Coexistence of Microgrids and the Government Grid in Rural India: A Study of their Respective Contributions to Social Well-Being at the Household Level

by

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Abstract

This paper examines the coexistence of microgrid and central grid connections for households in India and studies the relationship between these connections and their individual contributions to social well-being of rural households. As India's government grid reaches new rural communities, solar microgrids once providing stand-alone energy solutions are now used alongside centralized government grid infrastructure. This provides a unique opportunity to understand how both electricity options compete and how each energy supply contributes to social well-being. Our research administered surveys to 149 households across 8 villages in Northern India with access to microgrids developed by Boond Solar and the government grid. Energy access of the government grid was measured using the World Bank's multi-tier framework for energy access by surveying respondents about system capacity, availability, reliability, and safety. Social indicator measurements across economics, education, healthcare access, access to appliances and gender equity were also captured in the survey. Additional fieldwork was conducted in 4 of the surveyed villages to collect qualitative data in the form of semi-structured interviews to further evaluate energy consumption across microgrid and government grid sources.

Although communities with government grid access now have greater energy capacity to power appliances, this study identified a high number of households that were unable to make use of their expanded electricity capacity due to the inability to afford household and productive use appliances. This demonstrates that providing greater energy capacity will not continuously improve social well-being on its own. There is a tipping point where higher energy access does not accelerate well-being, but instead income and the ability to purchase appliances to use the extra power capacity are the limiting factor. To improve social well-being status in these rural communities, expanded electricity capacity must be accompanied by a holistic economic development approach to improvement that includes opportunities to increase household income. The work also found that the extension of the government grid relegated microgrids to a backup role and significantly lowered the profitability of the microgrids.

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1. Introduction

In April 2018 the Indian government claimed that 100% of the country's villages were now electrified by a newly expanded government grid [1]. As the government electricity grid expanded, it reached rural areas powered by solar microgrids, which left many citizens with dual sources of electricity. The consumption habits and subsequent impacts of having two sources of electricity have not been formally observed in these rural communities. This study aims to fill a gap in understanding by analyzing electricity use and the social well-being status of households with government grid and solar microgrid connections. Using data from a survey administered to 149 households across eight villages in the Unnao district of the northern state of Uttar Pradesh, India, as well as qualitative data from focus groups and semi-structured interviews, this study examines the relationship between energy access and social well-being among households with both a government grid electricity connection and a solar microgrid connection. This work provides insights into both the contributions of each power supply to well-being and the impact of increased energy supply to the well-being of communities who already had limited energy access.

1.1 ELECTRIFICATION

In the 21st century, electricity is the lifeblood of societies on every continent and in every country. Modern energy access powers lighting, cooking appliances, transportation, industrial processes, factories and more. Studies have shown that electricity access provides a variety of benefits like higher household income, education levels, and improved media access [2,3,4]. Additional studies focused on the impact of electrification, specifically in rural areas, showed correlations to improved indoor air quality, lower fertility rates, and the creation of micro-home enterprises [5]. Energy access is intrinsically linked to economic development and social well-being, as defined in the 17 Sustainable Development Goals outlined by the United Nations [6]. Yet, despite recent progress, approximately 840 million people (11% of the global population) remain without access to quality electricity today [7].

1.2 POLICY

The need to improve and expand access to electricity and more sustainable energy resources has gripped the attention of policymakers and an interest in measuring energy access has gained support from international governments and agencies [8,9]. Sustainable Development Goal (SDG) number 7 is centered around achieving access to reliable, sustainable energy by 2030, with a major focus on expanding energy access to unelectrified regions of the world, namely India and sub-Saharan Africa [6,10]. The United Nations describes the following vision for Goal #7:

> Ensuring access to affordable, reliable, sustainable and modern energy for all will open a new world of opportunities for billions of people through new economic opportunities and jobs, empowered women, children and youth, better education and health, more sustainable, equitable and inclusive communities, and greater protections from, and resilience to, climate change [11].

Originally defined as a binary between electrified and unelectrified, an appreciation for the need to accurately measure the complexities of electrification has driven the international community to develop a more granular system for measuring electricity access and its associated benefits [12]. Research has attempted to develop numerous frameworks for measuring multi-dimensional energy access metrics [13,14,15]. The World Bank, in partnership with Energy Sector Management Assistance Program (ESMAP) and the International Energy Agency (IEA), has developed a multi-tiered framework (MTF) under the Sustainable Energy for All (SE4All) initiative that assesses energy access across multiple dimensions on a scale from no access (tier 0) to the highest level of access (tier 5) [16]. Unlike previous electrification metrics, the MTF assesses the quantity **and** quality of the electricity being delivered. This work used the MTF Household Electricity Index as a guiding tool; further research should be conducted to understand the impacts of an expanding government grid on additional indexes developed by SE4All and the SDGs.

1.3 INDIA

As global policy continues to drive electricity access efforts around the world, India's path to expanding electricity infrastructure is ongoing. In a sweeping political effort to improve electricity access spearheaded by Narendra Modi, India's government grid has expanded and estimates from the country's Ministry of Power claim that 99.9% of villages throughout the country have been electrified (i.e., in India, electrified communities are defined as communities where 10% of households have government grid power supply [17]), including 100% of villages located in the Uttar Pradesh region [18,1]. Although these claims indicate massive progress towards a fully electrified India, millions of people are still reported to be without access to reliable electricity [19,20].

The growth of India's centralized grid has reached regions and villages that were once predominantly powered by solar microgrids. India's expanded government grid relies on thermal fuels (62.2% of generation), renewable energy sources (23.6% of generation), hydropower (12.3% of generation), and nuclear (1.8% of generation) [21]. This development initiative has created an environment where communities now have access to electricity sourced from microgrids and the newly expanded government grid. In rural villages that had formerly been powered solely by microgrids, many households now have two sources of electricity with differing characteristics of reliability, capacity, and cost. These differences add further complexity when considering the wide spectrum of energy access levels that exist between the binary states of unelectrified and fully electrified.

1.4 MICROGRIDS

In many rural villages across the world, microgrids provide the only source of electricity. The economic and social benefits derived from a shift from unelectrified to a small, but meaningful, electricity connection provided by a microgrid are visible and immediate [5]. Households can provide light for reading and cooking at night, charge mobile phones at home, and operate small fans to provide relief in warmer temperatures [5]. Studies have shown that microgrid electricity access has provided educational benefits for children, female empowerment within households, and operational improvements for small business owners across rural communities in India [22,14].

However valuable solar microgrids may be to unelectrified communities, these systems do have limitations. Previous studies focused on the reliability of microgrids in India found that systems were often susceptible to interruptions caused by changes in local weather conditions, overloaded system capacity outages, and mechanical issues with microgrid components [23]. Although microgrid systems experience reliability and capacity limitations, these systems have historically served a valuable role in electrifying parts of India where the government grid was unable to reach [24,25]. This value is well reflected in the growth of microgrid developers serving the state of Uttar Pradesh in Northern India, which quadrupled from 2005 to 2015 with the total number of microgrid connections reaching over 37,000 in 2017 [26,27]. Further, it has been shown that these microgrids are more reliable than the central grid, especially during peak hours and that households are willing to pay more for this reliability [28].

While microgrid development in India has flourished in recent years, the expansion efforts of the government electricity grid have created a relationship between the two systems with tradeoffs for the way villages throughout India consume electricity [28]. These tradeoffs between systems generally revolve around connection capacity. Solar microgrids in India typically provide a 30-35 W connection capacity per household to power light bulbs, small fans, and charge mobile devices while the government grid provides a 1,000 W connection capacity per household capable of powering a wider variety of appliances for cooking, refrigeration, and pumping water. In the rapidly developing rural regions of India, as government grid access begins to reach villages with microgrid access, an understanding of the underlying effect on social well-being is required to ensure policy and development practices are designed to maximize potential benefits and standard of living improvements. This is exacerbated by the fact that different stakeholders in the electrification landscape view microgrids as key but disagree in the way that the microgrid and government grid should interact, leaving microgrids in an unsure political environment [29].

1.5 THIS STUDY

Given the gap in understanding regarding the impact of having two sources of electricity, this study uses quantitative survey data and qualitative semi-structured interview reporting to assess the relationship between social well-being and energy access among households in India with government grid and microgrid electricity sources. In order to reach a statistically significant number of homes with both sources of electricity our research group partnered with Boond Engineering and Development Pvt Ltd (Boond Solar), a microgrid developer with a network of distributed solar developments throughout India.

Boond Engineering and Development Pvt Ltd (Boond Solar) is a triple bottom line enterprise specializing in renewable energy development in India. The company was founded in 2010 and has grown into a leading microgrid developer throughout Northern India. Boond Solar has expanded its operations to include a for-profit division that develops commercial and industrial solar systems in addition to their community-focused development efforts. Boond continues to foster strong relationships in the communities where their microgrids are located and provides ongoing operations and maintenance services to their microgrid customers. Boond's original founder, Rustam Sengupta, has an ongoing relationship with the University of Michigan and has worked with university researchers on a variety of energy focused studies.

2. Research Methods

To understand the social and economic impacts in villages as the government grid comes online the effects on and correlations between energy access indicators and social indicators were studied. Yet, it also requires a framework for determining the causal relationships that can describe the limiting factors to economic, social and energy access growth. This study was observation-based and consisted of a cross-sectional study comparing various social characteristics against electricity access and usage. The methodology consisted of a mixed-methods approach using sequential data collection steps with the quantitative questionnaires informing the qualitative focus groups and semi-structured interviews. Quantitative survey data was collected at the household level across numerous villages to develop a baseline understanding of conditions on the ground. Following the completion of the survey portion, the results informed the design of the interview and focus group question guides. The qualitative focus groups and interviews were conducted to uncover trends in energy usage and social well-being that are applicable to communities around the world.

To comprehend the impacts and effects of the government grid expansion across rural villages in India with solar microgrids, direct access to multiple villages with both electricity sources was essential. The Boond team provided access to their solar microgrids in the Uttar Pradesh region of India and facilitated the household survey collection process and focus group interviews within the communities they serve. In this case, a village with a Boond microgrid has, on average, between 50 and 60 households but is not defined by official parameters. To understand the role of both electricity connections, our surveys and interviews were limited to only households with both government grid and microgrid connections. Boond provided access to 8 villages in which they were operating and maintaining a DC microgrid (1 kW capacity). Each selected village had also received government grid access in the past two years. Boond employees and contractors supported the survey and interview data collection process.

2.1 SURVEY DEVELOPMENT AND COLLECTION

45-minute household surveys were developed with three major sections: household demographics, energy access and usage, and social well-being. The survey instrument can be seen in the supporting information.

Energy access and usage were initially measured using the World Bank's multi-tier framework (MTF) to measure household electricity access based on a number of different metrics [30]. Such a framework has been employed in rural regions and shown to be a strong determinant of how electricity is used and the level of capacity available [31]. The framework analyzes a number of metrics across a matrix of electricity characteristics to develop a composite index for different aspects of electricity access allowing more granular analysis and comparison. This study originally sought to leverage the MTF to develop an understanding of the electricity usage at each household between both types of connections. Specifically, our survey consisted of questions focused on the "Multi-tier Matrix for Access to Household Electricity Supply" attributes of capacity, duration, reliability and health and safety. However, as described below, capacity was limited not by available capacity, but by demand for capacity. As such the metric for capacity measured in the survey is representative of each household's demand for capacity, or power demand. Power demand is measured by the total power required to operate all appliances in each household based on generic averages for common appliances. Quality and legality were not included due to known challenges and sensitivities in asking directly related questions. Affordability was excluded as payment for the government grid is inconsistent and highly variable household to household and village to village.

To quantify the social well-being of each household, indicators were developed to establish a quantifiable, comparative result across multiple dimensions. This study focuses on indicators that are applicable at the local (household) level, as it strictly focuses on household level impacts (i.e., not community-wide impacts). Many studies have developed the use of indicators in the microgrid and electricity field [13,14,15,32]. These previous studies were used as the baseline for this study before adding site-specific knowledge to develop the final list of indicators (see supporting information). The survey collects data regarding indicators including household economics, education, healthcare access, and access to modern appliances. Survey data collection occurred over a 5-month period during the summer of 2019. A research assistant associated with Boond Energy conducted 172 surveys including 149 dual-connection households and data on 881 individuals across 8 villages in Uttar Pradesh, India.

Survey data was then tested for relationships between the electricity access indicators and social well-being indicators. Spearman's correlation coefficient (r_s) was used to analyze the relationship between electricity access indicators and well-being indicators as the underlying data are not normally distributed but are assumed to have monotonic relationships. Evidence of correlations is discussed in the Results section below.

2.2 SEMI-STRUCTURED INTERVIEW DEVELOPMENT AND DATA COLLECTION

Following the completion of the quantitative survey collection, the results informed the development of the interview guide (see Results Section 3.1 for more details). The semi-structured interviews contained two focus areas: (1) the typical use cases for the government grid and microgrid and (2) the social well-being value of the government grid. The first section of the interview included questions on the timeline on the connection process, the process for obtaining the government meter and the challenges faced by the households in the process (see appendices). The objective was to identify any economically or socially biased aspects of the connection process in the village. While no evidence of a selection bias was identified in the government grid connection process, individual households were selected randomly for interviews from the pool of households with both microgrid and government grid connections. It is possible that underlying bias in the microgrid connection process exists but was not detected in our interview process. If wealthy households are more likely to receive the microgrid connection, naturally our interviews would only be with wealthier households. The second section of the interview guide focused on how and why each household uses the government grid connection and the microgrid connection. The final section of the interview guide asked direct questions regarding the socioeconomic improvements felt by households as electricity access improved and the barriers to further economic and social advancement. Electricity access and social well-being indicators were used to design and analyze the household survey data, but were not used to support the qualitative interview/focus group analysis. Instead, interviews/focus groups sought to analyze the holistic household experience rather than quantify specific metrics.

Interviews were conducted in four villages by the authors in collaboration with Boond Solar staff. Each village consisted of a single focus group with input collected from multiple households at once. The focus groups centered around section 1 of the interview guide, the potential bias in the connection process to ensure all households had equal access to grid connection obtainment. Following each focus group, 3-6 individual household interviews were conducted focused on the second and third sections of the interview guide: the use case for and social impact value of the government and microgrid connections.

In addition to interviews within the local villages, the research team conducted interviews with Boond Solar field staff throughout the field research. Input from on-the-ground staff was collected to contextualize individual interviewee responses, gather feedback on interview session structures and success. The staff also provided supporting knowledge regarding Boond Solar's business model, current operation and financial status, and ongoing innovations (see Section 5).

Upon completion of the interview process, the research team's detailed memos and notes were analyzed to determine the frequency of specific responses and commonality of topics raised across households and villages. Focus group memos and notes were analyzed to determine the major themes and common issues faced by the households.

3. Results

3.1 SURVEY ANALYSIS AND RESULTS

Survey data was analyzed to develop an understanding of the correlations between electricity access (as measured across the demand capacity and MTF indicators) and social well-being (as measured across a number of indicators related to household economics, education and appliance ownership). Initial correlation analyses found a statistically significant relationship between increases in power demand and improvements across multiple key social indicators including: household income ($r_s(147) = .224$, $p < .01$); household primary education rates ($r_s(147) = .310$, $p < .01$); the highest level of education in a household ($r_s(147) = .277$, $p < .01$); and household literacy rates ($r_s(147) = .332$, $p < .01$) (see Table 1).

Electricity availability and outage rates as measured by the MTF were not found to be correlated with any of these social indicators (see Table 1). As such, our survey data suggests that wealthier, more educated households are not able to gain access to better electricity connections than their neighbors or are not inherently granted such connections through a biased process. Further investigation, with the objective of ensuring the selection bias is not part of the initial government grid connection process and thus influencing our survey household selection process, was conducted during the focus groups in each village.

Additional social indicators measured through the survey at the household level include access to credit, frequency of health care visits, and access to modern communication and lighting/cooling appliances. Questions related to each individual in the household centered around indicators measuring: household adult employment rate, adult productive hours per day, and children evening study hours. No correlations were found between measures of energy access and the household's access to credit and maximum productive hours per day. Given the technique of measuring power demand via access to appliances in each household based on appliances owned by each household, access to communication and lighting/cooling appliances correlates with power demand; however, neither correlates with availability and reliability, suggesting a better connection does not directly lead to the purchase of additional appliances. The remaining social indicators correlate with various energy access MTF indicators, but no discernable patterns and known challenges in self-reporting certain well-being indicators make it difficult to draw specific conclusions (see Section 7, Future Work, for more on this topic).

		Household Income (exact)	Percent of Household with at least Primary Education	Highest Household Education	Household Literacy Rate
Demand Capacity	Spearman Correlation	.224*	.310*	.277*	.332*
	Significance (2-tailed)	0.006	0.000	0.001	0.000
	N	149	149	149	149
Availability	Spearman Correlation	-0.108	0.096	0.093	0.049
	Significance (2-tailed)	0.190	0.244	0.258	0.554
	N	149	149	149	149
Reliability	Spearman Correlation	0.129	0.063	0.086	-0.039
	Significance (2-tailed)	0.116	0.444	0.295	0.639
	N	149	149	149	149

*. Correlation at 0.01 (2-tailed)

Table 1. Spearman Correlation Between Electricity Access Metrics and Social Indicators

3.2 INTERVIEW ANALYSIS AND RESULTS

The first section of our interview guide focused on the government grid connection process in an effort to uncover any selection bias in our surveys and interviews, as all survey respondents and interviewees were selected based on their possession of a microgrid and government grid connection. Conducted in focus group format with multiple households at once, the results were highly consistent across all four villages studied. Government grid connections were established across the entire village in an open enrollment period. While the exact details of the enrollment process varied, including enrollment period timing and advanced knowledge of the enrollment period, access was generally available to the majority of households and no initial set-up fee was required. Thus, no evidence of a selection bias was identified. There was potential evidence of biases and bribery in the process to obtain a connection after the initial enrollment period (see Section 7, Future Work, for more on this topic).

Individual household interviews were conducted for section 2 and 3 of the interview guide. Detailed information regarding the demographics of households interviewed can be found below (Table 2). Memos from the individual household interviews were scored across key questions related to the usage of the two electricity connections and efforts to procure additional appliances after each household received the government grid connection. Such results provide insight into the frequency of situations across households. In total, 17 interviews were conducted. The results of these interviews are shown in the table below as percentages of households responding in the affirmative or negative to each question (Table 3).

Interviewee Demographics (for main respondent)		
Gender	*Male*	9 *(53%)*
	Female	8 *(47%)*
Age	*Young Adult*	1 *(6%)*
	Middle-Aged	14 *(82%)*
	Elder	2 *(2%)*
Income Levels	*≤ 5,000 INR*	8 *(47%)*
	5,001-10,000 INR	6 *(35%)*
	>10,000 INR	3 *(18%)*
Education Level	*None*	4 *(24%)*
	Primary/ Lower Secondary	7 *(41%)*
	Higher Secondary/ Undergraduate	6 *(35%)*

Table 2. Household Interviewee Demographics. Demographic data for gender and age based on the main interview respondent. Age categories based on observations of the interview team. Income levels based on household total income derived from survey. Monetary values are listed in Rupee. Throughout the paper, we will use the Indian Rupee (INR) -- United States Dollar (USD) exchange rate from 1/1/2020: 71.3356 INR = 1 USD. Education level based on head of household response during survey responses.

Interview Questions on Productive Use Appliances		
Interview Question	***Affirmative (%)***	***Negative (%)***
1. Do you plan to purchase an appliance for productive use (e.g. submersible water pump, refrigerator, cooler)?	76%	14%
2. Are you limited in your ability to purchase new appliances due to financial constraints?	88%	12%
3. Have you acquired a productive use appliance after the government grid was installed?	53%	47%
Interview Questions on Ongoing Microgrid Use		
Interview Question	***Affirmative (%)***	***Negative (%)***
4. Do you use the microgrid primarily as a source of backup power?	59%	*n/a*
5. Do you prefer to maintain both your government grid and microgrid connections?	100%	0%

Table 3. Household Interview Response Results Summary. Questions not reflected in the interview guide in supporting information were included in a majority of interviews as follow-up questions. For question 4, 41% of interviews we did not explicitly discuss the primary use of their microgrids as a source of backup power (neither affirmative nor negative) and thus their responses are not included in the table.

3.3 SYNTHESIS OF SURVEY & INTERVIEW RESULTS

Data from our survey suggests that social well-being indicators like income, education, and literacy are, in fact, correlated with power demand, defined as the true capacity a household requires to run all of its appliances. Conversely, energy quality and reliability were not found to be correlated with social well-being. Although our survey indicated a correlation between social well-being and electricity demand it is also important to note that during the semi-structured interviews and focus group sessions conducted following the initial survey, our research team found that social well-being is highly constrained by household income regardless of energy capacity. Our discussions with Boond microgrid customers showed that even after receiving a higher capacity government grid electricity source, the majority of households interviewed were not able to take advantage of their enhanced electricity capacity due to overwhelming financial constraints. Higher social well-being is correlated with increased energy demand, but not with more power available. Even if the power available increases, an individual's well-being does not increase because use of the household’s electricity use does not increase, lacking any appliances or activities to use the excess energy on.

3.4 IMPACTS OF GOVERNMENT GRID ON BOOND SOLAR REVENUE

Through interviews with the Boond Solar field staff, it was discovered that the expansion of the government grid led to a significant financial impact on Boond's business. Arrival of the government grid generally downgrades the microgrid to a backup power (emergency power) role and reduces the financial viability of a previously profitable enterprise. As microgrid use was relegated to times of backup during government grid electricity outages, Boond Solar faced mounting financial challenges. Assets were found to be underutilized, storing energy in battery packs that went unused. Boond Solar field staff estimated a 40% drop in revenue for the average system. Although Boond Solar faced significant financial effects from the government grid expansion, their underutilized microgrid assets could be freed up, creating potential opportunities to meet unmet community needs at an aggregate level.

4. Discussion

The results of our research demonstrate two key findings that will further understanding of the future use cases of solar microgrids in rural Indian communities as these communities gain government grid power connections. We refer to our two primary findings as emerging themes and will dive into them in further detail in the two following subsections:

(1) The first emerging theme of our research illuminates the ongoing need for solar developers to reimagine the use case for solar microgrid assets in communities with recent expansion of government grid power. As demand for solar microgrid power decreases in these communities, there are ongoing unmet needs at an aggregate community level that could be served by underutilized solar microgrids. Small solar developers have the opportunity and need to reimagine how their assets can be utilized at the community-level to offer services, such as cold storage for milk, that are economically difficult to address at the individual household level.

(2) Our second emerging theme underscores that energy access is not an isolated barrier to community development but rather an integral part of holistic community-focused development in tandem with economic development. Our findings indicate that while there is marginal benefit from gaining access to higher-capacity government grid connections, social well-being is not constrained by energy capacity but rather by household income and the ability to purchase appliances. There is a tipping point of energy access where the social well-being and development trajectory of communities is no longer linked to incremental energy access but is restrained by household economic constraints.

4.1 EMERGING THEME #1: MEETING UNMET COMMUNITY ENERGY NEEDS WITH UNDERUTILIZED MICROGRID ASSETS

The first emerging theme from our field-based research relates to the need to reposition the use case for solar microgrids in rural communities that have gained higher-capacity government grid connections. The government grid expansion has resulted in households using their solar microgrid connection primarily as a source of reliable backup power. In 59% of household interviews, customers directly mentioned using their solar microgrid solely as a source of backup power for when the government grid connections fail or are unavailable, often during daylight hours occurring on an irregular weekly or daily basis. However, despite using their microgrids as a source of backup power, all customers interviewed reported a desire to maintain their microgrid connection even as their government grid connection has improved from less than 12 hours/day of availability to over 16 hours/day of availability over the past 6-12 months. Customers specifically noted the reliability of the solar microgrid (i.e. to serve as backup power when the government grid is down) and their ability to charge their mobile phones and power two small light bulbs (3-watts each) as a reason to maintain a dual-connection. Additionally, customers are only charged US$4.20 (INR 300) one time for the initial connection and then Boond collects fees on a pay-as-you-use system allowing customers to maintain their connection with no maintenance fees so there is little incentive to disconnect from the solar microgrid.

While community members indicated a desire to maintain their solar microgrid connection for its reliability, they also indicated a preference for a system with higher capacity—in this case, the government grid—because of its ability to power higher wattage light bulbs and a wider range of appliances simultaneously. The lack of reliability of the government grid connection encourages customers to maintain the microgrid system connection for backup power. The key message emerging from interviews and focus group discussions with community members is that customers in rural, agricultural villages seek both reliability and capacity from their sources of power and view maintaining both connections as necessary to satisfy both of those needs.

The transition to a source of backup power has led solar microgrid utilization to steadily decline in these communities since the installation of government grids and in particular, since the improvement in the quality of service offered by government grid connections. The solar microgrids in these communities are now regularly underutilized because community members desire to maintain their microgrid connection primarily to serve as a backup source of power for the higher-capacity government grid. Boond Solar's field-based team has reported an average drop in pay-as-you-use revenue of approximately 40% in villages where government grid connections have been installed. As we began to understand customer preference and the core values customers seek from their solar microgrid and government grid connections, we widened the use case lens to identify additional opportunities for currently underutilized microgrid assets in communities. In the Conclusions Section (Section 6), we will discuss the potential future uses cases for underutilized microgrid assets in rural, agricultural communities that have recently gained higher-capacity government grid connections. In particular, we will discuss a use-case scenario in which microgrid assets may serve as a source of power for a community-based asset like cold storage or refrigeration at an aggregate level, alleviating the individual cost of acquiring productive assets and increasing utilization rates of microgrids.

4.2 EMERGING THEME #2: ENERGY ACCESS IS NOT AN ISOLATED BARRIER TO DEVELOPMENT

As a result of our semi-structured household interviews, we found that although households have added government grid connections, unlocking access to greater electrical capacity, the majority of households lack the financial resources to acquire high-power appliances such as televisions, refrigerators, and cold storage units. While access to higher-capacity energy from a government grid connection may offer the opportunity for households to acquire brighter light bulbs, refrigerators, submersible pumps, and more, we found that a household's economic position imposes a limit on their ability to take advantage of additional capacity. Providing access to greater energy capacity will not continuously improve social well-being on its own.

Demonstrating this finding, the energy demand of appliances currently owned by households in the communities is often significantly less than each government grid connection's capacity of 1 kW per meter (see Table 4). For example, taking a representative case from one of the semi-structured interviews, the household gained a government grid connection with a capacity of 1kW. Before the head of household obtained the government grid connection, they were able to power two small light bulbs (1 watt each) and a mobile phone charger with their solar microgrid. After gaining the government grid connection, the head of household was able to purchase 2 tube light bulbs (18 watt energy demand each). The head of household indicated that they would like to purchase a television and a submersible water pump (20 watt and 500 watt energy demand, respectively) but they are unable to make these purchases due to financial constraints.

The added potential household use of the higher-capacity government grid connection is underutilized because the majority of households have limited financial resources to acquire appliances with higher power demand such as refrigerators and submersible pumps. Rural communities require a more integrated or holistic approach to community development that includes opportunities to steadily and reliably increase household income in conjunction with improvements in energy access.

Power Source	*Household Connection Capacity*	*Frequent Household Appliances (W) [33]*	*System Limitations*
Solar Microgrid	30-35 W	Light bulbs (1); Phone charging (1); Fan (15)	limited by low system and HH connection capacity
Government Grid	1,000 W	Lighting tubes (18); Television (20); Air cooling (240); Water pump (500)	limited by reliability issues; usage limited by lack of HH purchasing power for productive uses

Table 4. This table provides an overview of the differences in each household electricity connection system including the capacity and reliability limitations of each system.

Energy access expansion in these communities of Uttar Pradesh and the installation of higher-capacity government grid connections confirmed and further exposed financial constraints at the household level. In 76% of our interviews, heads of household expressed their desire to acquire a television, fan, cooler, and/or water pump but were limited in their ability to purchase new appliances due to financial constraints. Of households interviewed, 88% indicated that they intend to acquire these appliances or would acquire these appliances if they had the financial means to do so because they knew that the government grid connection had sufficient capacity to power these appliances as compared to their solar microgrid connection.

Within the category of appliances, our team has defined household appliances in two primary categories: appliances for productive uses and appliances for household comfort. Appliances with productive uses are those appliances which allow members of the household to work more efficiently, produce more goods, offer additional goods or store farm goods like water buffalo milk for longer (see Table 5). Appliances that allow community members to more efficiently and effectively grow, harvest, process, and store their agricultural products are extremely important as all households we interviewed, and 60% of households surveyed rely heavily on agricultural products for their livelihoods. Appliances for household comfort include light bulbs, table fans and televisions; while light bulbs do extend working hours, the light bulb itself does not produce income for the household. Evidence from our interviews suggests that productive use appliances have a higher financial barrier to acquire but heads of household are very interested in acquiring these productive use appliances because of their potential benefits. Interviewees indicated the cost of a submersible pump for community members was approximately US$360 (INR 26000) as compared to the cost of a higher-powered light bulb or table fan (US$1 and US$17, respectively).

Type of Appliance	*Examples*	*Household Impact*	*Energy Demand (W)*	*Cost Range [34]*
Productive Use Appliances	submersible pump, refrigerator, e-rickshaw battery charger	potential impact on HH income; improving and extending crop and milk storage	Refrigeration (300); Water pump (500)	US$250-400 (INR 17800-28500)
Household Comfort Appliances	table fan, light bulb	improved household comfort during hot season, reduced strain on vision	Light bulbs (3-5); Phone charging (5); Fan (22); Lighting tubes (18); Television (20)	US$1-20 (INR 17-1430)

Table 5. There are two main tiers of appliances powered by government grid, with different costs, energy demands, and benefits.

Of 17 households interviewed, 9 had been able to acquire appliances with productive uses after the government grid connection had been installed--a promising sign that some households are able to take advantage of access to higher capacity to a certain degree. However, nearly all of the households who had acquired productive use appliances and an additional 6 households (88% combined), expressed that their acquisition of productive use appliances was limited due to household financial constraints. Based on the data from Boond Solar's customers, we posit that a household must have relatively high financial standing independent of gaining a government grid connection to acquire appliances that significantly improve income and productive hours beyond what the microgrid already provided. While household monthly income was captured during the survey stage of the research, discussing these details is somewhat taboo in the culture and adds to the uncertainty of the results. Additionally, given the cyclical nature of agricultural income in the surveyed communities, it is a challenge to accurately calculate annual household income based on monthly income at a fixed date. This remains an area for future study to affirm our hypothesis that households who have been able to acquire productive use appliances had stronger economic positions before the government grid installation.

The simple fact of offering higher-capacity energy access to rural, agricultural households does not lead to an enhanced ability to purchase appliances with productive uses in the short term. Additional community economic development must accompany, and be integrated with, expanding energy access to rural communities or else rural villages with government grid connections and significantly less consumption capacity as compared to system capacity will continue to persist.

5. Case Study: Boond Engineering and Development Pvt Ltd (Boond Solar), and Holistic Village Development Models

Boond Engineering and Development Pvt Ltd (Boond Solar) is acutely aware of the limited benefits of providing enhanced electricity access and capacity without economic development opportunities. In an effort to foster greater social well-being in the communities they work with, Boond is striving to implement holistic development products to help pair their distributed energy services with economic opportunities allowing customers to take full advantage of the electricity capacity available to them. By better understanding the potential impacts of electricity and economic development on social well-being, research can help ensure policy and energy development practices are designed to maximize potential benefits and standard of living improvements in India and other countries navigating similar energy infrastructure environments.

Our research partners at Boond Solar have initiated a new type of community-centered product that offers one example of how small and medium-sized solar development firms in emerging markets may effectively respond to the policy implications and findings outlined in this study. After seeing their microgrid clients gain access to higher-capacity energy systems, the team at Boond Solar observed that the increase in access to capacity did not yield broad or sustained impact on the household social well-being of their clients. Instead, they noticed that their clients expressed interest in acquiring productive assets that required higher system capacity (e.g. a refrigerator to store their produce before transporting it to market). However, the economic position of the household did not allow for immediate or widespread acquisition of productive appliances as greater capacity was offered. In response to these observations across the villages where Boond Solar operates, the team at Boond began to design a new type of community development product that integrates access to higher-capacity energy as well as economic development opportunities.

In 2019, Boond Solar began designing and implementing a new approach to engaging customers in rural villages, their Holistic Village Development Model (HVDM). The HVDM addresses both research themes discussed in this study by integrating community energy access with strategic economic development at the community and household levels to increase household income. The model aims to address aggregate community-level demand for productive use appliances. The Boond Solar team will install a higher-capacity (30-35 kW) solar microgrid system in a rural, agricultural village, which will power community-level appliances such as cold storage and refrigeration for crops and milk produced by community members. In response to increased government grid connections and lower utilization of Boonds 1 kW microgrid systems, Boond's new model expands the solar microgrid products offered to rural villages.

By offering aggregated access to cold storage, refrigeration or field-based irrigation systems, community members will have access to productive use appliances without experiencing the financial burden of having to purchase expensive appliances independently. As discussed in the results section above, many households are unable to acquire appliances for productive uses because of their higher cost despite having access to a government grid system with the capacity to power these appliances. As the Boond Solar team has observed this dynamic in communities, their 30-35 kW solar microgrids and accompanying appliances specifically aim to close the gap between energy capacity and household financial constraints. Boond will additionally focus on increasing household income by offering services to aggregate milk production and crops, and offering cold storage and transportation to local markets. The solar developer also plans to bring agronomists to communities to work with growers and community members to increase crop yields, implement organic farm management practices, and improve water buffalo milk production.

The Holistic Village Development Model demonstrates one potential approach that small and medium solar developers could take to effectively integrate the SDG #7, affordable and clean energy access, with UN SDG #8, decent work and economic growth. Boond's response and shift towards experimenting with the Holistic Village Development Model aligns with the field-based observations and survey data presented in this study. Looking to the future, the Holistic Village Development Model will serve as an important case study of how small and medium solar developers can effectively adapt to emerging trends and integrate energy access and community economic development to increase both household income and access to higher capacity sources of power.

6. Conclusions

Our research shows that given financial constraints and dynamics of rural households, expanding grid connections and access to capacity without an integrated economic development approach will limit the potential impact and economic opportunity for households. In the initial survey, social well-being indicators around education, income, and literacy were found to be correlated with power demand; the semi-structured field interviews and focus groups conducted with survey respondents uncovered the fact that social well-being is highly constrained by household income regardless of energy capacity. Providing access to greater energy capacity will not continuously improve social well-being on its own. The inability of the majority of households participating in this study to take full advantage of the expanded electrical capacity from the government grid demonstrates that greater energy capacity access is not a direct vehicle to improve social well-being. There is a tipping point where higher energy access does not accelerate well-being, but instead income and access to appliances requiring the extra power capacity are the limiting factor.

It is fundamentally important that energy access planning in emerging markets also integrate community-focused economic development planning to ensure that households are able to increase purchasing power to obtain the productive use appliances that are most likely to contribute to longer-term increases in financial standing. This holds true for all levels of energy access planning, from the United Nations Sustainable Development Goals to municipal planners whose policies touch economic development and energy access.

The two emerging themes we have identified from our research relate to policy and practice from the level of individual solar developers in emerging markets all the way up to macro-level policy at the United Nations . Our findings offer insight into the future of products and services that small and medium community-centric solar developers may consider offering to ensure ongoing and sustainable use of their microgrid assets as government grid connections grow around the world. These findings have relevance globally as rural communities that have been primarily served by small and medium-sized solar developers as well as low-capacity distributed energy sources like diesel generators begin to gain access to higher-capacity government grid connections. Additionally, on the national and international scale of the UN SDGs and national energy policy, the findings in this study underscore the fundamental importance of integrating energy access efforts with economic development efforts in order for communities to actually benefit from expanded energy access.

In assessing the United Nations SDG #7, evidence in their reporting and evaluations publications indicates that there are limited linkages between affordable energy access and community economic development despite that being a primary outcome of expanding energy access. Current UN SDG reporting on Goal #7 focuses on access to electricity, expansion of renewable energy, and overall capital investment in developing countries without acknowledging the link between energy access and economic development [35]. In fact, 2018 reporting on the status of Goal #7 focuses on interlinkages between Goal #13 (climate action), Goal #5 (gender equality), and Goal #11 (sustainable cities and communities), but fails to mention Goal #8 (decent work and economic growth) [36].

We recommend that energy access policy at all levels of government and international cooperation must address household and community economic development to ensure SDG #7 successfully results in new economic development, job creation, and increased social well-being. Without integrating these policies, energy consumption will continue to be less than system capacity and the economic benefit of energy access will be limited around the globe.

The policy implications and recommendations of our research focus on addressing the fact that customers seek both reliability and capacity from their electricity connections. For customers with both government grid and microgrid connections, we identified evidence that customers will use microgrids primarily as a backup source of power given the system's reliability. Customers have shifted demand to government grid connections given system capacity, leaving microgrid assets underutilized. However, heads of household opt to maintain microgrid connections for use as a source of backup power even as government grid reliability improves.

Given these findings, we believe there is an opportunity to retool and reposition existing microgrids for productive use and backup power by expanding the use case of microgrid systems in villages where assets already exist. For example, in communities with 1 kW systems that have seen a significant decline in energy demand and the assets are being significantly underutilized, one option may be retooling the microgrid to power a 500 W submersible pump, available for community use on a pay per use fee schedule. Small and medium solar developers have an opportunity to use existing microgrid assets to aggregate productive uses at the village level by offering pay per use products like refrigeration and battery charging using excess system capacity. This repositioning of the microgrid offers the developer the opportunity to increase system utilization and revenue while also alleviating the economic burden on individual households to acquire expensive appliances such as refrigerators. Additionally, for communities seeking to install additional energy infrastructure through renewable microgrids, this key finding demonstrates the importance of considering aggregate-community demand as systems are being designed. These recommendations for repositioning of solar microgrid assets reflect an integration of our two emerging themes: households are currently constrained by their economic position from acquiring appliances for productive uses and the solar microgrids are underutilized assets given the expansion of government grid connections in communities.

7. Future Work

In the course of conducting research for this project and collaborating with our research partners at Boond Solar, our team has identified a set of questions and topics that we believe merit further work that will build upon our research and findings. We have split our ideas of future work into four categories where we have unanswered questions regarding: (1) equity in the process of obtaining additional government grid connections and quality variations amongst households, (2) unexplored correlations between energy access and social well-being factors, (3) the environmental impact of expanding government grid connections where generation comes from non-renewable sources, and (4) how future models of integrated energy access and economic development can be implemented and assessed in rural communities.

Given the limitations of our time in the field, our team had insufficient time to further explore the differences in energy quality between households. During the interview process, we did not explore the differences in the quality of energy between households as these underlying differences were not found to be related to social well-being factors, and thus may have been technologically driven or a result of inconsistent household reporting. We recommend future research to explore these differences. Through the focus group discussions, we were unable to identify inequitable aspects to the process of gaining a government grid connection, although anecdotal evidence suggests such biases and challenges may exist for those attempting to add a connection after the initial electrification of the village. In the same vein of questions around energy access and justice, several households shared experiences during our interview process indicating evidence of biases and bribery in the process to obtain a connection after the initial enrollment period.

Secondly, analysis of our survey data yielded a series of additional unexplained correlations between the MTF indicators for the government grid and a number of social indicators, including: number of household health visits and grid outages ($r_s(147) = -.236$, $p < .01$), household employment rates and electricity availability ($r_s(147) = -.310$, $p < .01$), and average evening study time and grid outages ($r_s(147) = .256$, $p < .01$). While these correlations appear to be unrelated to the consistent findings described throughout this report, future studies should focus on the potential relationships between grid availability hours,outage frequency and social indicators.

Our team would also like to recommend further investigation into the environmental impact of expanding the government grid in India. While solar installations in rural communities in India rely on a renewable source for power generation, the majority of power generation for the national grid in India is derived from hydrocarbons, namely coal and natural gas [21]. Our team believes it is vital to examine the environmental implications of expanding energy access using nonrenewable energy sources and the potential negative impacts on communities through increased air pollution in the short-term and significant climate change events in the long-term.

Finally, we are recommending that future policymakers, practitioners, and solar developers explore how to integrate community economic development into expanding energy access given that households are limited by financial constraints in their ability to obtain productive use appliances. Future research should center on understanding the range of viable program models and their implementation, as well as defining metrics to measure program efficacy. We hope that our research can serve as foundational work for future academics and practitioners to continue grappling with the future of energy access in rural communities around the globe.

Appendix A. Household Survey

SECTION 1	Household Demographics
Q1.1	What is your name? This is only used for my own purposes, all of your responses will remain completely anonymous.
Q1.2	What is your gender?
Q1.3	What is your current age?
Q1.4	What is the government assigned category of your caste?
Q1.5	How many total people usually live in the household, including yourself?
Q1.6	For each member of your household we are going to ask a number of questions about them and their education.
Q1.6.a	What is the age and gender of each member of your household?
Q1.6.b	What is the highest level of education received for each member including yourself?
Q1.6.c	Which members of your household can read a newspaper, including yourself?

SECTION 2	Energy Access
Q2.1	Do you currently use both your Boond electricity connection and your government electricity connection?
Clarification	if not both, why do you only use one of your connects?
Q2.2	How long have you been using the connection to Boond electricity?
Q2.3	How many hours per day do you use Boond's electricity?
Q2.4	How many hours during the night do you use Boond electricity?
Q2.5	At what hours of the day is your Boond connection typically available?
Q2.6	How reliable do you find your Boond connection? On a scale of 1-5 how reliable do you find the electricity connection, with 1 being totally unreliable to 5 being very reliable?
Q2.7	How often does your Boond electricity connection get disrupted per week (average number of times)?
Q2.8	For the Boond connection, when your connection does cut out, how long on average until it turns back on?
Q2.9	How long have you had the government connection?

Q2.10	Do you have a metered or fixed connection with your government electricity?
Q2.11	How many hours per day do you use your government connection?
Q2.12	How many hours during the night do you use government electricity?
Q2.13	At what hours of the day is your government connection typically available?
Q2.14	How reliable do you find your government connection? On a scale of 1-5 how reliable to do you find the electricity connection, with 1 being totally unreliable to 5 being very reliable?
Q2.15	How often does your government electricity connection get disrupted per week?
Q2.16	For the government connection, when your connection does cut out, how long on average until it turns back on?
Q2.17	How many hours do you would you like electricity per day?
Q2.18	Have you had an accidents or safety issues with your electricity connections in the past? If yes, please describe and with which connection?
Q2.19	Do you prefer using your government connected electricity or your Boond connected electricity?
Q2.20	On a scale of 1 to 5, with 1 being the worst to 5 being the best, how happy are you with your electricity connection?
SECTION 3	**Household Economic Questions**
Q3.1	What is your monthly household income from all sources, including farming, remittances, government support (Rupees)?
Q3.2	What is the primary occupation of the head of household?
Clarification	What are other occupations of the head of household?
Q3.2.b	What is the total monthly income provided by the head of household?
Q3.3	For other household members regularly contributing income: what is their occupation? What is their monthly income?
Q.3.4	Do any members of the household work within the home?
Clarification	Does the work require the use of electricity? What type of appliance or machinery is used for the work?
Q3.5	Does your household receive other sources of income outside of your occupation?
Q.3.6	Approximately how much money does your household spend on electricity per month?
Q.3.6.a	How often do you pay for electricity from the grid?

Q.3.6.b	How often do you add credit to your microgrid electricity account?
Clarification	How much money do you usually add to your account each time?
Q3.7	Do you have access to credit from any source, including microfinance (ROSCAs, Chit Funds, DWARCA), family or friends, employer, landlord, commercial bank, or agriculture cooperative?
SECTION 4	**Sociocultural Questions**
Q4.1	In the past 12 months, how often have you gone to the health clinic?
Clarification	Why have you not visited the clinic?
Q4.2	Where does the water you use to cook and drink come from?
Q4.3	Do you have a water pump for use in your home?
Clarification	What is the source of power?
Q4.4	Do you have an irrigation pump to use on your land/farm?
Clarification	What is the source of power?
Q4.5	Which of the following appliances do you own in your household? What is the source of power? How many do you own and how many hours do you use it per day? Radio Television Gas stove Kerosene stove Microwave Refrigerator Fan Light bulbs Washer Computer Electricity generator Cell phone Internet TV programs/media
Q4.6	For your microgrid powered appliances, what is the largest set of appliances you are able to run at the same time?
Q4.7	For your government powered appliances (grid connected), what is the largest set of appliances you are able to run at the same time?
Q4.8	Do you or your family members attend community events after sunset?
Clarification	What kinds of events do you attend in your community after sunset?

Appendix B. Field-Based Interview Guide

SECTION 1	**Grid Connection Process**
Q1.1	When did you obtain your government electricity grid connection?
Q1.2	What steps did you have to take to get the connection installed at your household? Who in your household was in charge of the process?
Q1.2.a	Was there an open registration period?
Q1.2.b	What is the government assigned category of your caste?
Q1.2.c	Had this service been previously offered or available in your community?
Q1.3	What type of documentation did you need to register for government electricity?
Q1.4	How did you learn about the opportunity to connect to the government grid?
Q1.4.a	Who did you communicate about the connection set-up with?
Q1.4.b	When did you first learn about the government grid opportunity?
Q1.5	What were the most difficult aspects of the process? Was there anything you struggled to complete or were unable to complete?
SECTION 2	**Connection Expectations v. Reality**
Q2.1	What information was communicated to you when the government grid connection was being installed in your village?
Q2.1.a	Was anything promised regarding the reliability of the government grid power?
Q2.2	Why did you want the government grid in addition to your MG connection?
Q2.3	What lights or appliances did you expect to be able to power with the government grid connection?
Q2.3.a	How does that compare to reality today?
Q2.3.b	*[HH only]* Do you have any new appliances that you are only able to power with the GG?
Q2.3.c	*[HH only]* Do you plan to buy additional appliances in the near future? Why or why not?
Q2.4	Is the government grid more or less reliable compared to what was promised when it was being set up in your village?
Q2.5	Do you notice any difference between the quality of your government grid electricity and others in your village?

Q2.5.a	Why do you believe the quality of the connections in your village differ?
Q2.5.b	*[Group]* Raise your hand if your connection is better than your neighbors? Worse than your neighbors?
SECTION 3	**Microgrid v. Government Grid**
Q3.1	Overall, do you prefer your MG or GG connection? Why?

SECTION 4	**Other Questions**
Q4.1	What changes have you felt since your received your government grid connection either in your household or in your occupation?
Q4.2	Have you or your community used either energy sources for productive means? Farming, industry, etc.

[HH] – questions asked during individual household interviews only
[Group] – questions asked during focus groups only

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