SUSTAINABILITY OF COMMUNITY-OWNED MINI-GRIDS: EVIDENCE FROM INDIA

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ABSTRACT

Background: Community-owned Solar Mini-Grids (SMGs) are increasingly promoted to provide communities access to reliable electricity, empowering local actors as they become active stakeholders in projects. However, early failures and difficulties in building local capacity have raised questions regarding their long-term sustainability and ability to be replicated to provide socio-economic benefits to the communities. This study assesses the sustainability of 24 community-owned SMGs in India operating over extensive periods of time using a novel scoring framework using mixed methods to derive its conclusions.

Results: The study found that institutional, financial and technical capacities, central for the SMG's long-term sustainability, could be achieved through community engagement from early stages, if communities are allowed freedom to develop governance procedures while at the same time clarifying roles and responsibilities. This creates strong sense of ownership that is key for effective and inclusive governance. User satisfaction, ensured through provision of usable supply in line with users' expectations, motivates actors to make regular payments, thus leading to economic sustenance. While social and environmental benefits were observed, energy consumption and engagement in productive activities remained marginal.

Conclusions: The study reports an example of community-owned SMG model that has been replicated sustainably over many cases, overcoming key challenges related to appropriate financial and technical management and producing positive social impact. Low engagement in productive activities was more a factor of the local socio-cultural contexts, rather than limited paying capacities of the users. To increase energy utilization and create environments for

sustainable rural living the study recommends implementation of systems that link energy with other rural development needs such as agriculture or water provision. The study also recommends more use of qualitative and quantitative data for impact analysis to ensure that conclusions are generalizable and provide rich contextual explanations for the observed phenomena.

Keywords: Solar mini-grid, sustainability, India, productive use, impact evaluation, community ownership, local governance

BACKGROUND

Although India declared 100% village electrification in April 2018, more than 26 million households still lack access to electricity[1]. Despite extension of the central grid continues to be the favourite vector to deliver electricity in the country, recent studies [1] highlight that poor reliability of supply is causing 34% of 'electrified'[2] households to rely on kerosene as their primary source of illumination. As an alternative solution, off-grid systems powered by renewable sources available locally such as solar or wind energies are being promoted, both by private actors [2] and the national government [3], has implemented mini and micro-grids in remote inaccessible villages to help India reach its electrification target.

Among the different ownership models, community-owned solutions, where the financial and technical responsibility for ongoing operations resides with the beneficiary communities, are gaining significance [4-9], with many studies highlighting how upfront community involvement during system's design and installation empowers local actors as they become active stakeholders in the project [10]. This facilitates the system's long-term functionality, as it creates stronger sense of local ownership [11], and increases user satisfaction [12]. For example, the

state of Chhattisgarh successfully installed more than 1400 Solar Mini-Grids (SMGs), involving local communities during needs assessment while leaving the responsibilities for daily technical and financial management with the implementing agencies [13]. This resulted in greater acceptance from the communities while at the same time it ensured prompt issue resolution, owing to clarity of roles among stakeholders. On the contrary, community engagement for SMGs in the Sundarbans Islands in West Bengal was less systematic, and the role of communities and their interactions with other stakeholders not clearly defined [14], ultimately affecting the system's functionality. Other examples include the failure of the Village Energy Security Program, a government-led biomass and biofuel-based mini-grid initiative, aiming to involve communities in the entire process of production and supply of electricity. In this case, limited local capacity and technical knowledge summed to unclear definition of roles and responsibilities among stakeholders, causing inefficiencies and plants shutdowns [15]. Studies of the economics and institutional barriers for community-owned systems also highlight how economic viability is contingent on local leadership [16] and appropriate institutional design [9], while others [17] warn that local level conflicts and elite captures may subvert the effective process of local participation and equity. With increasing emphasis on community participation in energy projects, there is a need to understand the conditions for effective community involvement and how responsibilities among stakeholders can be distributed in order to ensure their long-term operation [12,13].

To date, data showcasing performances of a wide range of community-owned SMGs operating over a long period of time is lacking. Studies available are either limited to individual projects [18,19], to a small selection of case studies [9], or rely on large surveys collecting quantitative information at a household level [1]. Ex-post evaluation of a large array of mini-

grids operating over extensive periods of time could provide key information on the factors affecting the models' effective ownership structure, with significant implications for practitioners and policy makers as they design long-lasting sustainable solutions. It is against this backdrop that this paper attempts to answer the following question: under which conditions can community-owned SMG systems[3] be sustained and replicated so as to provide socio-economic and environmental benefits for the communities?

Among the many types of community-ownership models, this paper focuses on SMG systems where community members, who are also the beneficiaries, are responsible for the plant's ongoing technical and financial management. Community members are also responsible for ensuring user satisfaction with day-to-day operational decisions, whereas ownership over assets is retained by other stakeholders. This model provides a good arrangement for decentralization of energy production and distribution and therefore is prioritized for the study. To answer the research question, this study uses a novel framework [20] where the systems' functionality is analysed across several sustainability dimensions usingmixed methods .

METHODS

Case selection

The research selected SMG installations by Gram Oorja (GO) a social enterprise operating in India. The companies' portfolio counted of over 24 SMGs in three different states operating from few months to over five years, thus offering a sufficiently varied sample for the study. Plants provide continuous supply for domestic users, household-level commercial activities, public spaces and, in some cases, water for drinking purposes. Installations are community-owned, with a locally elected Village Energy Committee (VEC) owning responsibility for daily technical and financial operations. The ownership of assets is retained by

the funder with the ability to withdraw the assets if the plant becomes non-operational for reasons that are attributable to the community. The financial model is hybrid where capital costs are provided upfront, whereas recurring Operations and Maintenance (O&M) costs are addressed through billing from metered household consumption. Payments are collected by a local Plant Operator (PO) and deposited in a bank account that is managed by VEC members.

The Framework

This analysis uses the framework and scoring methodology proposed by Katre, Tozzi [20] to assess performances of SMGs individually, according to the specific model implemented. The framework looks at five *Dimensions* (Technical, Economic, Institutional, Social and Environmental), each described by a set of *Measures* selected to reflect sustainability characteristics for the model considered. Each *Measure* is composed of a number of *Indicators* (either quantitative or qualitative) and is assigned a score from 1 (lowest) to 5 (highest) reflecting the performance of the installation analysed under the *Measure* considered. The procedure to arrive to a *Measure*-level score is described in detail in the Data Analysis section. For GO's community-owned model, each installation is described through 12 *Measure*-level scores across the 5 *Dimensions*, as depicted in Figure 1, where colour coding highlights whether *Indicators* are composed of quantitative (green) or qualitative (yellow) data.

Figure 1: The Framework and its components: Dimensions, Measures, and Indicators

Note: Adapted from Katre, Tozzi [20] Figure 1a&b - removing data sources for clarity.

Last line represents legend.

Technical Dimension

This dimension evaluates the usability of the electricity supply adopting the same approach proposed by the Multi-Tier Framework (MTF) [21] alongside three *Measures*:

- Domestic Supply: assesses usability of supply for domestic consumers based on seven *Indicators;* capacity, duration, reliability, quality, legality of connection, affordability of the service and safety of the installation;
- Public Lighting: assesses the service provided for night-time illumination in public spaces based on five *Indicators*; capacity (e.g. share of village covered with poles), duration, reliability, quality of illumination, and safety of the installation;
- Household (HH) Energy Consumption: looks at individual household energy consumption expressed in daily Wh per household as per meter reading.

Economic Dimension

This *Dimension* focuses on the sustainability of the financial model [22] and its ability to generate income opportunities locally [23]. It is defined through two *Measures*:

- Model's Sustenance: in the case of hybrid financial models where upfront capital costs are donated, this looks at system's financial functionality expressed in terms of regularity of tariff collection and recurrences of households not meeting payments; and the status of the bank reserves, which is assessed comparing the actual money deposited in the bank against the expected amount at time of visit which accounts for monthly O&M costs, operator salary and battery replacement cost after 5 years;
- Livelihood Generation: looks at the ability of the SMG to stimulate productive use of energy and spur economic growth. This is assessed by looking at the number and types of business activities in each village that use SMG electricity.

Institutional Dimension

This *Dimension* looks at the efficiency of the governance mechanism [9,22], its inclusiveness and the satisfaction of all users with the solution. It is defined by three *Measures*:

- Effectiveness of Governance: for community-owned energy systems this is represented by the capacity established with local stakeholders to ensure continued operation and prompt issue resolution with minimal external intervention needed. It is evaluated through five *Indicators;* regularity of meetings, degree of local ownership, the ability of VECs members to manage institutional procedures, the operator's ability to manage technical supply as well as the household's report on local governance and procedures;
- Community Participation: looks at two *Indicators* of users' participation and the sense of inclusion of different groups in the local governance;
- User Satisfaction: investigates satisfaction of local users across five *Indicators*, household's satisfaction with the supply, with public lighting, with tariffs, that of households with governance procedures and that of the operator with the training received.

Social Dimension

This *Dimension* focuses on improvements to the lives of the community [23] looking at two *Measures*:

- Household Wellbeing: defined by *five Indicators*; increase in study hours for children; health of the family (e.g. reduced eye problems, respiratory problems and/or body strains etc.), sense of safety, increased time available for women and sign of their increased independence;
- Community Connectedness: defined by *two Indicators;* namely increased connection among community members and with the external world, and community-led activities linked to electricity.

Environmental Sustainability

This *Dimension* looks at any environmental improvements through substitution of old energy source with solar electricity alongside two *Measure:*

- Local Scale: reported improvements in indoor air quality;
- Global Scale: reduction in carbon emission from decrease use of kerosene for lighting.

Data Collection

The research assessed 24 of the 26 SMGs operative at time of the study, leaving out two sites due to logistical reasons. Mixed data were collected from a range of sources, using semi-structured discussions with VEC members, surveys with households and local operators, and recording data from energy meters and bank passbooks. The use of an interview protocol (see Appendix A) to guide the semi-structured discussions with VEC members and framing context-specific open-ended questions in the household surveys ensured that the data gathered were relevant, meaningful and reliable. In each village, approximately 20% of the households were interviewed following a stratified sampling procedure to ensure good representation of the population in the analysis. Sampling focussed mainly on capturing differing levels of wealth, engagement in livelihood activities, female and male-headed households, including households located at the centre and the periphery of the village. All data were collected in person by independent trained staff, with no affiliation with GO nor with any of their partnering organizations. Interviews were held in the local language facilitating freedom of expression and reducing chances of socially desirable responses.

Data Analysis

To begin with, for each installation quantitative data were mapped to their respective *Indicator*. For example, information around bank balance, frequency of bank transaction, date of last transaction, was mapped to “Status of Bank Reserves” *Indicator* under the Model Sustenance

Measure. In every village, percentages of responses for each question in the household surveys were computed to arrive at *Indicator* scores. For example, percentage of participants who responded being "satisfied" to the question about their satisfaction with the energy system, was aggregated to arrive at a village-level score for "HH Satisfaction with the Supply" Indicator. For qualitative data, each researcher independently listened to the VEC interviews several times, read the transcripts and coded them to highlight significant passages. Attention was paid to trace relevant information which was mapped and marked to specific *Indicator(s).* For example, the narratives, *"we skip bank deposits during monsoon months"* or *"the monthly collection is deposited by the operator with [the VEC] …because the bank is quite far, the money is deposited when somebody travels to [the place where the bank is located]"* were coded as important for the "Status of Bank Reserves" *Indicator*. For each *Measure* and its *Indicators*, quantitative data were combined with relevant qualitative data from various sources, compared against benchmarks to arrive at scores. Tables 1 through 12 (adapted from Tables 3 through 12 from Katre, Tozzi [20]), report benchmarks for each *Indicator* and how these are aggregated to *Measures.* For example, if the inspection of bank passbook revealed that only half of the expected reserves had been deposited against the battery replacement target, but qualitative data provided a reasonable explanation of the infrequent deposits (like in the example above), then the score was mediated to account for both information. Each time, *Measure* score was determined by the lowest scoring *Indicator* to highlight bottlenecks and areas for improvement of performance, using the same approach suggested by the MTF. When scores spanned across multiple benchmarks, the highest score was applied. Each researcher followed this procedure independently to arrive at individual scores for *Indicators* and *Measures*. These were then compared, deliberated upon as a group, rationale for assigning scores discussed, and differences, if any, resolved to arrive at a final score

for each *Measure*. The approach followed, involving specific *Indicator* benchmarks, rigorous coding procedures, independent scoring by each researcher, group discussion and deliberation, minimized subjective bias in the process and ensured the validity of the resulting analysis. Notable quotes that provide thick description of some of the final *Measure* scores are provided in Table 13.

Tables 1 to 12 about here

Table 13 Relevant quotes under key *Measures* and *Indicators*

Measure	Indicator(s)	Participant Quotes
Livelihood	Commercial Activities	Q1*:"If some hand holding is done and support is provided, we could venture into some business in the future. It gets very difficult to start on our own."* Q2: "*I wanted to buy a small pump to irrigate my field, but when I asked the VEC they denied the permission because they said not enough capacity was available."* Q3: *"We don't try new things* [eg. productive loads] *with the installation…we just turn the switch on and off. If we try something new and if there is a problem, then who will take care of it? we will be left in the dark again for may days"*
Model Sustenance	Systems Functionality	Q4*:"We are aware that when the battery needs replacement, it must be purchased from our funds. If we fall short, then we* [the households] *are willing to contribute and cover the deficit."* Q5: "*Since not enough money is collected from houses we are thinking about a late fee and disconnection after six months. This may encourage people to pay on time. We will discuss this in the next meetings and decide*"
Effective Governance	Local Ownership	Q6:*"Few months ago we found that the person collecting payments did not deposit the money for six months. We called Gram Oorja to report the issue and get help, but they said it was our problem. So, we met as a village and decided to remove this person from the committee."*
	VEC Report on Governance	Q7: *"After different attempts, we decided that roles should rotate between all VEC members each month, who will collect money, who will clean the panels etc. We rotate because then everybody knows how to do it."*

	Local Ownership/ VEC Report on Governance/ Regularity of Meetings	Q8: *"Meetings are held every two weeks. We go to each household and tell them a day in advance about the meeting. Everybody raises topics for discussion. We look at the funds collected and note down in the register after which the treasurer is responsible for depositing the money in the bank."*
Community Participation	Participation in Meetings	Q9*: "The foundation on which the meter is mounted has broken. So we discussed that we should use the money from our bank reserves to fix this problem. Everybody in the meeting agreed.*
	Inclusion	Q10*: "We do not go to meetings. Mainly men go there and discuss"*
User satisfaction	Satisfaction with Public Lights	Q11: "*I used to go to visit other woman in the village in the evening but now that lighting outside is not available, so I don't go"*
Household Wellbeing	Safety	Q12*: "I can sleep much better at night. With electricity I can check if my baby is sleeping safe next to me and I can calm her down when she wakes up and fears the darkness"*
Environment	Local & Global	Q13: "*We do not use kerosene anymore for lighting and only have little amount for emergencies. For cooking we use firewood, see the kitchen wall are all black*."

After assigning scores for each installation, they were analysed using central tendencies, visual time graphs, pie charts and histograms to examine trends and highlight performance variations across sites. Before starting data collection, GO was also asked to provide internal targets for technical *Indicators.* This information was used to understand whether any discrepancy between expectations set with the community during participatory planning and service delivered had caused discontent, institutional or financial inefficiencies. Visualization of scores was backed with thick descriptions from qualitative data and, when needed, looking back at individual scores corresponding to the underlying *Indicators*. This allowed to better understand the patterns exhibited and capture emerging trends across groups of *Measures.* From this analysis, a narrative emerged across the whole set of sites that lead to conclusions for sustainability conditions and replicability of the community-owned model analysed.

RESULTS

In this section, we show results from scores across all *Measures* supported by the quotes presented in Table 13 (referred as Q followed by relative number as coded in the table).

Scores for all three Technical *Measures* are reported in Figure 2, and mode values for *Indicators* in Table 14. Granular scores for Reliability and Quality for Domestic Supply are also reported in Figure 3 and Figure 4 respectively, due to the large variation these *Indicators* displayed across sites. In the time graphs, each geographic cluster is represented by a different colour[4] , the size of the circles represents the number of households connected to the grid in each village and, where shown, the dotted line represents GO's internal target.

Starting with Domestic Supply, *Indicator* scores matched GO's targets, highlighting consistency of performance, particularly with respects to quality and durable supply throughout the day. The 54% percent of sites with a score of 2 were found to be limited by the installed capacity which, in most cases, sat at the higher end of the benchmark (an average of 220Wp per household). Sites that demonstrated poor Reliability (Figure 3) and Quality (Figure 4) were due to severe weather conditions resulting in failure of components, a one-time event in the green cluster, and limited battery capacity during summer nights, particularly relevant in the yellow cluster that saw a surge in fan utilization at night.

Figure 2: Scores for all *Measures* pertaining to Technical *Dimension*

Table 14 *Indicator* scores and GO target scores for Domestic Supply and Street Lighting

Indicators	Domestic Supply		Street Lighting	
	Mode Score	GO Target	Mode Score	GO Target
SMG / SL Capacity	3	3	3	4
Duration	5	4	5	4
Reliability	4	4	4	4
Quality	5	5	2	5
Affordability	4	4	NA	NA

Legality	5	5	NA	NA
Safety	5	5	5	5

Figure 3: Domestic Supply *Measure* – Scores for Reliability *Indicator*[4]

Figure 4: Domestic Supply *Measure* – Scores for Quality *Indicator*[4]

Public Lighting scores, on the other hand, showed large variations and relatively poor performance, with only 13% of the sites meeting the internal target (Figure 2). Issues were due to poor quality, including malfunctioning or non-operative poles, and limited capacity leading to large unlit areas in villages.

Energy Consumption remained largely low and below expectations (Figure 2), with 73% of the villages scoring 1. Meter readings showed that the average daily energy utilization was 37%[5] across all sites, with some sites utilizing as low as 9% of the maximum available energy. Despite GO's expectation of a growing trend with time, represented as dotted line in Figure 5, the oldest site only reached 48% of its targeted value. The same image shows how the average daily consumption varied significantly across sites, showing some signs of levelling within a geographical cluster and for installation of comparable size.

Figure 5: Scores for Household Energy Consumption *Measure*[4]

Moving onto Economic *Measures*, Livelihood Generation (Figure 6) revealed low-to-modest engagement in commercial activities, across time. The participants' narratives indicated the need for handholding and support to venture in commercial activities (Q1). Individual entrepreneurship also seemed to be hindered by VEC members themselves due to perception of limited energy availability (Q2), which was often linked to fear that that adding productive loads could have harmed the system, depriving the community from basic electricity for lighting (Q3). On the other hand, Model Sustenance (Figure 7) suggests that most villages set tariffs in line

with battery replacement target and were able to maintain rigor in billing, collections and financial operations (score 3 or above). Interestingly, some cases scoring 1 or 2, indicated awareness of the need to raise funds internally to cover the deficits when the battery would be up for replacement (Q4), and some VECs were considering of establishing a late fee and a household disconnection mechanism for prolonged missed payments (Q5).

Figure 6: Scores for Livelihood *Measure*[4]

Figure 7: Scores for Model Sustenance *Measure*[4]

An analysis of the Effectiveness of Governance shows that most villages had well defined structures, locally customized processes and rules, and were able to handle operational issues autonomously with limited external intervention (score 3 or above). This was attributed to the role of GO and local NGOs, which closely assisted the communities in the process of building internal capacity while at the same time pushing back responsibilities to let the VEC gain authority in front of the community (Q6). Generally, procedures for enforcement of rules and money collection were found to vary, as illustrated by Q7 where a committee member explained a unique mechanism for money collection established in the village. This decision, arrived at after experimenting with other mechanisms, also indicates that establishing governance strategies that reflect the local needs takes time. In villages with well-functioning Self-Help Groups (SHGs)[6], women's organizational skills were leveraged for a more rigorous and structured approach, often resulting in highly effective systems, see for example Q8 collected from a women VEC head. Villages that scored 2 were found to be culturally heterogeneous, with sub-groups representing different castes or having contrasting views. Their governance committees struggled to generate consensus, address situations in a timely manner and enforce rules, occasionally causing the plant to shut down until external intervention facilitated a resolution. Often the small size of villages, where only a couple of voices dominated the local

affairs, aggravated these situations, as formal procedures for authority and accountability were highly informal and harder to establish. Community Participation reveals high involvement from the communities and a pattern where participation increases with time (Figure 9). Qualitative data showed that decisions were taken by the VEC in consultation with the community following a common pattern showed in Q9. Women involvement in meetings was found to be generally low (Q10) and to be highly dependent upon facilitation by the local NGO. Interestingly, sites with very low (score 1) or very high (score 5) effectiveness of governance displayed a similar trend for community participation, suggesting a possible relation between the two *Measures*. With regards to User Satisfaction, results highlight high satisfaction reported by stakeholders (Figure 10). Despite some dissatisfaction was reported with respect to street lights (Q11), this generally did not result in significant reduction in the overall feeling of the users towards the solution.

Figure 8: Scores for Effectiveness of Local Governance *Measure* [4]

Figure 9: Scores for Community Participation *Measure*[4]

Figure 10: Scores for User Satisfaction *Measure*[4]

Analysis of *Measures* pertaining to Social and Environmental *Dimension* is presented in Figure 11. Time graphs are not provided since this score did not vary across time nor location. High scores for Household Wellbeing indicate that children generally experienced increased hours for study in the evening, household members, particularly women, experienced reduced drudgery, improved health, and a feeling of safety at night (Q12). When asked about the use of extra time, most women reported being able to manage their work more flexibly, take care of their children, or work more in the farm. Signs of increased independence for women were generally poor, except for sites where women were involved in the governance, thus suggesting a positive effect of women inclusion in the supply of energy. With regards to Community

Connectedness, a feeling of unity was attributed to community participation in planning stages and in the governance, whereas the availability of mobile phones and TVs enhanced the sense of connection with the outside world. Villages performed poorly when it came to channeling internal unity towards new community initiatives. With respects to environmental *Measures*, most of the houses registered a reduction of 75% of kerosene use. However, improvements in indoor air quality were found to be limited due to continued use of firewood for cooking (Q13).

Figure 11: Scores for Household Wellbeing, Community Participation, Local and Global Environmental *Measures*

DISCUSSION

This analysis focuses on the conditions for long-term sustainability of community-owned SMGs and their ability to be replicated so as to provide socio-economic and environmental benefits to the local communities. This section discusses two elements based on key themes emerging from the findings: first, it describes the core features that underpin successful community ownership; and second, it highlights the replicability of the model and its impact, emphasizing some of the untapped potential to achieve higher socio-economic and environmental benefits.

Community Ownership: Core Features for Success

A central role for enduring community-owned systems is strong local capacity in the areas of governance, financial and technical management of the installation [24]. While strong local governance and financial capacities determine the ability to define and enforce mechanisms for payment collection, deposits and penalties [18-22], local technical capacity ensures quick resolution of issues and a continuous supply [15]. Contrary to the often mentioned ‘limited paying capacity’ of the users leading to missed payments and affecting the system’s economic viability [25-27], this study reported several cases of systems that managed to be financially self-

sustaining over many years, offering an opportunity for meaningful learnings. The study suggests two strategies to achieve technical, financial and institutional sustainability.

First, allowing communities the freedom to define governance procedures and manage finances allows local actors to come up with solutions that are appropriate to the local contexts. To make sure that such autonomy is not misused, clarity should be provided upfront around responsibilities and to place accountability in the hands of local actors. This means that, together with educating communities about the energy source and its use, assistance provided early on when governance procedures are established, and communities familiarize with financial management and technical instruments is equally crucial. This process usually takes time [11,28,29], as is suggested by the increasing trend observed for the institutional *Measures* of Effectiveness of Governance and Participation. Second, as suggested by Mishra et al. [17], effective local governance goes hand-in-hand with high community participation and involvement. This starts from initial engagement to understand local aspirations for growth [30], involving communities in capacity planning, setting tariffs and construction. The ability for anybody to raise issues, discuss them collaboratively and adapt the rules to local needs [31-33] is critical to instil a sense of ownership in the community.

Prior research suggests the importance of socio-cultural contexts for successful rural energy interventions [34]. This research adds to this dialogue, as it found that institutional and economic *Measures* in particular were influenced by cultural homogeneity, community size and women participation, with the latter having a crucial role in creating more inclusive and effective interventions [35]. Finally, the research also confirms the importance of evaluating energy access beyond connections. Like in other cases [36], duration, reliability and quality of power to

domestic users, were crucial to drive user satisfaction, particularly as the technical performance of the systems matched the expectations set upfront by the supplier.

Replicating the model and its impact: Considerations

Analysing the Off-grid Access Systems for South Asia projects, Bhattacharyya et al. [37] highlight that most community-based energy access projects are not able to endure beyond their pilot phase, even if this were to be successful. Theirs and other research [15] call for a step change to replicate successful community-owned cases at a faster rate. This study illustrates a model that was successfully replicated across several cases in just over five years. The model was able to overcome challenges highlighted by scholars related to assembling technical, human and financial resources [27,37] as well as those of establishing appropriate local management for community-owned systems, the strategies for which have been discussed in the previous section. The study also shows the ability of the model to produce consistent social impact across several installations. As in other energy access studies [16,38-40], positive social impacts are observed in the areas of education, health, safety, connection with the outside world and increased time availability for women.

While this study substantiates evidence of energy access providing improvements in women wellbeing [41], as highlighted by other studies[42] it also showed that these rarely translate in higher independence. Particularly for community-owned systems, this calls for further investigation regarding strategies to meaningfully integrate women in the processes for energy supply to achieve greater impact in terms of gender equity. Contrary to expectations from a participatory model, the study also found limited community-led initiatives, which is worth further investigation.

Moreover, despite evidence over the replicability of the community-owned model, the study highlights untapped potential in the form of limited energy consumption and engagement in business activities. The high levels of affordability and high collection rates from the majority of sites seem to contradict the idea that the cause for low utilization is the limited paying capacity of the users [25-27]. Particularly, qualitative narratives collected in this study offer alternative contextual explanations for this phenomenon. The mindset of living within one's means, a characteristic of many tribal communities visited in this study, results in a perception that electricity should be preserved for basic lighting. In addition, physical isolation, limited market links and small customer base also constrain the potential and viability of local businesses [37,40] to those linked with agricultural activities and small shops serving local customers. Low levels of energy use suggests that access to reliable and affordable energy alone does not ensure that the consumers will climb up the energy ladder. Instead, interventions that engage with the cultural mindset as well as address market linkages can produce greater economic impact than currently observed. Regarding environmental benefits, despite a considerable reduction in kerosene use, indoor environments continued to be unhealthy due to persistent use of wood as primary energy source for cooking. This suggests that, if energy access is to create healthier environments for people to live in, electricity interventions should go together with those tackling clean cooking.

CONCLUSIONS

This study is first of its kind collecting mixed data from a large number of community-owned SMGs that have been operational for many years and in different geographies. The study makes several contributions which are useful for practitioners, policy makers and researchers,

offering guidance for the design of interventions that are scalable as well as suggesting methodological approaches for their operational evaluation.

First, by substantiating a rigorous scoring approach with qualitative description of actors' motivations and experiences, the framework provides thick explanation of patterns emerging across *Measures*, bringing to fore narratives that would have otherwise been overlooked using a purely quantitative evaluation. Importantly, qualitative data provided an alternative explanation for the limited energy consumption and engagement in livelihood activities that are not linked to limited paying capacity of the users but rather to more contextual realities relating to the experiences of those living in remote areas. Qualitative narratives also revealed temporal patterns relating to building institutional sustainability and effectiveness of governance. This suggests that shortcomings of purely quantitative or qualitative ex-post sustainability assessments can be overcome by utilizing mixed methods to arrive at conclusions that are contextually relevant and provide more nuanced explanations of the phenomena.

Second, the study provides mechanisms by which strong community-ownership for long-lasting SMGs can be created. The research suggests that allowing communities to directly influence decisions from the very early stages and set their own agenda, enables them to craft rules that are more in line with their means and needs, including overcoming perceived financial capacity constraints. Engagement with the local community results in higher social acceptance where their views, interests and needs are reflected through co-creation of projects, be it setting the tariff, identifying the land for the infrastructure and participation in construction, or selecting members and organizing the VEC matters. Enabling active participation of women also increases rigor in the governance processes and achieve equity. Community-ownership created in this manner is sensitive to the specific socio-cultural contexts, leading to systems that are responsive

to upcoming challenges and therefore more resilient. However, building strong ownership takes time to establish; calling for engagement that begins early on and continues well after the installation is completed. The limited ability or willingness of many stakeholders to provide continued and tailored assistance may be an underlying reason as to why many community-owned interventions implemented in a 'one-size-fits-all' manner have failed in the past.

Third, while prior research shows cases of successful community-owned energy access solutions, these are limited to pilot projects and lack evidence of replicable lasting models. This study shows an example of a community-ownership model that has been replicated successfully over many cases, consistently producing positive social impact. It was found that if on the one hand sensitivities to socio-cultural contexts are crucial to create a model that is sustainable and replicable, these same cultural contexts can also act as a limiting factor for expanding energy use and producing greater economic impact. Since increasing energy demand remains a challenge, tools that offer real-time traffic light signals about the resource position can heighten awareness of the excess capacity and promote greater utilization of energy for economic activities. These discussions also suggest that to produce greater socio-economic impact, rural development agenda must go beyond the mandate of energy interventions carried out by social entrepreneurs. A collaborative approach is necessary where government agencies, NGOs, social enterprises and the private sector work together to create the necessary nexus between energy, agriculture, water supply, health and communication to create an environment for smart sustainable rural living.

The findings, like any other research, come with limitations. This study was cross-sectional, and it is recognized that longitudinal studies are best suited to study temporal variations. However, the cases studied share commonalities including their remote nature, relatively small sized villages, often composed of tribal population, similar economic status,

dependence on agriculture and seasonal migration of residents for economic activities. This motivated the researchers to explore the time dimension of sustainability by comparing installations that were younger with those that were in operation for several years. Our findings provide preliminary insights into the temporal aspects of sustainability of community-owned models, particularly as regards the process of building institutional capacity and provides the basis for further investigations.

DECLARATIONS

List of Abbreviations

GO – Gram Oorja

HH – Household

MTF – Multi-Tier Framework

NGO – Non-Governmental Organization

O&M – Operations and Maintenance

PO – Plant Operator

SHG – Self Help Group

SHS – Solar Home System

SMG – Solar Micro Grid

VEC – Village Energy Committee

Ethics approval and consent to participate: The research team assessed the ethical issues involved in the work during the research design phase and found it to be limited due to the following reasons. First, the data (surveys and open-ended semi-structured interviews with VECs) were designed to be anonymous and did not need any personally identifying information. Second, an informed consent drafted in the local language, was shared with each participant which among other points clarified that their participation was voluntary and that they have the opportunity to opt out at any time with no consequences if they so desired. Third, there were no direct benefits of participation to either the individuals, the VEC or other participating organizations. Finally, all information was designed to be stored securely only with the researchers. Field staff were trained to work under the supervision of the researchers. Based on this evaluation, no major ethical concerns emerged and accordingly, no formal approval from the research committees was sought.

Consent for publication: Not applicable

Availability of data and material: Data can be shared on request. All requests can be sent to the corresponding author.

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Competing interests: The authors declare that they have no competing interests.

Authors' contributions: All authors have collaboratively contributed to all phases of the research and in the development of the manuscript.

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[1] Saubhagya Dashboard (http://saubhagya.gov.in/, last accessed on 23/07/2018)
[2] In the study referenced , electrified meant having a sort of electricity connection either by means of central grid as well as from other decentralized sources (Solar Home Systems, Mini Grids, Pico Grids)
[3] This research focuses on Off Grid Solar Mini-Grids, these are decentralized village-level systems for solar energy provision. Solar lantern and Solar Home Systems are excluded from this analysis
[4] Khunti and Gumla districts in Jharkhand (Green), Palghar (Yellow), Amaravati (Red) and Pune (Blue) (these are districts in Maharashtra), Uttar Kannada in Karnataka (Purple). Size of the circles are representative of the number of HH connected to the grids in each village.
[5] Calculation for Utilization Factor is based on an average India yield for solar panels of 1000kWh/kWp per year, assuming 25% losses at Maximum Power output.
[6] SHG is a development sector initiative comprised of 10-20 individuals (generally women) supporting each other, usually through monthly financial contributions that can be used to assist members at time of needs.

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Appendix A: Interview protocol

- To begin with tell us a bit about the village energy committee (VEC) – when was it formed, how was it formed, any document which describes the VEC and its functioning, how many members does it have, number of women on the VEC, when and how do the members of the VC change, what is the purpose of the VEC?
- Explain the hierarchy, if any as regards the structure and functioning of the VEC. How often do you interact with other agencies like the NGO or Gram Oorja for guidance?
- How are the members of the VEC elected? When was the last change to the committee members made? How are new members to the committee elected? Describe the process.
- How often does the committee meet? Describe a typical meeting - how is it called, who sets the agenda, how does follow up happen? How do you maintain records of the meeting?
- Tell us about an incident that was escalated to the VEC? What was it, why was it escalated, how did the VEC resolve it, who was involved in the decision process then? Who makes the final call in case of disputes?
- Likewise, tell us about a more memorable incident.
- Describe a situation when the VEC was working at its best/worst? Why did that happen?
- Is there anything you would like to share that we have not addressed?

Thank you for your time and participation.

Table 1

Benchmarks for Domestic Supply *Measure* and its *Indicators*

Indicator	Score 1	Score 2	Score 3	Score 4	Score 5
Capacity (W/HH)	Min 3	Min 50	Min 200	Min 800	Min 2000
Duration	>4 hours >1 hours at night	>4 hours >2 hours at night	>8 hours >3 hours at night	>16 hours >4 hours at night	>23 hours >4 hours at night
Reliability (monsoon months)	Frequent outages >5 days/month		2–5 days/month	1–2 days/month	No unscheduled outages
Quality	Frequent issues with V and *f* affecting use of appliances		Few issues with V and *f*	No issues with ability to use appliances when needed	
Affordability	House unable to pay at time of collection and still in debt		House unable to pay at time of collection and facing difficulties in paying on following month	House unable to pay at time of collection but easily paid back the following month	No difficulties with regular payments
Legality	Illegal connections and irregularities with payments		No illegal connections and bills paid to authorized representative		
Safety	Unsafe connection and installation		Absence of past accidents and perception of risk in the future		

Table 2

Benchmarks for Public Lighting *Measure* and its *Indicators*

Indicator	Score 1	Score 2	Score 3	Score 4	Score 5
Capacity (village coverage)	1 street light	>25%	>50%	>75%	>95%
Duration	>2 hours	>4 hours	>50% night	>75% night time	>95% night time

(night hours)			time		
Reliability (monsoon)	Frequent outages >5 days/month		2–5 days/month	1–2 days/month	No outages
Quality	No functioning lights	Failures, brightness flickering issues	No early failures, no issues with brightness, flickering, etc.		
Safety	Unsafe connection and installation		No perceived risk of electrocution due to poor installation or maintenance		

Table 3

Benchmarks for Household Energy Consumption *Measure*

Indicator	Score 1	Score 2	Score 3	Score 4	Score 5
Daily Consumption (Wh/HH)	≤12–200>	≤200–1000>	≤1000–3425>	≤3425–8219>	≥8219

Table 4

Benchmarks for Model Sustenance *Measure* and its *Indicators*

Indicator	Score 1	Score 2	Score 3	Score 4	Score 5
System's functionality	Payment discontinued due to technical issues or internal disputes.		Despite payments are ongoing, issues are reported by users around timely collections, payment delays and deposits.	Users report sound financial management, timely collection and limited-to-no payment delays.	
Bank reserves	Less than 20% of expected reserves is collected, or data not available. Passbook shows no	Between 20% and 40% of expected reserves are collected. Passbook shows no entry in	About half of tariffs collected compared to expected reserves. Passbook shows dispersed payments. Qualitative data from	About 60-70%of expected tariffs are collected. Passbook shows regular payments	About 80% or more of expected tariffs are deposited in the account. Regular

	entry in last several months.	recent months. No other explanation from qualitative data for missed payments.	discussion with stakeholders provide an explanation for recent missed payments.	over extensive periods of time.	entries in bank account.

Table 5

Benchmarks for Livelihood *Measure*

Indicator	Score 1	Score 2	Score 3	Score 4	Score 5
Commercial activities	No economic activities linked to energy use. Users are not reporting increase in productivity linked to electricity.	Limited livelihood activities, those available are linked to lighting provided for small household-scale commercial activities. No increase in productivity registered in other areas.	Use of electricity for some livelihood activity is observed and some users are purchasing equipment primarily for agricultural purposes.	Few users engaging in new businesses activities. These are linked to processing of agricultural products such as rice huller or flour mills.	Engagement in livelihood activities is extended to several households. There are many examples where users actively engage in new businesses activities, purchasing electrical equipment beyond those used to process agricultural products.

Table 6

Benchmarks for Effectiveness of Governance *Measure* and its *Indicators*

Indicator	Score 1	Score 2	Score 3	Score 4	Score 5
Regularity of meetings	Institutional meetings for energy-related issues are infrequent and ineffective.		Meetings are happening, though not very frequently. High disagreement among	Frequent meetings and stakeholders recollect with fair precision the date of the previous meeting.	

		household on date of last VEC meeting.		
Local Ownership	If system is operative, major external interventions were needed to keep the project going	External interventions from higher organizational level is largely needed to initiate meetings and discuss issues.	Local actors demonstrate autonomy in governance procedures, however external intervention may still be needed to take care of technical issues, or to solve internal disputes.	Local actors have been able to autonomously craft and modify rules around the use and management of the system to accommodate local necessities, timely seeking help in cases when external support was needed.
VEC Report on Governance	VEC is very ineffective and members are not identifiable.	VEC members are identifiable, however there is no clear structure defining member's roles and responsibilities. If in place, procedures are highly informal. There is inconsistency when VEC articulate rules in place.	Members are identifiable, able to describe procedures, rules and how these are enforced. VEC members may still seek local actors to solve internal issues and disputes. There may be cases in which VEC members have left and have not been replaced.	Members are identifiable, able to describe procedures, rules and how these are enforced. VEC report how issues are attended to in a timely manner with limited to no system downtime due to institutional inefficiency.
Operator Report on Governance	If identifiable, Operator has repeatedly been unable to take care of minor technical issues with domestic connections, like assisting with replacement of light bulbs or small issue with connections at home. He/she is also unable to maintain clean panels/control room.	Operator has been able to solve most of issues with domestic connections but seeks external help for any matter concerning equipment in control room or street light. Panels, control room are well kept.	Operator has been able to take care most of the issues arising with domestic connections. Panels, control room are well kept. He/she demonstrated ability to identify issues in control room, performed based troubleshooting, fixing those in his/her competency and actively seeking support from GO when more expert support was needed.	

Households' accounts of issues' management	HHs report institutional inefficiency and severe issues with technical equipment at home which are not being solved	HHs report few institutional and technical issues, some of which led to temporary dissatisfaction or discomfort (irregular meetings, issues with street light)	HHs report institutional and technical issues, most of which were solved on time, some issues took longer to fix or were outstanding.	HHs report few institutional and technical issues, all of which have however been solved by those appointed in a timely manner.

Table 7

Benchmarks for Community Participation *Measure* and its *Indicators*

Indicator	Score 1	Score 2	Score 3	Score 4	Score 5
Participation	Less than 30% of HHs surveyed report participation in meetings. This is also backed by remarks on non-usefulness of meetings.		About half of HHs surveyed attend meetings and have general feeling of these being useful.	Over 70% of HHs surveyed attend meetings regularly and mention raising issues for discussion.	
Inclusion	Less than 30% of HHs surveyed report a feeling of ownership of the installation and do not feel included in key decisions. Women in particular and representatives from households that appear marginalized are particularly disengaged.		About half of HHs surveyed report a feeling of ownership and inclusion in key decisions. Engagement is low for women and marginalized households.	More than 70% of HHs surveyed report a feeling of ownership and inclusion in key decisions, including women and marginalized households.	

Table 8

Benchmarks for User satisfaction *Measure* and its *Indicators*

Indicator	Score 1	Score 2	Score 3	Score 4	Score 5
HH Satisfaction	About 20%-30% of HHs surveyed express high		About 50% of HHs surveyed express high	About 70% of HHs surveyed express high	More than 80% of HHs surveyed express high satisfaction with

with Supply	satisfaction with usability of supply to domestic users	satisfaction with usability of supply to domestic users	satisfaction with usability of supply to domestic users	usability of supply to domestic users
HH Satisfaction with Public Lighting	About 20%-30% of HHs surveyed express satisfaction with public lighting	About 50% of HHs surveyed express satisfaction with public lighting	About 70% of HHs surveyed express satisfaction with public lighting	More than 80% of HHs surveyed express satisfaction with public lighting
HH Satisfaction with Tariffs	About 20%-30% of HHs surveyed express satisfaction with tariff levels and collection	About 50% of HHs surveyed express satisfaction with tariff levels and collection	About 70% of HHs surveyed express satisfaction with tariff levels and collection	More than 80% of HHs surveyed express satisfaction with tariff levels and collection
HH Satisfaction with Governance	About 20%-30% of HHs surveyed express satisfaction with governance mechanism (VEC and Operator)	About 50% of HHs surveyed express satisfaction with governance mechanism (VEC and Operator)	About 70% of HHs surveyed express satisfaction with governance mechanism (VEC and Operator)	More than 80% of HHs surveyed express satisfaction with governance mechanism (VEC and Operator)
Operator Satisfaction	Operator expresses high dissatisfaction with training received and ongoing support from GO	Operator express partial satisfaction with training received and ongoing support from GO	Operator express satisfaction with training received and ongoing support from GO	Operator express high satisfaction with training received and ongoing support from GO, showing willingness to learn more about plant operation to take on more tasks

Table 9

Benchmarks for Household Wellbeing *Measure* and its *Indicators*

Indicator	Score 1	Score 2	Score 3	Score 4	Score 5
Education	No improvements in terms of increased study time for children		Households reporting about an hour of extra study time for children	Households reporting more than an hour of extra study time for children	
Health	No improvements in terms of		About half of HHs surveyed	More than 70% of HHs surveyed report	

	regarding health	report improvements in terms of better eyesight, reduced respiratory problems and body pain.	improvements in terms of better eyesight, reduced respiratory problems and body pain.
Safety	No improvements in terms of increased safety at night or in the house	About half of HHs surveyed report feeling of increased safety at night and/or at home	More than 70% of HHs surveyed report feeling of increased safety at night and/or at home
Women's time	No improvements in terms of increased time available for women	Women reporting about an hour of extra time	Women reporting more than an hour of extra time
Women independence	Women are not able to conclusively communicate an increased sense of independence in the home or within the communities.	Women highlight some degree of increased autonomy, particularly in the home.	Women provide rich description of examples where they took decisions autonomously or are more independent in areas previously not allowed to them. Examples include purchase of equipment, ability to move freely in the village or visit the market, visit friends, participate in meetings.

Table 10

Benchmarks for Community Connectedness *Measure* and its *Indicators*

Indicator	Score 1	Score 2	Score 3	Score 4	Score 5
Unity and Connection	Less than 20% of HHs surveyed reported sense of connectedness with outside world and within the community		About 50% of HHs surveyed reported greater sense of connectedness with outside world and within the community	More than 70% of HHs surveyed reported greater sense of connectedness with outside world and within the community	
Community activities	No community activity reported by the users at time of visit nor any was noted by field staff		Some community level activities reported by the users at time of visit and/or noted by field staff	Several HHs are engaged in community activities as a result of the arrival of electricity	

Table 11

Benchmarks for Local *Measure*

Indicator	Score 1	Score 2	Score 3	Score 4	Score 5
Improved indoor air quality	Less than 30% of households surveyed reported improvements in indoor air quality		Between 30% and 70% of households surveyed reported improvements in indoor air quality	More than 70% of households surveyed reported improvements in indoor air quality	

Table 12

Benchmarks for Global *Measure*

Indicator	Score 1	Score 2	Score 3	Score 4	Score 5
Reduction in kerosene use	Less than 30% reduction in monthly kerosene usage by households		Between 30% and 70% reduction in monthly kerosene usage by households	More than 70% reduction in monthly kerosene usage by households	