charger	3	5	60	180	12:00	00:00	00:00	4:00
	Radio	1	5	60	120	6:00	12:00	18:00	21:00

data of the actual load. This data is plotted in yellow in Fig. 9, and used as comparison and data validation. A detailed data validation analysis is beyond the scope of this paper and will be addressed in future work, once a more extensive dataset is collected. However, at this point, there are some observations that are significant and worth mentioning in this paper: A good correlation of appliances' time of usage between simulated and measured data was present. However, it was observed that peaks in modeled data have a tendency to be higher, even twice as in actual measured data. This is partially expected since the households reported on their energy needs exceeding their current use, thus this needs to be considered in further discussions. The demand for these four HH is modeled for whole year with a time resolution of 10 min for further use in the swarmgrid model.

Fig. 10 presents a comparison of measured PV data at our site Raqaypampa and simulated PV data with pvlib using the meteorological data from PVGIS. The measured PV data from an off-grid system does not necessarily fully capture its potential generation, as curtailment occurs when the PV power is not utilized by the user of the SHS. This is resulting in unrecorded potential PV output, and therefore such measured PV data cannot be used for further modeling purpose, where the goal is to study the surplus energy of such systems. This makes it also challenging to compare and validate the measured data with the modeled data.

However, in 10 we present a week in July from one of the SHS where the PV generation was fully utilized and further it showed several days with a typical clear-sky PV power curve. This data was crucial for validating our simulation, particularly for adjusting the system power loss factor in pvlib. Initially set to the default value of 14%, we determined that a factor of 5% more accurately represents our system.

Further, Fig. 10 presents a comparison of measured and simulated data for one week in May. Here, the measured data plotted in yellow, shows significant PV curtailment on day one, two, three and four. This was observed when looking at these PV generation curves and the respective loads from their SHS. It can be seen that the PV curve drops during the second half of the day, down to a constant minimal flat generation (as in day one in the week in May) or a fluctuation (as in day two in the week in May). The constant value refers to an internal loss to keep the system running, while the fluctuation actually represented a load following control mode of the PV panel, delivering direct PV generation to the load. During the first half of the day the total generated PV energy was stored in the battery, additionally to serve the load.

The results of the modeled PV generation for the installed SHS in Raqaypampa for a Typical Meteorological Year (TMY) are presented in Appendix B. Fig. B.14 in Appendix B showcases the simulated PV generation for a $20W_p$ panel during the initial week of each month, highlighting the significant daily fluctuations in PV output. Conversely, Fig. B.15 in Appendix B illustrates the daily energy yield over an entire year, distinctly revealing the impact of seasonal variations on energy production. The PV generation is modeled for a whole year with 10 min time resolution for further use in the swarmgrid model.

4.3. Swarmgrid model

Energy sharing's potential benefits for the Raqaypampa community are evaluated through simulation with the swarmgrid model. We compare energy-sharing scenarios to the current status quo. Fig. 11 shows the annual energy sums without energy sharing. The plot reveals that the first three households' energy demands are below what their SHS generate, whereas the last household faces a demand exceeding its SHS capabilities. This assessment is based on comparing each household's total demand against total PV generation.

Additionally, the figure elucidates how effectively the SHS meets demand when accounting for all losses and constraints associated with charging and discharging, delineating the proportion of demand met versus unmet, alongside the utilization of PV energy and resultant surplus. Notably, systems with PV generation initially surpassing total demand may not invariably satisfy said demand, as exemplified clearly by HH2 and HH3, but only slightly by HH1 where the dark green bar is almost invisible. HH4 faces a considerable unmet demand, clearly highlighting the potential benefit that energy sharing could offer to this household. The cumulative shortfall over all households appears to be in the same range as the available surplus energy. However, while energy sharing can enhance energy access, it may not wholly compensate for all deficiencies.

Subsequently, energy sharing is simulated with the swarmgrid model, incorporating various setpoint combinations for the battery state of charge to determine if and how much energy is shared. Fig. 12 illustrates the unmet demand after energy sharing, delineated against the two operational setpoints for battery management: the charging maximum threshold (b-cha-max) and the discharging minimum threshold (b-dis-min), expressed as fractions of the battery's total capacity.

For instance, a setting of b-cha-max = 0.60 signifies that the battery will only accept charge from the swarmgrid if its current level is below 60% of its full capacity. Conversely, a b-dis-min = 0.80 configuration

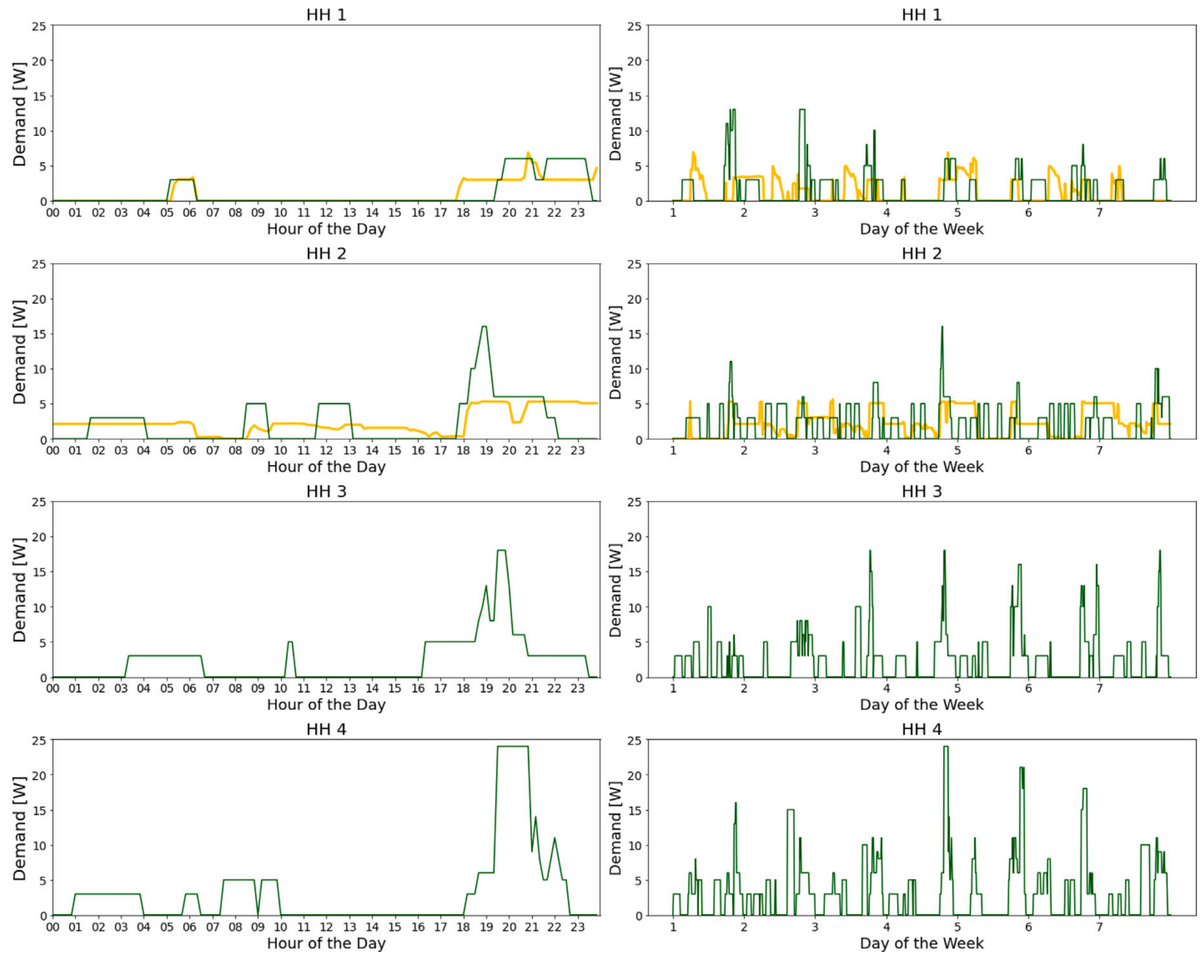

Fig. 9. Simulated demand (green) and measured load (yellow) for one day (left) and one week (right) for each household type in 10 min resolution.

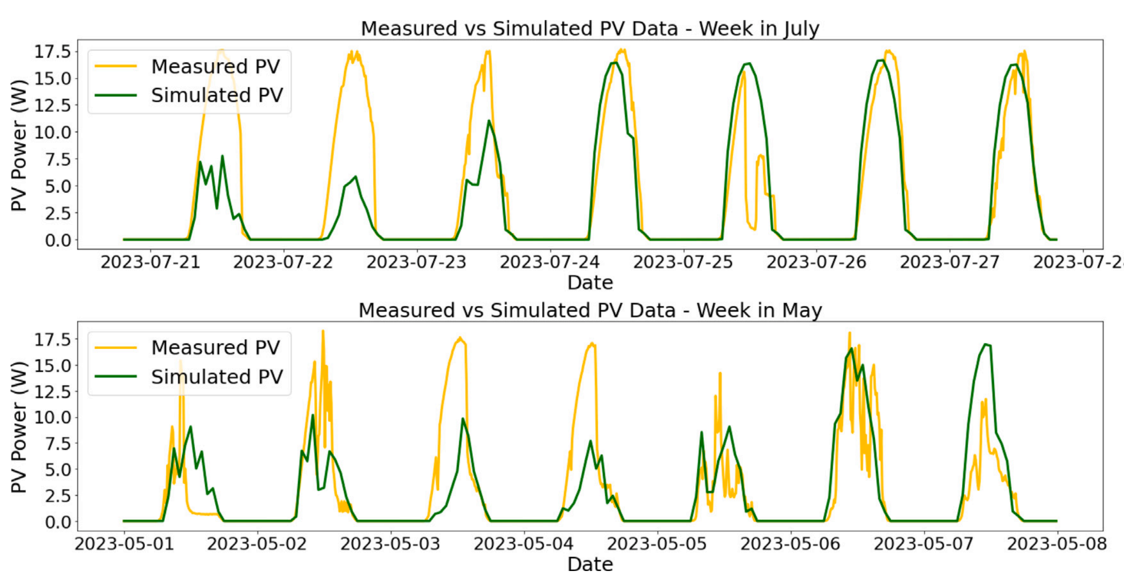

Fig. 10. Comparison of measured and simulated PV data.

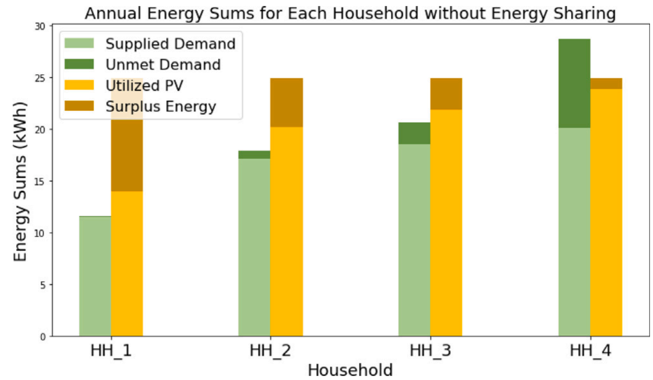

Fig. 11. Annual energy sums from individual SHS before interconnecting into a swarmgrid. Unmet demand and surplus energy at each household as initial starting point for a swarmgrid.

indicates that the battery will only supply energy to the swarmgrid if its charge exceeds 80% of its capacity. Under these operational parameters, the 3D plots chart the annual unmet demand across all possible b-cha-max and b-dis-min pairings for each household, offering insights into the variability of unmet demand in response to different battery operation strategies. Notably, for HH1 and HH2, the optimal outcomes typically arise with higher b-dis-min settings, suggesting that setting a higher threshold for energy contribution is beneficial. In contrast, for HH4 — a household characterized by substantial initial unmet demand — a lower b-dis-min setting, facilitating easier access to energy from neighboring batteries, proves most advantageous. For HH3 the outcome strongly depends on both setpoint parameters: it only improves at higher b-dis-min if at the same time b-cha-max is high, too.

To further elucidate the impacts of energy sharing, we introduce Fig. 13. This figure re-examines the unmet demand post-energy sharing, utilizing a 2D plot to integrate additional insights. The x-axis of the figure is structured to sequentially represent the interplay between the b-cha-max and b-dis-min values as follows: Each tick labeled with a b-cha-max value marks the beginning of a sequence where b-dis-min starts at the same value as b-cha-max and incrementally increases by 0.1 steps up to 1. Subsequently, the x-axis transitions to the next tick, indicating an increase in b-cha-max by 0.1 from its prior value. This pattern repeats, illustrating a step-wise progression of both b-cha-max and b-dis-min values along the x-axis, where each b-cha-max serves as a baseline for the corresponding b-dis-min values that follow, ascending incrementally until the cycle recommences with a new b-cha-max.

The top segment of the figure delineates the individual households' unmet demands, while the bottom segment aggregates the unmet demand across all four households. For coherence and comparability, unmet demand in the upper segment is expressed as a percentage of each household's total demand, and as a cumulative percentage for all households in the lower segment. Additionally, to facilitate comparison, horizontal lines are incorporated: continuous lines represent the baseline unmet demand prior to energy sharing, serving as a reference point, while dotted lines indicate the minimal achievable unmet demand with energy sharing for each household or for the collective grid. The intersections of the dotted lines with the data points highlight the optimal setpoint combinations for minimizing unmet demand per household. Notably, for HH1, the dotted and continuous lines coincide, suggesting that the lowest unmet demand is achieved without participating in energy sharing within the swarmgrid. The data points of HH4 that coincide with the continuous line indicate that energy sharing does not change the unmet demand for HH1. In this case, HH1 might share only surplus energy that otherwise would be curtailed. Conversely, HH4 exhibits all values of unmet demand beneath their pre-sharing baselines, indicating a potential reduction in unmet demand – or at the very least, maintenance of baseline levels – regardless of the b-cha-max and b-dis-min settings applied. The outcome differs for HH2 and HH3, where the impact of setpoint configurations varies, potentially yielding either a positive (below the continuous line) or negative (above the line) effect. This is significant for HH2 where most of data points lay above the continuous line, and only slight for HH3 where just a few data points at low b-cha-max lay above the continuous line.

For HH2 and HH3, the minimal unmet demand aligns with b-cha-max = 1.0 and b-dis-min = 1.0, a setting that maximizes battery charging opportunities (e.g., during direct PV surplus) while generally restricting battery discharge in response to unmet demand. HH1 is indifferent at that data point, since it faces no change compared to no energy sharing. This configuration also emerges as the collective optimum across all household demands, as it can be seen in the lower plot in Fig. 13. However, it does not represent the best scenario for HH4, which finds its optimal settings at b-cha-max = 1.0 and b-dis-min = 0.0, suggesting that the other HH should allow discharging of batteries. However, this would dis-improve the situation for HH1 and HH2. Despite this, HH4 would significantly improve its situation at b-cha-max = 1.0 and b-dis-min = 1.0, compared to its pre-sharing state, underscoring the nuanced benefits of energy sharing.

5. Discussion

5.1. Choice of setpoints and their implications

From these differences in unmet demand per household before and after energy sharing with different setpoints for sharing options, it becomes clear that energy sharing itself might seem attractive to some households but not necessary to others, when unfavorable setpoints are chosen. Notably, there is the possibility to minimize all energy discharge from batteries to neighbors, by setting b-dis-min to 1, meaning the state of charge has to be above 100% to allow sharing from batteries. This state never occurs and therefore sharing from batteries does not happen. In that case, the only energy sharing received comes from direct PV surplus energy. This does not influence the value of the unmet demand of the system that is sharing. This effect has been demonstrated by Fuchs et al. [24] for both a Kenyan and a Norwegian case study, where two households share energy. There, the authors only show the two extreme cases with either no sharing from battery, meaning only direct PV surplus energy is shared, or full sharing from battery, meaning both charge and discharge at any time without restriction. The first case would translate to a b-cha-max = 0 and b-dis-min = 1, while the second one translates to b-cha-max = 1 and b-dis-min = 0. In their case, the authors have modeled the second case as just one battery for the total system. The authors show that in the case when battery is utilized freely for sharing, the household with the initial lower unmet demand would increase it, while the household with the higher one would decrease its unmet demand. In our paper, we confirm this, but we also show the whole range of setpoint combinations and how it is affecting households with different initial percentages of unmet demand. We identify three outcomes of households that can occur during energy sharing that includes the sharing of energy stored in the battery. Based on different setpoints for sharing these are the Outcomes and they are explained below:

- Outcome I: Improving households
- Outcome II: (setpoint) Depending households
- Outcome III: Deteriorating households

Outcome I, the improving households, is characterized by the fact that no single setpoint combination can make these households worse, meaning increasing the unmet demand. In the worst case for these households, the unmet demand stays at the same level as it is. From our case study, it can be seen that this is true for HH4. From our previous Fig. 11 presenting the energy sums for the households before sharing it can be seen that HH4 has a lower total PV generation than total

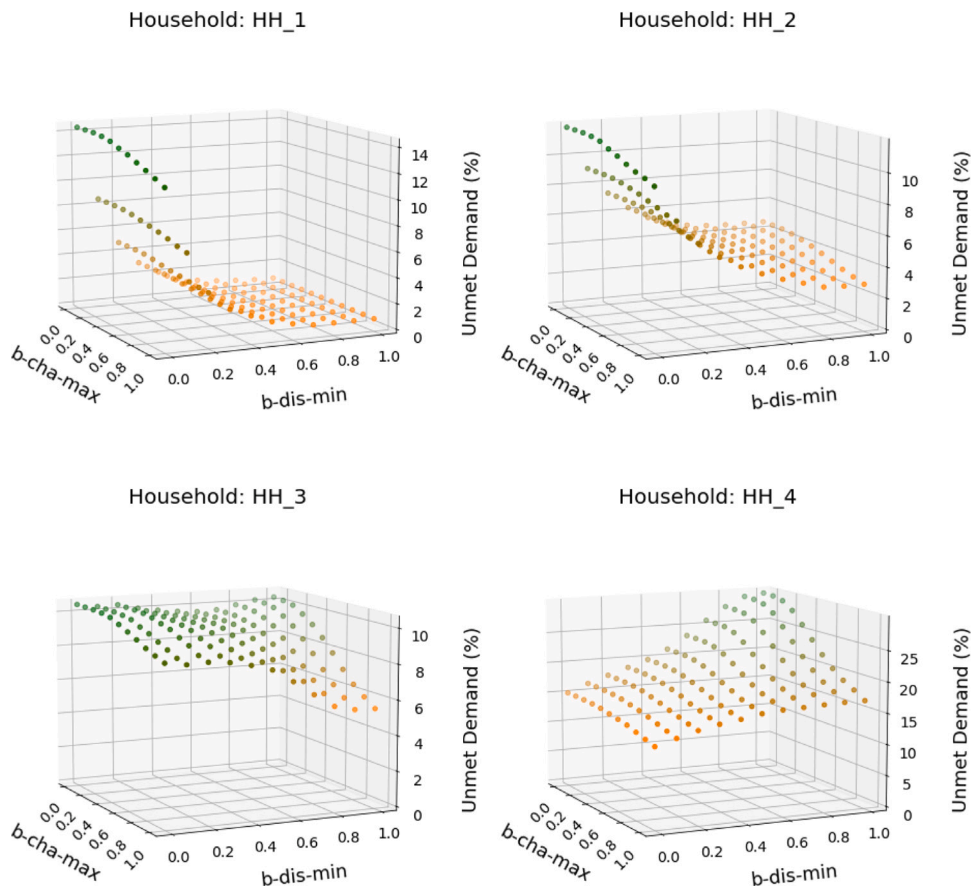

Fig. 12. Unmet demand (as % of demand) after sharing energy is plotted over the variation of battery setpoints for charging maximum (b-cha-max) when receiving energy from and discharge minimum (b-dis-min) when sending energy to the Swarmgrid.

demand, which is a driving factor that any form of energy sharing and access to additional energy would improve this households.

Outcome II comprises the setpoint depending households, where the benefit depends on the actual choice of setpoints. In our case, such an outcome is true for HH2 and HH3 as it can be seen in Fig. 13. These households either dis-improve during lower b-cha-max values and improve during higher b-cha-max values.

Finally, there is Outcome III, households that tend to deteriorate with most setpoint combinations. However, they stay at the same level of unmet demand if sharing from the battery is disallowed. These households initially have a high rate of supplied demand, meaning they experience almost no unmet demand. This makes it challenging to improve their situation with just a modest increase in capacity. In fact, these households require a substantial capacity addition or a significant amount of available shared energy to actually reduce their remaining unmet demand. This is demonstrated by Fuchs et al. [25], where different household profiles are analyzed for their surplus energy potential for sharing. In our study, such an outcome is true for HH1.

Both Richard et al. [8] and Sayed et al. [9] have chosen a high value for b-dis-min and both papers present sharing benefits for the interconnected network and community. This is in line with our findings, where Fig. 13 shows how the total unmet demand decreases with higher b-dis-min, however, only when b-cha-max is high (above 60%). In [8] b-dis-min is set to 80%, however already above 60% the battery would potentially contribute with energy injection to the network, if the voltage level at the sharing network is low. Further, b-cha-max is set to 60%. An analysis of the individual effects on the specific nanogrids that are sharing energy is not done in [8], however, the nanogrids in the case study seem to be dimensioned according to always meet the load and the study only looks at a short period of a couple of days. Sayed et al. [9] studies longer time periods and presents the benefits for both monthly and yearly energy deficit and surplus. The authors have used values of 90% for b-dis-min and 40% for b-cha-max. The results are in line with our results, however, Sayed et al. [9] did not give a reason why 40% and 90% were chosen. Our paper presents the benefits in unmet demand based on all different combinations of setpoints, showing that these benefits can vary strongly from different viewpoints and it is not straight forward which combination should be chosen.

One best possible result in terms of minimal total unmet demand for the community in Raqaypampa achieved from introducing swarm electrification is the combination of b-cha-max = 1.0 and b-dis-min = 1.0. This combination makes sure that batteries always charge if there is surplus energy, however, batteries never discharge to serve the community. In other words, the existing surplus energy from direct PV generation is maximally distributed to both load and filling batteries.

Another best possible solution could be defined: Achieving equal or maximal similar percentages of unmet demand. This would mean each household has equal access to electricity based on their own needs and could be perceived as a fair distribution of available resources. In our case study this occurs for b-cha-max = 1.0 and b-dis-min = 0.0, where the values for unmet demand four each HH are between $12.5 - 8.5\%$. In contrast, when the total unmet demand for the whole community is minimized and b-cha-max = 1.0 and b-dis-min = 1.0, would be chosen, the individual percentages for unmet demand range between $1 - 17\%$. This means some households have very good access to electricity, with only 1% unmet demand, while others have still a level of 17% of unmet demand.

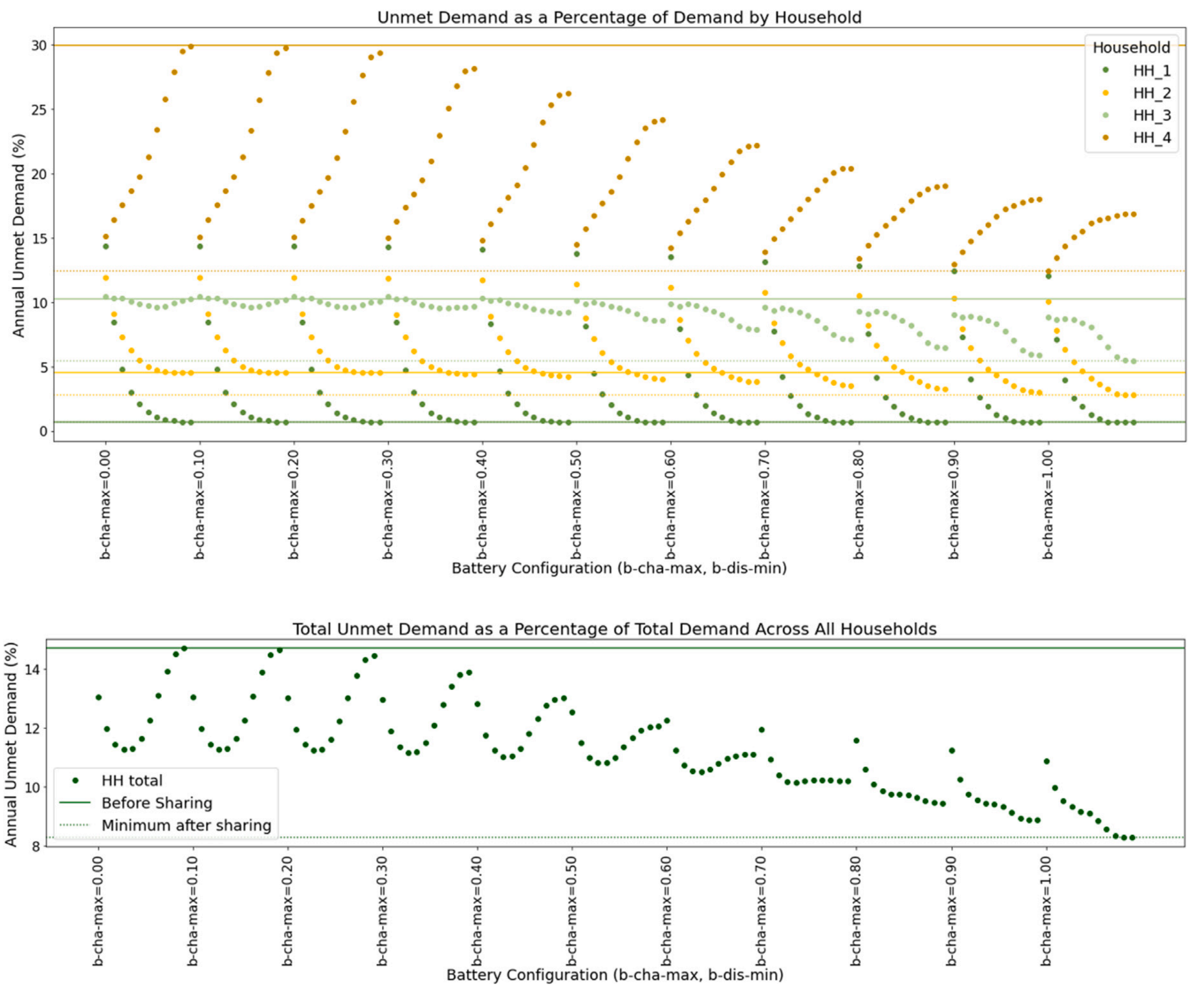

Fig. 13. Percentage of unmet demand after sharing energy is plotted over the variation of battery setpoints for charging maximum (b-cha-max) when receiving energy from and discharge minimum (b-dis-min) when sending energy to the Swarmgrid. Individual unmet demands in the upper plot and total unmet demand in the lower plot. The straight lines symbolize unmet demand before sharing (as continuous line) and minimal unmet demand possible found with sharing (as dotted line).

5.2. Evaluation of energy justice

It is clear from the simulation that some households will be better off, for others it does not matter, and yet others will be worse off, if energy sharing through swarm electrification is introduced. This is obvious, as that is the essence of the idea of sharing. Yet, taking goods, in this case electrical energy, from one member of a community and giving it to another is essentially a matter of distributive justice. This raises the question posed in Section 1.3. To make the introduction of swarm electrification a just affair, we suggest the following way of proceeding. We assume here that the simulations we presented above will at some point have been sufficiently fine-tuned so as to produce a realistic picture of the entire collective energy system.

The first question to ask is: how does the (re)distribution of energy relate to the community's understanding of fair sharing? If it is in line with their schemes of fair distribution, then there may not be a problem at all and no further correction is needed. This is the question of distributive justice, and the answer to this question might be different from the answers one may get in individualistic, industrialized societies.

The second question is whether the view is sufficiently complete to include the interests of all affected parties. For example, in patriarchal communities, it can happen that the household work carried out by women remains invisible in discussions, which is particularly problematic if exactly this household work is affected by new schemes of energy distribution. This is the question of recognition justice.

The third question, when we have a complete picture of all people affected, is what would be a proper way of decision making. Any community is likely to have means of deciding and making things collectively binding. Are the decision-making procedures sufficiently robust to ensure recognition? Are the outcomes such that indeed all members of the community can accept them as legitimately made, even if they themselves disagree? Also here, the answers to these questions might be very different than one may get in industrialized societies, and they are also most likely to be more complex than 'majority vote'.

And the final question to ask then is how the answers to the previous questions relate to questions of decolonization. The balance to strike is intricate. On the one hand, it is vital to respect communities' values and to align technologies with those values. But on the other hand, it is also not given that just any way in which a community organizes itself deserves to remain in place. The invisibility of female work might be a case in point: it can be argued that some emancipation is due there, and the introduction of the technology might be a perfect opportunity to accomplish this and nudge a community in that direction. We surmise that the best way to achieve this is to open up the decision-making processes and allow all affected parties to contribute, and moderate such processes with a keen eye on issues of procedural and recognition justice.

Only after these considerations does it become meaningful to ask whether further compensation in either direction is needed, and whether metering and billing are meaningful additions to the system in the first place. Here, we should be mindful that simply introducing the technology and correcting skewed distributions with financial transactions would be a typically Western solution, and potentially colonial at that. Especially if the monetary compensation is only geared towards rectifying the losses incurred by any community member, the overall distribution of wealth remains the same and existing inequities are reproduced and even solidified.

One additional thing to consider here is to think about the possible alternatives. While many other solutions are thinkable, one prevails across the field of development work, namely the case in which NGOs provide the same size of system to all households, irrespective of the household size. From the simulations in the current study, it clearly follows that this will never lead to optimal energy use and the waste of a valuable resource. To this problem, the benefit of the proposed technology is primarily visible at the aggregate level of the overall community. While not in itself being a knock-down argument, this might be brought into the discussion, and tip the balance in favor of some imperfect distribution scheme if the only alternative is to have no form of distribution.

5.3. Limitations of the study

Below, we outline some limitations of our study that could influence the results or necessitate further in-depth research in the future.

Our study examines energy sharing among four households, each representing a distinct household type. In the village, not all types may be present, or some types may be more prevalent than others. In our study, all households have the same size of SHS, which is a common practice in many rural electrification programs where SHS are distributed. However, if these systems were more tailored to the size of each individual household, it could potentially alter some of the results.

Our study employs an energy flow model with a rule-based approach to control energy sharing. Although this approach effectively estimates the available energy for each household, incorporating a power flow model with a more detailed representation of the network could influence the results and warrants further investigation. Additionally, a power flow model would better capture scenarios where energy supply fails to meet power demand, leading to network outages—an aspect that an energy model might overlook by calculating partial load fulfillment. As a result, the energy model may present a somewhat optimistic view, whereas a power flow model would offer a more realistic depiction of these events.

In our case study, we gathered information from a limited number of households, but a larger sample could provide additional insights. The households we studied fall within the range of very low energy consumption, and examining those with higher consumption profiles could yield new findings. Additionally, our study covered only one year and did not account for the effects of load growth or changes in demand over time.

6. Conclusion

This paper has examined the benefits and challenges of interconnected Solar Home Systems (SHS) within the context of the indigenous rural Highlands of Bolivia, specifically in Raqaypampa. Our findings highlight that while swarm electrification and interconnected SHS offer significant potential for improving access to sustainable and affordable electricity, the distribution of energy within the community can vary significantly based on the decentralized battery control setpoints.

Our analysis reveals three distinct outcomes for households in an energy-sharing setup: (1) Improving households that benefit from enhanced energy access, (2) Depending households where the benefit strongly relies on the choice of setpoints, and (3) Deteriorating households that can face reduced energy availability. These outcomes underscore the critical role of energy justice in designing decentralized energy systems.

A key takeaway from our study is that a common techno-economic solution alone (often the minimization of total unmet demand) is insufficient to ensure equitable energy distribution. The choice of setpoints for battery state of charge, which governs energy sharing, profoundly influences the fairness and efficiency of energy allocation among households. Therefore, it is imperative that discussions regarding justice and community goals be integrated into the design process from the outset. Engaging the community in defining what constitutes a just distribution of energy and aligning the technical design with these values is crucial. This proactive approach contrasts with the common practice of devising a technical solution first and addressing issues of justice and governance only retrospectively.

In conclusion, the success of decentralized energy systems in achieving equitable and sustainable electrification depends not only on technological innovations but also on inclusive and participatory design processes that prioritize energy justice from the beginning.

CRediT authorship contribution statement

Ida Fuchs: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Claudia Sanchez-Solis:** Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sergio Balderrama:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. **Govert Valkenburg:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization, Investigation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Claudia Sanchez-Solis reports financial support was provided by Académie de recherche et d'enseignement supérieur (ARES). The other 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.

Data availability

Data will be made available on request.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT in order to improve language. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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Appendix A. Surveys

See Table A.1.

Table A.1
Surveys

1. Socio-economic aspects	
Date:	Time:
Consent of participation:	Location:
Name:	Community:
Household constructionmaterials:	Number of rooms:
Number of peopleliving in the HH:	Daily activities in the HH:
Means of transport:	Main economical activity:

2. Energy supply				
Do you have access to an energy supply?	Micro-grid	( )	Main grid	( )
	Solar Home System	( )	None	( )
	Other:			

3. Appliance Use								
Appliance	Nominal Power (W)	Average use (h/day)	Min. time of use (min)	Period of use (morning)	Period of use (afternoon)	Period of use (night)	Weekly frequency of use	Weekly frequency of use

Appendix B. PV generation

See Figs. B.14 and B.15.

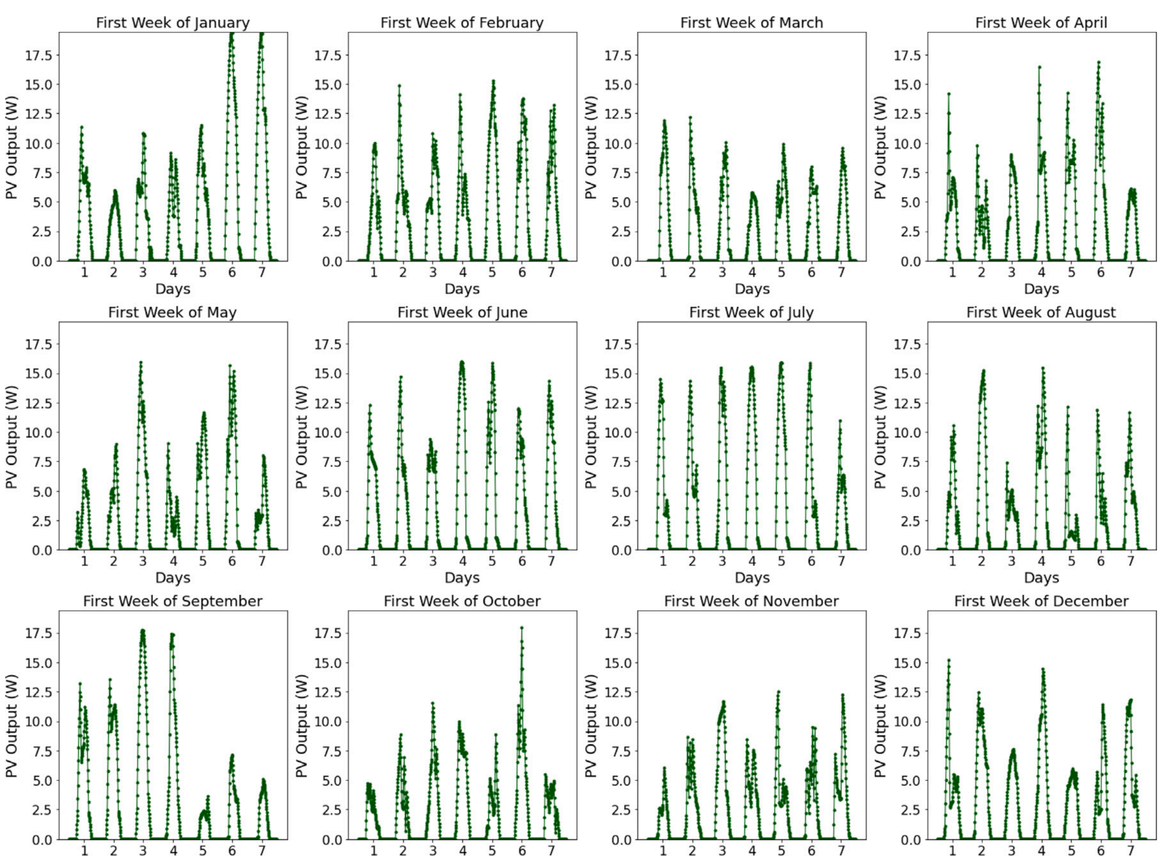

Fig. B.14. PV power output for the first week each of month simulated with PVGIS for a TMY for the used SHS system with a $20W_p$ PV panel.

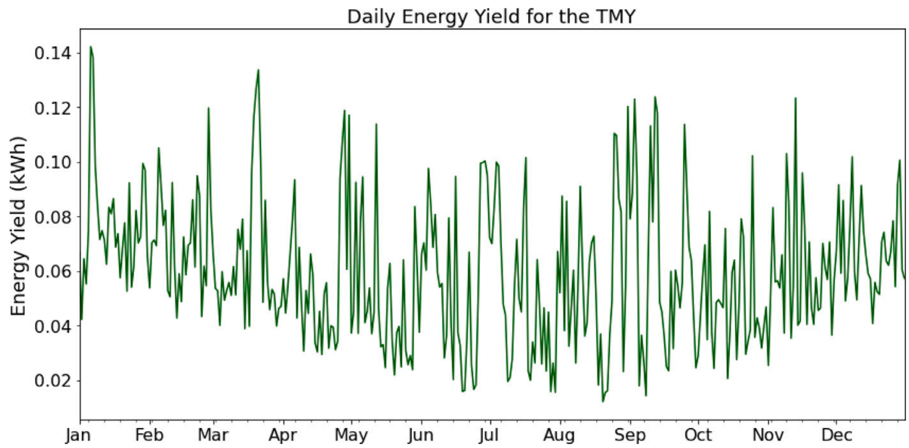

Fig. B.15. Total PV energy yield per day simulated with PVGIS for a TMY for the used SHS system with a $20W_p$ PV panel.

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