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A Capabilities-Led Approach to Assessing Technological Solutions for a Rural Community

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Abstract: To improve access to affordable, reliable and sustainable energy in rural areas of the global south, off-grid systems using renewable generation and energy storage are often proposed. However, solution design is often technology-driven, with insufficient consideration of social and cultural contexts. This leads to a risk of unintended consequences and inappropriate systems that do not meet local needs. To address this problem, this paper describes the application of a capabilities-led approach to understanding a community's multi-dimensional energy poverty and assessing their needs as they see them, in order to better design suitable technological interventions. Data were collected in Tlamacazapa, Mexico, through site visits and focus groups with men and women. These revealed the ways in which constrained energy services undermined essential capabilities, including relating to health, safety, relationships and earning a living, and highlighted the specific ways in which improved energy services, such as lighting, cooking and mechanical power could improve capabilities in the specific context of Tlamacazapa. Based on these findings, we propose some potential technological interventions to address these needs. The case study offers an illustration of an assessment method that could be deployed in a variety of contexts to inform the design of appropriate technological interventions.

Keywords: capabilities approach; wellbeing; energy services; energy storage; solar; renewable energy; energy poverty; Mexico

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1. Introduction

The United Nation's Sustainable Development Goal (SDG) 7 is to "ensure access to affordable, reliable, sustainable and modern energy for all", which is particularly important for rural communities in low-income countries that typically have limited access to energy. International and national initiatives have been dedicated to transferring clean-energy technologies and knowledge to low-to-middle income countries, including the International Energy Agency, Mission Innovation and the UK's Global Challenges Research Fund.

The emergence of low-cost solar photovoltaic (PV) has provided a potential solution for affordable and clean energy access in rural communities, with global off-grid solar PV generation globally increasing from 73 GWh in 2000 to 5170 GWh in 2018 [1]. To balance the variable supply of renewable resources with user demand, energy storage (ES) has been recognized as an important element and is being promoted for off-grid applications, including through the World Bank's Energy Storage Programme, which is committing $1 bn for battery storage in low and middle-income countries [2]. However, technology-driven solutions risk negative impacts if the technology is inappropriate and unsupported. At best, it may be unused or operate with reduced performance [3,4], at worst it can have a harmful environmental impact if discarded as waste [5]. To avoid such unintended consequences, interventions to provide clean energy should meet the needs of people from their own perspectives, through co-developed solutions. The needs-driven approach and consideration of social impact have often been lacking [6].

The aim of the paper is to develop an interdisciplinary approach for understanding the energy service needs of rural communities, such that appropriate technological interventions can be developed in partnerships between local and international stakeholders. The paper focuses on a case study of a rural community in Tlamacazapa, Mexico, where our project objective was to investigate the potential for relieving energy poverty and aiding development through the deployment of renewable and ES technology. We approached the assessment of energy poverty and energy needs through a capabilities framework [7], an approach growing in popularity that connects the demand for energy to multi-dimensional wellbeing and human development, taking into account the specific social and economic context. The capabilities approach has recently been applied to assess the impact of energy projects at different scales in low and middle income countries [8–13], for instance, Velasco-Herrejon and Bauwens [9] used it to assess community acceptance of utility scale wind energy in Mexico, and Fernández-Baldor et al. [10] used the approach to assess renewable energy-based electrification projects in Cajamarca, Peru. These studies have shown that using the capabilities approach as the assessment framework reveals a wider set of impacts and outcomes than conventional approaches, can reveal unequal impacts, and that it is valuable in understanding the perspective of individuals and communities themselves [8,10]. However, to date, the approach has not been used as a starting point to understand local people's needs a priori, before discussing and designing potential energy interventions for specific communities. We argue that it is crucial to understand the communities' current status of capabilities, and their perceived needs, as the baseline for discussing and selecting the type of energy projects that will most benefit them. In our study, we consulted with a cross section of the case study community, with attention to age and gender, to understand the relationship between their capabilities and energy services in their day-to-day lives, and their ambitions for their development. Following this, renewable energy and ES technology options to meet their priorities were assessed.

The paper is organized as follows: Section 2 introduces the background of the case study village. The capabilities approach, data collection and methods are described in Section 3. Key findings on the link between capabilities and energy services in Tlamacazapa are presented in Section 4. That is followed by Section 5, which discusses potential renewable projects and ES technology options to deliver the energy services needed in Tlamacazapa. An overall discussion and conclusions are drawn in Section 6.

2. Background of the Case Study Area

This section introduces the general background information of the case study area of Tlamacazapa as context to the subsequent sections. Tlamacazapa is a typical rural community in the arid mountains of Mexico, located towards the north of the state of Guerrero, approximately 170 km south of Mexico City. Of the 1114 households (88%), 982 have electricity (from the national grid), but the electricity supply is unstable and expensive relative to income levels [14]. Among all households, in 2018, only two had a computer, 12 had a washing machine and 686 had a television [14]. The secondary school does not have a connection to the electricity network, despite its close proximity to power lines.

Tlamacazapa's population in 2018 was approximately 5460, with 51.8% female; 39.7% were children or minors and 60.3% adults, with 9.9% of the total population over 60 years old [14]. There are three neighborhoods in Tlamacazapa—San Lucas (19% of the population), San Juan (25%) and Santiago (56%) [15]. The Indigenous culture is very important in the village, with 47.4% of the population classed as Indigenous [14]. A majority of the population of Tlamacazapa earn below the national minimum wage [16]. To make a living, many households in the village are dedicated to making handicrafts using palm leaves, which are sold in towns in the region.

The level of education in the community is extremely low. Of the adult population in 2018, 61.7% were recorded as illiterate and 61.3% had never attended school; only 4.8% had completed basic education and 19 people had a post-basic education [14]. The schools in Tlamacazapa include two kindergartens, two primary schools and one secondary school, which currently serve around 60% of school-aged children in the communities; the other 40% of school-aged children are unable to attend school due to poverty, school costs and lack of capacity [15].

The town also has limited access to drinking water and no sewer system or sanitation. The water supplies include small lakes or ponds on the perimeter, which are highly contaminated with animal waste and other pollutants [15], and five open water holes or natural wells within the town, offering access to groundwater that is limited in the dry season, and also contaminated with heavy metals [15]. The water contamination has caused serious long-term health effects in the community [17]. Groundwater is also pumped from sources several kilometers away, available on an intermittent basis due to the limited supply and pumping capacity. The sustainability of the groundwater supply and the extent to which it would support a much higher level of extraction is uncertain without further investigation. Pumped water costs each household around US$ 6.75 per month; this had risen steeply recently due to the increased cost of electricity for pumping.

3. Materials and Methods

3.1. Capabilities Approach

The first stage in our project was to understand the nature of energy poverty and energy needs in Tlamacazapa to form the baseline for selecting suitable energy projects, and to do this we took a capabilities-led approach [7,8,18]. Using the concepts of capabilities and functioning from the work of Amartya Sen and Martha Nussbaum [19–21], this approach links energy demand with the pursuit of capabilities, which are defined as the opportunity to engage in valued 'beings and doings' [19] (p. 40) (and where functionings are the active engagement in these beings and doings). Energy poverty in this approach is understood as an inability to realize essential capabilities as a direct or indirect result of a lack of access to safe, affordable and reliable energy services [7]. We chose this approach over alternatives such as focusing on the affordability of energy, access to clean energy, or the achievement of basic energy services, all of which are alternative approaches to assessing energy poverty, because of the capability approach's better focus on the diverse wellbeing and development outcomes that energy and energy services are needed for [8,10,13].

Building on the earlier work of Day et al. [7], we made use of a distinction between basic and secondary capabilities. Basic capabilities refer to the most fundamental dimensions of wellbeing, for example, the capability to maintain good health. Secondary capabilities are the ability to engage in the 'beings and doings' that, in a given specific context, are deemed necessary to achieve the basic capability. For example, secondary capabilities necessary to achieve good health may include being able to take exercise; obtain, prepare and consume nutritious food; and access healthcare at a clinic or hospital. It is these secondary capabilities (or functionings) that often involve the consumption of energy services, and ultimately create demand for energy. Crucially, whilst basic capabilities are fundamental across societies, secondary capabilities are much more specific to local culture and context.

Figure 1 shows the framework used in this paper to conceptualize the relationship between basic and secondary capabilities, energy services and energy.

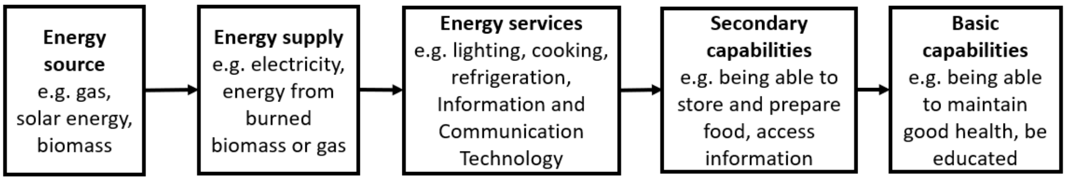

Figure 1. Relationship between energy and capabilities [7].

We used this conceptual framework to structure the way that we explored energy needs in Tlamacazapa, so that at the next stage we could design appropriate interventions. Specifically, we wanted to know how community members felt that their current energy situation constrained their essential (basic) capabilities, and how they thought that improved energy services could expand their essential capabilities, in both cases by understanding and charting the relevant intervening secondary capabilities. In order to do this, we needed to discuss basic capabilities, and our reference point for this was Nussbaum's list of 'central capabilities' [21] (pp. 33–34). This is a list of 10 broad, non-overlapping capabilities, theoretically derived, which are intended to cover the irreducible, non-overlapping basic dimensions of a life of dignity that would allow an individual to flourish. An alternative approach (more in line with Sen's perspective) would be for the basic capabilities in question to also be established through in situ discussion and deliberation. In this project, we decided to take a defined set of basic capabilities as a starting point, in order to limit demands on participants, and in order to focus the discussion on the necessary secondary capabilities and energy services. However, we acknowledge that there is a debate over the potential paternalism of Nussbaum's list [22], and future work might usefully devote more time to working with participants to establish an agreed set of basic capabilities, in a participatory way.

3.2. Data Collection and Analysis Methods

To understand the relationships between energy services and capabilities in Tlamacazapa, four focus groups, arranged by age and gender (older men; older women; younger men and younger women), were organized and carried out to discuss the issues. The arrangement by age and gender was for two reasons: first, the relationships between energy services and secondary and basic capabilities are likely to vary according to gender [10] and generation; and second, to allow free discussion, recognizing that this might be inhibited for some in mixed-gender or mixed-age groups. Taking care to cover all three sub-villages/neighborhoods of Tlamacazapa, purposive sampling was used to invite participants to the appropriate group discussion meeting, aiming for groups of 6–10. In practice, group sizes ranged from 5 to 15 and there was some overlap between the age ranges (but not gender) of those who attended the groups. The discussions took place in a central community building where drinks and snacks were provided. Participants were verbally informed of the purpose of the discussion when invited, and again before the discussion commenced; anonymity and the voluntary nature of participation were stressed. Facilitators from INEEL were matched to the group, (i.e., a younger female facilitator for the younger women's group, etc.), and assisted by Mexican team members to write the main points on wall charts. At the end of the discussion, participants were thanked with a gift of a small rechargeable torch. This gift was not announced at the time of recruitment, and so did not act as an incentive.

The topic guide for the focus groups was developed by the research team and based around Nussbaum's central capabilities. From Nussbaum's list, we selected seven basic capabilities for discussion that we felt, in the local context, could most clearly require energy use for their realization. Nussbaum's list of ten central (basic) capabilities and the selected seven capabilities for our project are shown in Table 1. As these basic capabilities are quite broad and sometimes abstract, to facilitate discussion, we put some of these into more concrete terms. The list of basic capabilities discussed in focus groups included bodily health (e.g., cooking, food and water supply, healthcare and space cooling), bodily integrity (e.g., safety and movement), senses/imagination/thought (e.g., education and religious practice), affiliation (e.g., relationships with relatives and friends, dignity and self-respect), other species (e.g., relationships with animals and nature), play (e.g., recreation), and control over one's environment (e.g., earning a living). Political participation (as another dimension of control over one's environment) was also considered for discussion, but, on the advice of Mexican team members, was felt to be too sensitive at that time. While 'earning a living' is not precisely one of Nussbaum's central capabilities, 'being able to work as a human being' is covered by 'control over one's environment', and from preliminary knowledge of the community, we were aware that earning opportunities would likely be a core development concern; therefore, we included it.

Table 1. Selection of basic capabilities for focus group discussion.

Nussbaum's List of Central Capabilities [21]	Capabilities Selected for Discussion in Relation to Energy Use
Life (being able to live to the end of a human life of normal length)	
Bodily health (being able to have good health)	Discussed in relation to clean air and water, nutrition, healthcare and sleep
Bodily integrity (being able to move freely from place to place)	Discussed in relation to safety and safe movement
Senses, imagination, and thought (being able to use the senses, to imagine and think)	Discussed in relation to education and religious practice
Emotions (being able to have attachments to things and people)	
Practical reason (being able to form a conception of the good)	
Affiliation (being able to live with and toward others; having the social bases of self-respect)	Discussed in relation to relationships with relatives and friends; dignity and self-respect
Other species (being able to live with concern for other species)	Discussed in relation to relationships with animals and nature
Play (being able to laugh and play)	Discussed in relation to recreation
Control over one's environment (being able to work as a human; being able to participate effectively in political choices)	Discussed in relation to earning a living. Political participation excluded as too sensitive.

The focus group discussions first covered how energy currently links with people's lives in ways related to the basic capabilities; and second, if they had more energy, how they would like to improve those areas. The discussions were open and informal. They proceeded well, although we noticed that we sometimes needed to put the more abstract capabilities into more specific terms. Participants voluntarily discussed both their own perspectives and community needs, thus covering both individual and collective capabilities. At the end of the session, participants were also asked which areas they would prioritize for any future improvements.

The focus group discussions were recorded with consent, later transcribed into Spanish and also translated into English for analysis across the research team. Qualitative thematic coding and analysis were carried out by the research team using the software NVivo, and was structured around themes relating to basic and secondary capabilities. The aim of the coding and analysis was to (i) understand how the local community's current energy situation constrained their basic capabilities, where appropriate by understanding the secondary capabilities involved, and (ii) following that, to understand how they would most like to direct any improved energy resource, to improve their essential basic capabilities via secondary capabilities and energy services. To put it another way, we were interested in the nature of the energy poverty, in capabilities terms, and hence in how their energy poverty could best be relieved through the improvement of their energy resources.

4. Results from the Focus Groups

This section presents and analyses of how each basic capability discussed in the focus groups was related by participants to energy services via secondary capabilities (i.e., what people do in everyday life). To summarize and visualize these relationships, we use diagrams to show the identified links across basic capabilities, secondary capabilities and energy services; the boxes and arrows show the connections that participants made during the focus groups. Traffic light colors for the arrows indicate the current state of the connection between the different elements of the diagram: green indicates that the connection is currently secure or good; amber indicates that the connection is there to some extent, but needs to improve; and red indicates that the connection is severely constrained. The diagrams represent a summary across all groups, which is possible as there were no contradictions between groups, but in the subsections below, we note some of the differences in emphasis between the focus groups.

4.1. Health

The basic capability of achieving and maintaining good health was one of the most discussed in the focus groups. In terms of how this was connected with energy, there was a specific discussion around cooking fuel and its impact on health. This discussion happened in all groups, but was longer and more detailed in the older women's group (which also contained some younger married women). All participants reported that routine use of firewood for cooking and water heating in households, and they discussed how this negatively affected women's health due to the smoke produced indoors.

> *"Over the passing of time, the smoke is harmful to our health, because when we light the firewood we inhale the smoke, if we are near it and we are breathing it. It doesn't affect you at first, but through time it damages our lungs and our eyes."*
>
> (Younger women's group)

Breathing clean air is then a secondary capability that is necessary for the basic capability of good health, as indicated in Figure 2. Currently, the means of cooking severely interferes with this secondary capability, hence this arrow is colored red, and this is a strong constraint on health, so the arrow between breathing clean air and the basic capability is also red.

A second major theme of discussion in connection with health was the community's water supplies, which are highly problematic in terms of quality and availability. Women walk to the nearby wells and carry the water to their homes for household use, including sometimes cooking, but generally not drinking, even though they are aware that these supplies are contaminated. Some people said they would use chlorine tablets to sterilize this water. The ponds are used for laundry and bathing. Participants in the younger male group believed that water from the tap is contaminated and avoid it for drinking. Due to the limited supply of pumped water, most households purchased water in containers for cooking and drinking, delivered by road transport every few days. Many people also bought bottled water from shops for drinking, but not all households could afford this.

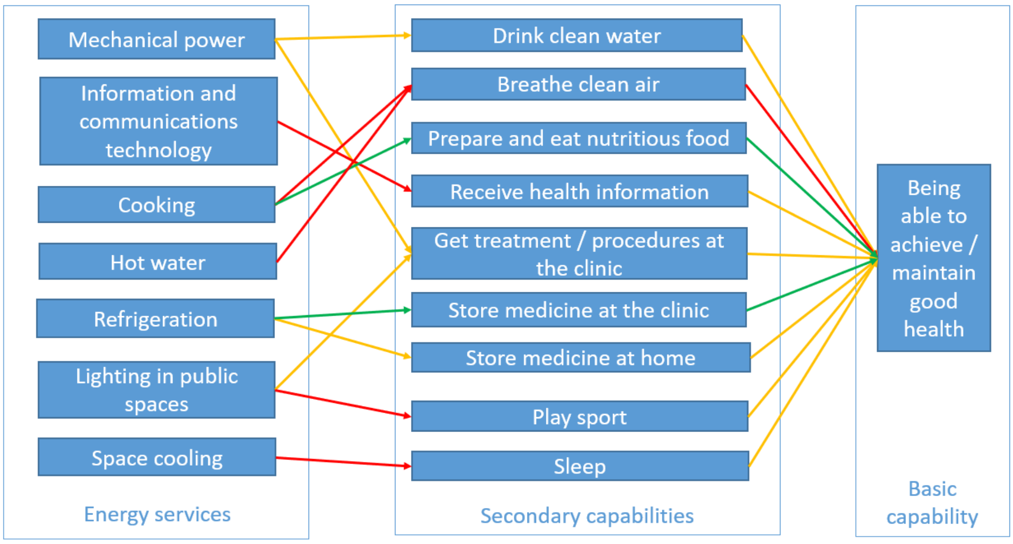

Figure 2. Connections between energy services, secondary capabilities and the ability to maintain good health.

The supply of electricity is a limiting factor (although potentially not the only one) on more frequent supplies of pumped water. The focus group participants therefore felt that, with improved energy resources, they would increase water pumping to improve their supply of cleaner water, rather than use water from the wells.

> *"When there is no water, even the dishes are washed with [water from the wells]. And because the wells are in open places, the wells are contaminated . . . [The animals] do their needs. We step on them and we contaminate the water without wanting to. If we had energy, all that could be avoided."*
>
> (Younger men's group)

A further identified energy service need in relation to health was refrigeration in order to be able to store medicines at home (secondary capability). Refrigeration for food was not felt to be a need, as generally food was bought regularly from local markets. Diabetes is at high rates in the community and many households needed to store medicine in a cold environment. Anecdotally, the lack of drinking water in the village leads to a high consumption of sugary/fizzy drinks, which in turn contributes to diabetes. As most did not have access to a fridge, they often used an insulated flask with ice, which they had to buy.

> *"I had a brother who suffered diabetes and had to take his insulin, he had to buy his ice and keep it in a thermos, so that the ice lasted at least 2 days."*
>
> (Younger men's group)

The town health clinic does have a refrigerator for medicines, but limited and unreliable power supplies limit its capacity. With more energy, participants suggested that the health center would be able to improve its services by offering electronic health information such as videos, and also some procedures that required appliances, and to do lab work. Additionally, in relation to accessing healthcare, people felt a lack of street lighting made it difficult for them to attend the clinic or find a doctor after dark.

> *"In an emergency, we are afraid to go out at night, because it's dark and we feel as if something or someone is there."*
>
> (Younger women's group)

> *"[The health centre] do not have [enough energy]. There are times when electric power goes almost 12 h, in rainy season we suffer more energy [cuts] throughout the town. The health centre suffers the consequences."*
>
> (Older men's group)

Being able to play sport was also identified as important for maintaining good health, especially for children and young people. It was mentioned more than once that, with lighting, there would be more opportunity to use sports and play areas in free evenings.

Finally, with regard to health, though less discussed than other aspects, a connection was made between a lack of space cooling, quality of sleep and health, but also education as it was mentioned that a lack of sleep interfered with school attendance and concentration. Some households used electric fans during hot weather, but only to a limited degree due to the cost.

4.2. Safety and Security

Participants across all four focus groups highlighted the main safety issue for people in the village as walking outside after dark, because of the lack of street lighting. This led to other restrictions, such as visiting relatives and friends, going to the doctor, or practicing sports, as described in Section 4.1. Due to the lack of public lighting, there is a general expectation that households will leave an external light on in their backyard to help light the streets, but few people did this in practice due to the cost.

> *"It generates a problem of insecurity because it is dark. You do not know at what moment an animal or someone who is dedicated to making [trouble] is going to come out, or what is going to throw you".*
>
> (Younger men's group)

A further safety issue that was raised, by the female focus group participants only, was firewood collection, especially during rainy weather, when they explained that there was a high danger of slipping and falling. Along with cooking, collecting firewood was women's work, hence this was a relationship between energy services (cooking) and capabilities that were largely gender specific (Figure 3).

> *"When it's the rainy season we can't go because it's too wet, and the road it's pretty bad, and we can fall, so that's why we don't go out to get [the firewood]."*
>
> (Younger women's group)

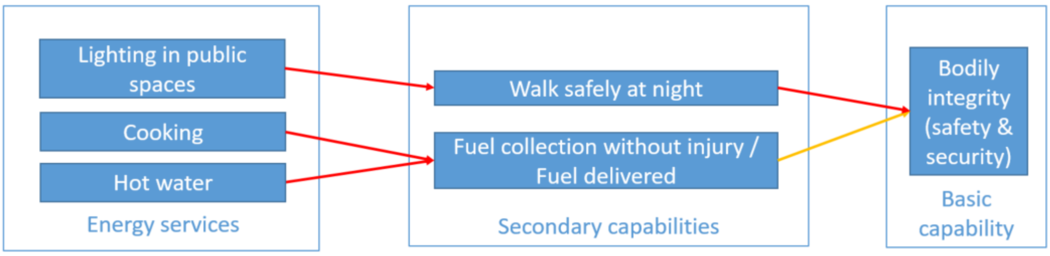

Figure 3. Connections made between energy services, secondary capabilities and bodily integrity.

4.3. Making a Living

Making a living is not explicitly listed on Nussbaum's list of central capabilities, although employment rights are covered under her 'control over one's environment' capability (part B: material). We included this topic for discussion in focus groups, here because of prior knowledge that this would be considered a pressing development-related need in the town. As introduced in Section 1, an important source of income for people in Tlamacazapa is making and selling palm-based handicrafts.

Focus group participants explained that productivity is limited by a lack of affordable home lighting in the evenings, and also to some extent by the availability of hot water, which is needed for the dyeing process. Ideally, participants explained that they would like to be able to power sewing machines to increase their output and to be able to make more standardized products that are required to sell to large retailers. They also suggested that young people could benefit from being trained in workshops if mechanical power and machines were available (Figure 4).

> *"If we had energy, we would be better and could compete with several states to be the best in the commercialization . . . for example, machine products and that all have to be of the same size. In our case, we cannot compete and we cannot sell to large companies like Wal-Mart, for example . . . if you take to Wal-Mart a thousand pieces and 300 of one size, 200 of another size and the rest of other sizes, they return the merchandise . . . because everything that is made by hand, it will never be the same, and what is done by machine is the same."*
>
> (Younger men's group)

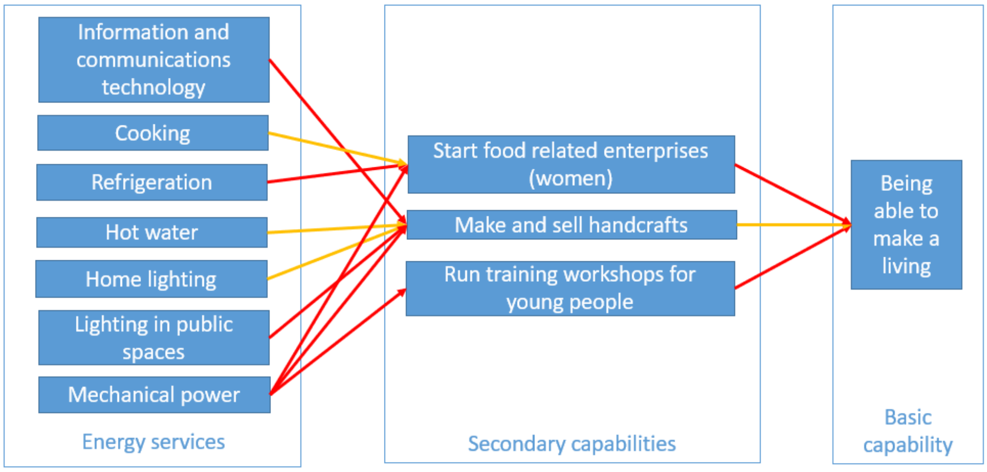

Figure 4. Connections between energy services, secondary capabilities and the ability to make a living.

Furthermore, they also argued that the lack of public lighting in the town limited their opportunities to sell products of various kinds locally, and suggested that a lit market would be good for the local economy.

> *"The space where they sell, for example, everything we consume closes early because they do not have lighting, like the market, . . . the little square. If there were energy . . . they would close later because they have power. Because where they sell their products, . . . they do not have lighting due to lack of energy."*
>
> (Younger men's group)

Some of the participants of the men's focus groups also highlighted that lacking Internet and computer technology has restricted them from exploring and contacting potential business customers (Figure 4).

Some female participants explained that they would like to start food-related enterprises, such as selling ice cream, but they lack relevant appliances and could not pay the electricity costs of running them.

> *"Sometimes, due to lack of energy, we do not have internet. [. . .] If we had internet, we were connected with all the people and in this way, we promote everything that is done here so that it could be commercialized, so that people could somehow sell their products."*
>
> (Younger men's group)

> *"And if we want to open a business, we would have to use lots of appliances."*
>
> (Younger women's group)

4.4. Education and Religious Practice

Education and religious practice were discussed in relation to Nussbaum's central capability of 'senses, imagination and thought'. For young people in Tlamacazapa, both learning at school and doing homework at home were restricted due to a lack of energy services. The schools in Tlamacazapa had no electrical connection to the grid at the time of the focus groups, therefore no lighting or ability to connect information and communication technologies (ICT). Lighting at home for doing homework is also restricted due to the high cost of electricity. Older school students used mobile phones for study to some extent, but were limited by charging costs, data costs and power cuts (Figure 5).

"It affects us because as you say, to do homework we have to be there with a candle."

(Younger men's group)

"On the cell phone we have PDF virtual books and then, [the electricity cut] sometimes prevents our learning . . . we cannot see the virtual book and we delay in learning."

(Younger men's group)

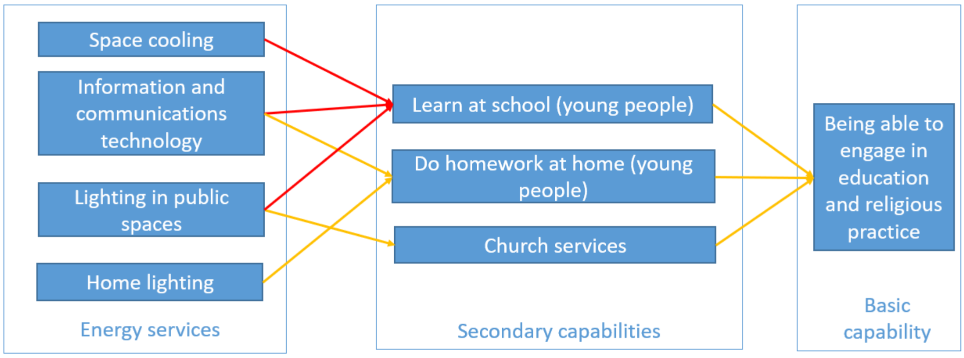

Figure 5. Connections made between energy services, secondary capabilities, and education and religious practice.

With regard to religious practice, each neighborhood (San Lucas, San Juan and Santiago) has its own church. The lighting in churches is limited for affordability reasons, thus restricting people's engagement in activities carried out there (Figure 5).

"In the churches, they also limit themselves lighting up the lights they have because then the bills are very expensive. And in the three churches and in the other churches that are in the community, the courtyards are dark in the evenings because of the lack of energy."

(Younger men's group)

4.5. Relationships with Others

'Affiliation' is one of Nussbaum's central capabilities that involve maintaining meaningful and good quality relationships with others, such as relatives, friends and neighbours. As described in Section 4.2, focus group participants said that the lack of street lighting restricted people from visiting others in the evenings due to safety concerns.

"Sometimes when we go to the hill to get the firewood, we do other chores, and then at night if we had more light we could go visit my dad, for example. I live around here, and my dad lives on the other side of town and is a little far . . . we can't go out because of the same thing. It is too dark".

(Older women's group)

People in Tlamacazapa also struggle with getting in touch with distant family and friends due to charging costs (as described in Section 4.4 above) and poor cell-phone coverage, which was ascribed to the positioning of antennas to be near the electricity infrastructure.

"Obviously the antenna needs to be there due to lack of energy, where there is signal, there are wires. [If] we had energy, we could move [the antenna] to another place . . . but for lack of energy it has to be there, because if we move it higher or lower, there are no electricity cables."

(Younger men's group)

The lack of ICT has not only constrained people from making phone contacts, but also from engaging in social media for networking, especially among young people.

Apart from worship, the churches are the focus of social activities in the town, with gatherings taking place in the grounds, generally involving food and music. Electricity costs and outages affect both music and communal cooking—electric blenders being necessary for production of local style food in large amounts—despite firewood being the main cooking fuel. Figure 6 depicts these relationships between energy services, secondary capabilities and maintaining relationships.

> *"Here we celebrate the day of the dead and we make a gathering, and we could not make it because the electricity went off. Everyone was disappointed. Some had to blend the salsa, and here we grind the nixtamal with electricity."*
>
> (Older women's group)

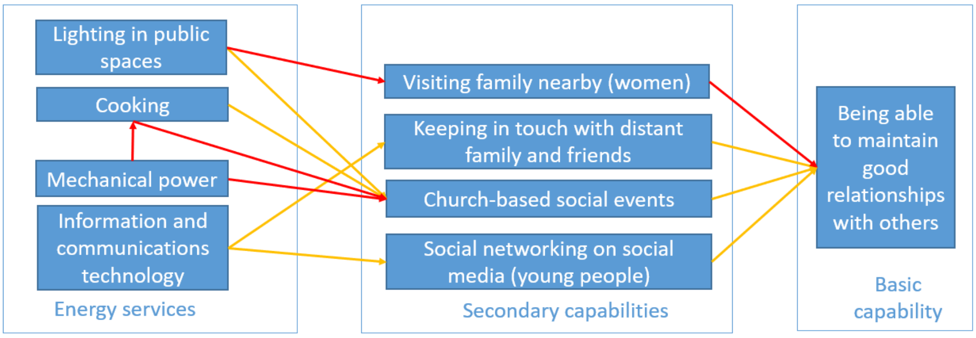

Figure 6. Connections between energy services, secondary capabilities, and ability to maintain relationships.

A further aspect of affiliation, according to Nussbaum's definition of this capability, is the ability to maintain dignity and social respect. In Tlamacazapa, guided by the Mexican team members, we discussed this in terms of personal cleanliness — washing and laundry. Bathing, washing clothes and ironing were all brought up by participants as limited by the lack of clean (pumped) water, the limited ability to heat water, and the lack of mechanical power and appliances at home. They would have liked the ability to do all of these things more (Figure 7).

> *"Here, in my case, we are six people in the house, and I have to reuse the clothes so that I don't have to wash too often. When there is a water shortage we go to the hill and there is a lagoon, despite it is very dirty, we wash them there."*
>
> (Older women's group)

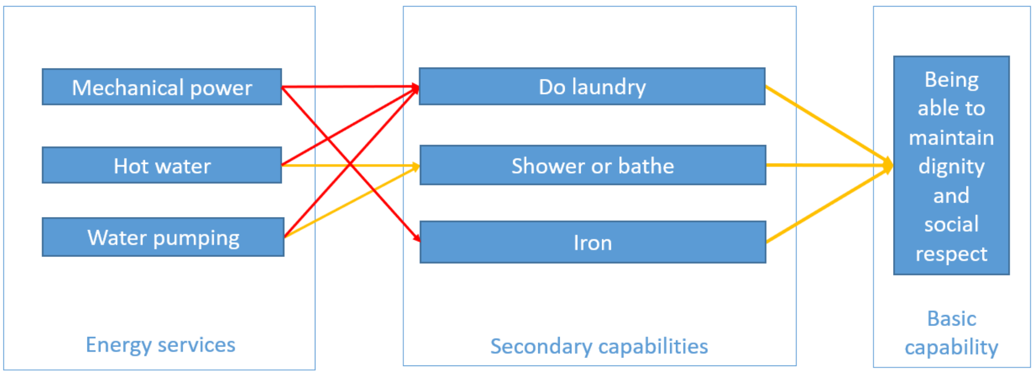

Figure 7. Connections between energy services, secondary capabilities, and ability to maintain dignity and social respect.

4.6. Other Basic Capabilities

Relationships with the environment and other species (Nussbaum's 'other species' central capability), as well as recreational activities (the 'play' central capability) were also discussed at the focus groups. In terms of the environment and other species, participants commented that using less firewood would benefit local forests (Figure 8), although women commented that they only collected dried firewood rather than cutting live trees. In addition, participants highlighted that having more pumped water would also allow people to grow plants and raise animals, which would have the added benefit of giving earning opportunities, or reducing their shopping expenses.

"If there was an opportunity with the electric light we would no longer use the wood. That would prevent cutting of the trees, and with that we would avoid deforestation."

(Younger men's group)

"If we had energy, we would also use it for example, doing planting grounds in the houses because we would already have water, to plant everything that we consume. For example, radishes, onions, chilies, would be planted with pumping water, because we have energy."

(Younger men's group)

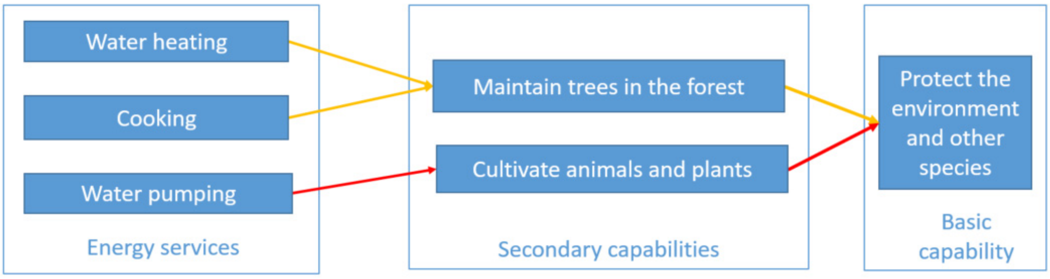

Figure 8. Relationships between energy services, secondary capabilities, and being able to live well towards other species.

Out of all the basic capabilities discussed at the focus groups, recreation is the lowest priority for people in Tlamacazapa, as they had little free time after making a living and other chores. They listen to the radio, but ideally, with greater availability of electricity, they would like to be able to watch TV more. As already discussed, they felt that public lighting would enable sports and evening outdoor recreation as well as enable them to visit others in the town (Figure 9).

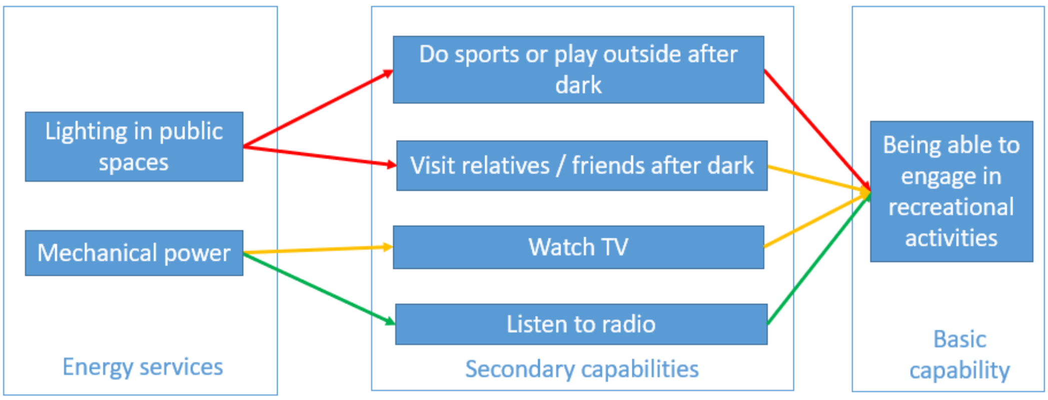

Figure 9. Relationships between energy services, secondary capabilities and ability to engage in recreation.

4.7. Barriers for Capabilities

From the diagrams in Sections 4.1–4.6, it is clear that very few relationships between energy services and capabilities are good or secure. Over half the links (27 out of 49) between energy services and secondary capabilities are bad or non-existent, and just under half (19 out of 49) are in need of improvement. There are fewer bad or non-existent relationships (7 out of 30) between secondary and basic capabilities, but only a tenth (3 out of 30) are good or secure.

The already secure secondary capabilities that underpin basic capabilities are: being able to prepare and eat nutritious food; being able to store medicine at the clinic to achieve and maintain good health; and being able to listen to radio as a recreational activity. Even for those links in green, having cheaper, cleaner and more reliable electricity would help. For example, with refrigeration at home, people would be able to store their personal medicines in a fridge at home rather than buying ice flakes. All other connections between the basic capabilities and secondary capabilities require significant improvement or need to be established.

As reflected in the focus groups, the main barriers for achieving the secondary capabilities needed in Tlamacazapa through energy services relate to cost, reliability and resource constraints. They are explained in detail in this sub-section.

4.7.1. Cost of Electricity and Water

The cost of electricity is barely affordable for most households in Tlamacazapa. People in the village are constrained in various secondary capabilities, such as breathing clean air, storing medicine, walking safely at night, as well as making and selling handicrafts due to the high cost of electricity. Those secondary capabilities could be improved through energy services, such as cooking, refrigeration, lighting, mechanical power, as well as information and communication technologies if cheaper electricity was available. The high cost of electricity has limited people in buying and using appliances to deliver the energy services needed.

> *"If I know that, in my house, the energy was cheaper, then I could buy an iron, a microwave, or, I don't know. Then we have more confidence, we could buy more. Now it is difficult and we limit ourselves in everything. We need to see the way to see how those devices are ordered."*
>
> (Older men's group)

Both female and male participants at the focus groups showed interest in using an alternative fuel source and stoves for cooking, such as electric and gas stoves. Unlike in other studies, e.g., Reference [8], participants in Tlamacazapa were not concerned about any potential change of the taste of food from different cooking methods. The male participants commented that when they travel away from the village to sell handicrafts, they eat food cooked in other ways, and are used to the taste. However, people do not have or use electric stoves in Tlamacazapa due to the high cost of electricity. Cooking with gas is also expensive, even for the households that already have a gas stove.

> *"When we wanted to buy an electric stove, they [their husbands] told us that is too expensive, and this and that … 'if you want to, you can read it on the packaging that comes with the stove it is written that it uses a lot of energy, and then, can you imagine to cook this or that'"*
>
> (Older women's group)

> *"I have a [gas] stove too but, … I feel that gas is too expensive. Sometimes they come to sell, two hundred pesos, and sometimes I buy but rarely, not always. I better use the firewood, because the gas is expensive."*
>
> (Younger women's group)

The cost of water is also very high, due to the high cost of electricity for pumping and the initial charge to have a tap installed. There are frequent cuts to water supply by the water company due to some households not being able to pay their bill.

> *"We are a low-income community, and not everyone pays the water bill. Many people owe on the water bill, and the company shuts the water supply for everyone."*
>
> (Younger women's group)

There was a belief expressed in the focus groups that cheaper electricity would allow more pumping of water, which would improve health and wellbeing. However, it must be noted that the water situation in Tlamacazapa is complicated and local groundwater supplies are likely both stressed and contaminated. Therefore, more investigation of water sources would be needed to establish whether increasing water pumping would be viable and prudent in the longer term.

4.7.2. Reliability and Security of Electricity Supply

The reliability of the electricity supply was raised as a particular issue, which restricts people's activities and affects their health, education, work and religious practice. The clinic in Tlamacazapa suffers the consequences of frequent power-off that could last for 12 h, affecting the treatment for patients and refrigeration for storing medicine. Furthermore, when households are disconnected due to non-payment, people need to pay a significant penalty cost for reconnection, causing more poverty.

> *"There are times when electric power goes almost 12 h. Rainy season is when we suffer more energy throughout the town. The health centre suffers the consequences."*
>
> (Older men's group)

As explained in Section 4.4, the lack of electricity in the school affects young people's education, which participants in all focus groups were concerned about. Power cuts also restrict people from working or carrying out church-related activities.

4.8. Overall Capability Assessment

At the end of each focus group, participants were asked to prioritize capabilities and energy services. Due to a general reluctance for group members to argue publicly with each other, even constructively, this was a rather limited discussion, but across the four groups health needs were felt to be the greatest priority; followed by security and safety; then earning a living, education and religious practice, and affiliation in a similar position; followed by the wider environment/other species, and lastly recreation. In addition, participants in all four focus groups were concerned about opportunities for young people, including education, job and sport activities.

The different basic capabilities are interrelated in many instances, via the secondary capabilities and their lack. For example, in order to make the handicrafts for earning a living, water needs to be heated for dyeing the palm leaves. To heat the water, women need to collect and use firewood, which is time consuming and produces indoor air pollution that affects their health. In addition, due to the time required for collecting firewood, women end up having less time for other activities, including making handicrafts as well as visiting friends and relatives. Therefore, they are not able to make a good living or maintain close relationships with their relatives and friends nearby as they would like.

Table 2 summarizes the number of green, amber and red arrows between energy services and secondary capabilities in Figures 2–9, which represent the secondary capabilities being secured, partly secured, or unsecured, respectively. The background colors in Table 2 indicate the corresponding links on Figures 2–9. Considering how the different energy services are potentially connected to capabilities, it appears that the greatest deficit is in lighting (Table 2), with several other energy services also inadequate, especially for mechanical power, cooking, hot water and ICT. Some of these services could be provided from a number of sources, but electricity is the only option for lighting and can cover other energy services. Electricity can also be generated locally from low carbon sources, avoiding supplier costs though requiring initial capital investment. Therefore, when considering how capabilities could be secured by specific interventions in order to turn the red or amber connections into green ones, we focus on renewable electricity generation in the following section.

Table 2. Summary of the current state of energy service connections to secondary capabilities in Tlamacazapa.

Energy Service	Secondary Capabilities			Energy Source or Fuel Options
	Not Secured	Partly Secured	Secured	
Lighting	7	5	-	Electricity
Mechanical	5	3	1	Liquid fuel/electricity
Cooking	3	3	1	Wood/gas/electricity
Hot water	3	3	-	Wood/gas/electricity
ICT	3	3	-	Electricity
Pumping	2	1	-	Liquid fuel/electricity
Cooling	2	-	-	Electricity
Refrigeration	1	1	1	Electricity

5. Technology and Project Options for Delivering Energy Services

The results in Section 4 have shown that more reliable electricity supplies would do the most to improve people's secondary capabilities in Tlamacazapa, and as a result improve their basic capabilities related to health, safety, education, religious practice, relationships and economy. Whilst, in principle, 100% of the population in Mexico has access to electricity, the residents of Tlamacazapa reported that use is limited by cost and reliability. To deliver the energy services for improving the secondary capabilities and turn the red or amber connections into green ones, several small-scale project options were considered, using renewable generation from solar PV to align with SDG7 and the Paris Agreement, to which Mexico is a signatory. The available solar resource is described in Section 5.1.

Sections 5.2–5.4 describe the technology options that could meet the energy service needs, which were discussed with local residents during a revisit to Tlamacazapa in April 2019. Option A provides lighting in the town, potentially turning the seven red and five amber connections between lighting and secondary capabilities (Table 2) into green ones; Option B provides power to community buildings, such as schools, health center and churches, potentially addressing the five red and three amber connections from community building lighting, ICT in schools, and mechanical power in the health center and church to secondary capabilities (Figures 2, 5 and 6); Option C provides clean cooking from electric stoves, which potentially could turn the three red and three amber connections related to cooking (Table 2) into green.

Whilst a detailed costing would be the subject of a subsequent phase of this project (discussed in Section 6), an estimate that would allow options to be compared by residents is given below. It is also clear that costs of solar PV, LED lighting and batteries are declining rapidly [23–25], so detailed techno-economic analyses would be quickly out of date. The costs are in the form of an annualized cost in US$ over a 20 year lifetime, using a 10% discount rate, as commonly used for energy projects in low and middle income countries [26].

5.1. Solar Resource in Tlamacazapa

Tlamacazapa is well-suited to generating electricity from PV with a high level of solar resource given its location at 18.5° N. Figure 10 shows (a) the monthly solar surface irradiation in Tlamacazapa, and (b) the electricity generation from domestic PV panels sized at 1 kW_p in March and September (the annual maximum and minimum, respectively) [27]. The average daily electricity generation for panels sized at 1 kW_p varies moderately across the year, between 4.2–5.7 kWh. While 58% of residential houses in Tlamacazapa are made with stick, palm or adobe, its schools, health center and churches have concrete roofs that could support solar panels.

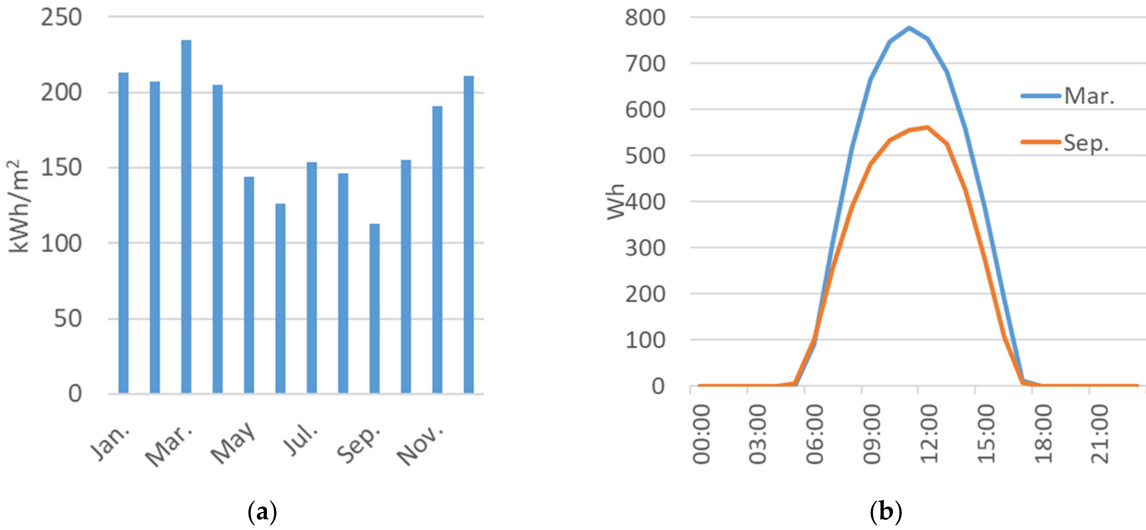

Figure 10. Solar Resource in Tlamacazapa: (**a**) Average monthly solar irradiation; (**b**) hourly generation from 1 kWp PV in March and September [27].

5.2. Option A: Providing Electricity for Street lighting

As indicated from the analysis in Section 4, providing lighting would have multiple benefits for the residents in Tlamacazapa. Such public lighting for about 2 km across the town would allow people to visit friends and family safely, go to the health center, attend community activities, and undertake work. This is consistent with findings of Jordan et al. [28] who looked at the benefits of energy efficiency measures in developing regions.

Off-grid lighting systems, using solar PV and LEDs with integrated battery storage, have been assessed in a number of studies [29–34], but these focus on cases of streets for motorized traffic, where luminance levels are higher than for pedestrian use. Reported costs are highly variable, which may be due to how many opex/capex factors have been considered, the timing of getting costs, and the pricing of goods in different markets. One more recent study considers a case in Turkey [29], with lower levels of solar irradiation than Tlamacazapa, having a Net Present Cost of US$24,296 per km; the annualized cost is US$2594 per km. Sutopo et al. [34] conducted a cost-benefit analysis for solar-energy-based street lighting in Indonesia, which again has lower irradiation than Tlamacazapa. The scheme had 74 lighting units spaced 25 m apart (i.e., 1.85 km), requiring a total investment cost of 560,176,000 Indonesian Rupiah (IDR) (US$40,000 at December 2020 foreign exchange rates), and annual operational costs 33,744,529 IDR (US$2400); the annualized project cost is US$6400, with an annualized cost of US$3460 per km.

For comparison, we have sourced a solar light fixture from a UK-based company, with sensor-controlled 40 W LED output, 42 W solar panel and 300 Wh Li-ion battery. With 50 units spaced at 20 m intervals, the price (not considering installation or maintenance costs) is US$17,000 per km (at December 2020 foreign exchange rates) [35], with an annualized cost of US$1800 per km.

The average annualized cost of providing street lighting is therefore approximately US$2500 per km, or US$5000 for 2 km that would allow residents to travel across the town. An alternative approach would be to provide portable lighting to residents. 'Pico-solar' products that give 1–10 Watts of output power are sold for US$5–20 [36].

5.3. Option B: Supplying Power to Community Buildings—Schools, Health Centre and Churches

Supplying electricity to community buildings has the potential to meet basic capabilities across health, education and social relationships, where they are currently constrained by poor or no provision of power. Schools in Tlamacazapa are not connected to the grid and therefore do not have electricity that would allow for the use of lighting, computers and other IT facilities for teaching and learning, despite computers having been provided to the secondary school in Tlamacazapa. The health center would benefit from a reliable supply of electricity, given frequent power cuts that could take hours/days to reconnect, which can put stocks of vaccine that are stored in its refrigerator at risk. Furthermore, with an increase in supply, the health center would be able to improve its services, offering, for example, health education using ICT and procedures using small appliances. Churches, as important social and community hubs in the three neighborhoods, could also benefit if more affordable and reliable electricity was available for better lighting and mechanical power for social gatherings.

For the analysis of potential project interventions, we consider both room lighting and provision of power for IT equipment, which could be applied to community buildings, classrooms in schools or a health center. We assume 60 m^2 of space with LED lighting, requiring 155 W for 6 h/day, with a demand of 0.9 kWh/day [37]. Providing IT equipment for education, business or leisure, with six computers drawing 200 W, each running 3 h/day, gives a demand of 3.6 kWh/day. Total demand is therefore 4.5 kWh/day, approximately the energy generated daily from 1 kWp solar PV in Tlamacazapa. The costs are calculated using commercially available PV and battery systems scaled to this level of demand [38], with a 4 kWh battery to cover a day's demand, but not including installation costs. The initial capital cost is $9600, with a new inverter and battery installed after 10 years (the battery cost drops according to BloombergNEF [39]). Over a 20 year lifetime, at a discount rate of 10%, we found an annualized cost of US$1175.

For refrigeration in the health center, Park et al. [40] considers a 100 L fridge with PV and battery (which can support three days' demand) as part of an off-grid solar home system, at a comparable location with 5 kWh/m^2 solar resource. The annual consumption is found to be 220 kWh/year (600 Wh/day) for the base case, with an annualized cost (including the refrigerator) of approximately US$320, dominated by PV and battery costs (approximately US$290).

5.4. Option C: Clean Cooking with Renewable Generated Electricity

The impacts on health from cooking with wood were well understood by the residents of Tlamacazapa from their lived experience. Globally, 2.85 billion people rely primarily on solid fuels for cooking [41], and household air pollution due to the use of solid cooking fuels is ranked the highest among environmental risk factors and one of the major risk factors of any type [42]. In Mexico, biomass was used for cooking in 40% of rural households in 2013 [43]. In addition, focus groups noted the physical and time burden of collecting wood and environmental impacts of deforestation.

The participants in our study talked of cooking tortillas, nixtamal (from maize) and beans and vegetables for casseroles on open fires. Improved cooking solutions have been developed that could be used as alternatives to open fire wood-burning for both these use-cases, including Patsari plancha-type stoves (closed with chimneys) for tortillas [44], and 'eCook' battery-supported electric devices for stove-top cooking [45,46]. Such "fuel-stacking" [47,48], whereby multiple fuels are used by households, is almost inevitable in the transition away from traditional cooking methods, and does not undermine technological change where it can have benefits.

Here, we consider the eCook option proposed by Batchelor et al. [45] using solar energy, hence has zero emissions of both particulates and greenhouse gases. Such solar eCooking devices have been designed to meet household needs, with 630 W_p PV panels and 2.2 kWh lithium-ion battery (LiFePO4); though the device is sized for conditions in Kenya, the average capacity factor for solar PV in Tlamacazapa is slightly higher at 19.8%

compared to 18.4% in Kenya. Notwithstanding differences in cooking practices between Mexico and Kenya, the device costs have been calculated by Leach et al. [47] using current prices and repayment over a 20 year lifetime, with a 10% discount rate, to be US$145–180 per year. At the global level, ESMAP [46] finds that supporting 50% of cooking loads from off-grid solar PV with a battery cost of US$84–276 per year.

6. Discussion and Conclusions

Conceptualizing energy poverty in the capability space has some distinct advantages. It allows for a multi-dimensional assessment, which connects the shortage of energy services to curtailed wellbeing and development in a holistic sense, rather than focusing on a more limited set of concerns, such as health and economic productivity. In Tlamacazapa for example, we were able to see how health, economic development and education were limited by energy poverty, but also the impacts on community life, especially based around churches, on recreation, and on relationships with family members outside of the immediate household. In contrast to many approaches to energy poverty that focus on households, it pays attention to individuals, which allows for differences, e.g., according to gender to be visible, but it also allows for discussion of community needs, especially when focus groups or other forms of group discussion are used. Understanding the role of secondary capabilities that mediate between services and basic capabilities is crucial. This allows for a clear picture of the role of energy services in everyday life in that specific socio-cultural context, and based on this, a clearer idea of how improvements in any services might improve wellbeing, and for whom, is possible. The results therefore help design more context-specific energy interventions for capability and wellbeing enhancement, while reducing the potential for negative impacts and unintended consequences that can occur if the technology is inappropriate and unsupported by the local community [8,49]. Our study also addresses the particular gap in the literature where the capabilities approach has been used to assess energy projects, but not used as a starting point to understand local communities' needs in the first place, and to inform design.

In Tlamacazapa, as discussed in Sections 4 and 5, we found that, in areas where access to energy is limited, the social and development ambitions of the community could be significantly contributed to by small-scale renewables combined with energy storage. Such systems are increasingly available, with prices decreasing for solar panels and batteries. However, the financial costs of providing such technological solutions are still high relative to the local economy, and the initial investment would not be affordable by the town. This is an example of where external support for direct local interventions could help achieve SDGs and bring other benefits, including empowering communities, and providing resilience against disruptions to national supply and price increases. Such distributed technological solutions are scalable and can be adapted to local contexts as part of a wider program to address energy poverty.

In practice, any interventions should have both a robust technology and community support. Assessing needs and identifying potential projects that meet community needs is a critical first step. For the next 'implementation' stage of the project, in which technologies are deployed and the impact measured, these principles must continue to be followed. In particular, given a limited budget, selecting which projects to go forward with should be decided by the community. Our analysis finds how the annualized cost of the options ranges from (in round numbers) US$150 for clean cook stoves, to US$300 for refrigeration, to US$1200 for lighting and power in a school or community building, to US$5000 for 2 km of street lighting.

Prioritizing the project options could be carried out using an approach based on Multi-Criteria Decision Analysis (MCDA) [50]. The MCDA allows the options to be scored according to a number of criteria where each criterion is given a different weighting to reflect its importance. In addition to the enhancement of capabilities, selecting potential projects also need to consider the environmental impacts (e.g., effects on water system by increasing extraction and waste management), being equitable across different groups (e.g., by age, gender, neighborhood), maintenance of the system and local training required, regulatory issues with the grid network, as well as the practicalities for safe installation. The approach can also be an effective methodology for engaging stakeholders in discussion that can lead to consensus on an outcome.

Our overarching recommendation is that technology-based programs driven by national or international organizations should first incorporate an assessment of community needs that is sensitive to potential differences between different social groups, and which takes a wide view of development and wellbeing. The capabilities approach that we have illustrated is suitable for this and may be adapted for a variety of contexts. Technological interventions should be seen in a whole-systems context, recognizing that they will be taken up within social settings and they need to be designed to fit with local practices and culture. Interdisciplinary teams are essential in identifying opportunities to address the global challenge of providing clean and affordable energy for development. Future work for achieving SDG 7 would benefit from interdisciplinary teams who could assess the local communities' needs using the capabilities approach first, before designing energy projects such as technological solutions. This would reduce the risks of energy projects being operated with reduced performance, or leading to harmful or unintended environmental and social impacts.

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Informed Consent Statement: Informed consent was obtained from all participants involved in the study.

Data Availability Statement: The aggregated anonymised data presented in this study is available on request from the corresponding author. The data are not publicly available due to confidentiality reasons in line with ethical requirement.

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