Forgotten spaces: how reliability, affordability and engagement shape the outcomes of last-mile electrification in Chocó, Colombia

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Abstract

A key global challenge is the provision of access to modern energy services to all. Indicators such as national electrification rates can mask significant inadequacies in supply, while delivering electricity for last-mile communities involves particular challenges. This paper presents a timely and important contribution by employing a novel mixed methods approach to understand the process and impacts of electrification in Chocó, a 'forgotten space' within Colombia. Chocó is a densely forested, post-conflict region that is characterised by low socio-economic indicators. The paper examines the extent to which the benefits of electricity access have been realised for five villages in the municipality of Bahia Solano. A longitudinal study including surveys, interviews and a classification of households with the World Bank's Multi-Tier Framework provides insights into household energy use, expenditure and outcomes of the electrification process. Using these findings to define future demand scenarios, an energy system optimisation model was used to design a renewable micro-grid for the study villages revealing that distributed renewable energy systems can provide a sustainable and cost-effective alternative to grid extension. The research shows that the benefits of electrification cannot be assumed, particularly where programmes have a narrow focus on energy infrastructure alone. The delivery of electricity access is not a one-step intervention. It must involve ongoing engagement and consider the social, environmental, economic and political contexts in which people live. Only through this more grounded approach will the benefits of energy for sustainable development be realised.

Keywords: energy access; Colombia; social research methods; energy system optimisation model; micro-grid; Multi-Tier Framework

1 Introduction

Energy underpins the achievement of sustainable development [1,2] and the provision of access to modern and clean energy services is a key global challenge [3]. As shown by the network of synergies between Sustainable Development Goal (SDG) 7, which aims to promote affordable and clean energy for all by 2030, and the other Goals of the UN 2030 Agenda [1], it is increasingly recognised that energy access is not an end in itself. The supply of clean affordable electricity and cooking fuels is desired because of the energy services (such as lighting, refrigeration, communications, etc.) which it facilitates. These, in turn, are desired for their positive impacts on health, access to education, work opportunities and community services [2]. However, electricity infrastructures are deeply implicated in the reproduction of political and economic power and, as such, reflect wider social and political patterns of inequality [4]. Energy should therefore be understood not as an individual service, but as one thread in a social fabric of household and community service provision and infrastructure [5].

If the wider goals of energy access are to alleviate poverty and achieve sustainable development, then the needs and aspirations of the end user must be understood [6]. However, evidence on the local-level benefits of energy access is scarce. Studies have tended to analyse electrification from either a social [7,8,9], geospatial [10,11] or techno-economic perspective [12,13]. Few combine these approaches, focus on last-mile electrification or examine how electrification is delivered and how this affects the beneficiaries. This paper addresses these research gaps through a case study of a rural electrification process in Chocó, Colombia. It asks: to what extent have the benefits of electricity access been realised in a remote municipality, and how does this relate to the way in which access has been delivered? In order to answer this question, the paper has the following research objectives, to: (1) analyse the electrification process in a last-mile setting, including infrastructure and means of electrification; (2) investigate the extent to which the benefits of electrification are realised; (3) test the applicability of the World Bank's Multi-Tier Framework (MTF; a measure of energy access) to this setting; and, (4) suggest alternative energy system options accounting for these learnings. In order to provide much needed evidence on the outcomes of electrification, this research adopts a mixed methods approach that combines social research methods and energy system modelling. The aim is to provide a more holistic understanding of the challenges and potential solutions for last-mile electrification, specifically focussing on an often-overlooked post-conflict region in Colombia.

The rest of the paper is structured as follows. First, the paper examines recent progress in energy access and the ways in which we measure it, and presents the case study used in this research. Second, it describes the research methodology, including the social research methods used to generate data, the application of the MTF and the approach to energy system modelling. Third, the paper describes the characteristics of the study communities and the electrification process, before it presents an analysis of the tiers of electricity access and potential alternative electrification options. Finally, the paper discusses the key findings of the research, including an evaluation of the applied methods, and draws conclusions.

1.1 Measuring Progress

While there have been some advances in addressing the energy access challenge, progress remains slower than required [14]. Worldwide, there are an estimated 1.06 billion people who lack access to electricity, while a further 1 billion people have only intermittent access to electricity. Around 3 billion people continue to rely on traditional fuels, such as biomass, for cooking and heating [14]. Energy access has traditionally been measured with regional or national rates of electrification that use binary indicators of has/has not access to electricity. While they are clearly useful for tracking broad progress, these simple indicators can obscure the real performance of supply systems such as the availability, affordability and reliability of electricity. They also overlook inequalities within countries and reduce the emphasis on the quality of the services the energy supply delivers. The World Bank's MTF aims to add some nuance to this issue by recognising the different attributes of energy access, specifically capacity, availability, reliability, quality, affordability, legality, and health and safety. As shown in Table 1, the MTF measures energy access in six tiered stages rather than as a binary indicator, thus recognising energy access as a transition [15].

	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Indicative electricity service	-	Task lighting + phone charging or radio	General lighting + phone charging/ radio + air circulation	T2 + small appliances	T3 + medium/ continuous appliances	T4 + heavy/ continuous appliances
Power (W)	-	Very low power (>3W)	Low power (>50W)	Medium power (>200W)	High power (>800W)	Very high power (>2kW)
Availability (hours per day)	-	Min 4 hours	Min 4 hours	Min 8 hours	Min 16 hours	Min 23 hours

Table 1. Key elements of the Multi-Tier Framework for electricity access. *Source*: adapted from [15, 16]

While this represents a vital step-forward in measuring and understanding energy access, the MTF remains a predominantly technical approach and assumes that, once provided, access to modern energy services endures [17]. This is by no means assured and it is therefore also important to examine the outcomes of individual electrification projects through repeated engagement with last-mile communities. Such research will enable a greater understanding of what happens once communities are provided with access to electricity, and whether access delivers the broad range of benefits that it is posited to provide. As described in Section 2, this paper uses the MTF to assess tiers of electricity access pre- and post-connection to a municipal grid and to project scenarios of future demand in last-mile communities in Colombia. We combine this quantitative assessment with empirical data to enrich the study, note challenges for applying the MTF in this setting and suggest further potential improvements.

1.2 An improved approach to energy projects

A central challenge in the achievement of SDG7 relates to the tension between the need to rapidly provide access to modern energy services, and the need to do so in a way that delivers environmentally sustainable energy [1]. Until recently, the cheapest and quickest way to deliver electricity access to remote communities has been through diesel generators or connection to local electricity grids which are often powered by fossil fuels. While diesel generators are quick to install, they have several disbenefits, including high and variable operating costs, local air quality and greenhouse gas emissions. Grid connections can offer economies of scale for electricity generation, but installation of overhead lines can cause disruption to the local environment and involve significant challenges for operations and maintenance. Achieving SDG7 requires supplying clean affordable energy without undermining the environmental and social integrity of communities.

To facilitate the wider goals of sustainable development, the quality of energy provision and the manner in which it is provided are key. For example, electricity supply should be consistent rather than intermittent, and faults should be fixed promptly so that the supply can be relied upon. Social orientation of energy projects should revolve around not just the provision of energy, but also the 'complementary services' that enable communities to take up, use and benefit from electricity [6, 18]. This may include business training and development, financial products based on micro-finance models, access to new appliances such as electric cookers and computers, and access to other kinds of infrastructure such as mobile networks, internet and transport. Finally, energy projects may be seen as an opportunity for empowerment, by involving communities in decision-making and co-design [5, 19]. This may result in better maintenance of the supply system itself, and also better uptake of the services it can provide.

1.3 Electrification in Colombia

There has been good progress in Latin America and the Caribbean on delivering access to modern energy services. However, around 4% of the region's population, or 26 million people, still lack access to electricity, and 87 million still depend on solid fuels for cooking and heating [20]. It is expected that universal access to modern energy services will be achieved in Latin America and the Caribbean by the mid-2020s, but achieving this last mile in energy access is a key regional challenge [20]. It will involve reaching people who live in isolated and often impoverished rural communities; tackling this will require creative solutions, which are both scalable and adaptable to local contexts.

National statistics indicate Colombia has very high access to electricity, reaching 96-98% of the population in 2016 [21,22]. The vast majority of households are connected to the national grid, with just 2% having access to electricity via off-grid, distributed networks. As shown in Figure 1, the national grid extends only over the central mountainous region and the northern coastline, areas which also contain the country's economic and political powerhouses. Those areas that are not connected to the national grid are known as *Zonas No Interconectadas* (ZNI, or non-connected areas) and are equivalent to 52% of Colombia's territory [23]; in these regions some households have electricity supply via small local grids or household diesel generators. Electricity use in rural communities is currently low, but demand is likely to increase with improved access. Further extension of the national electricity grid to ZNI is hindered by geographical and political factors, including dense jungle, mountainous terrain, conflict, and limited institutional capacity. This means that there is, and will continue to be, a strong need for decentralised energy solutions.

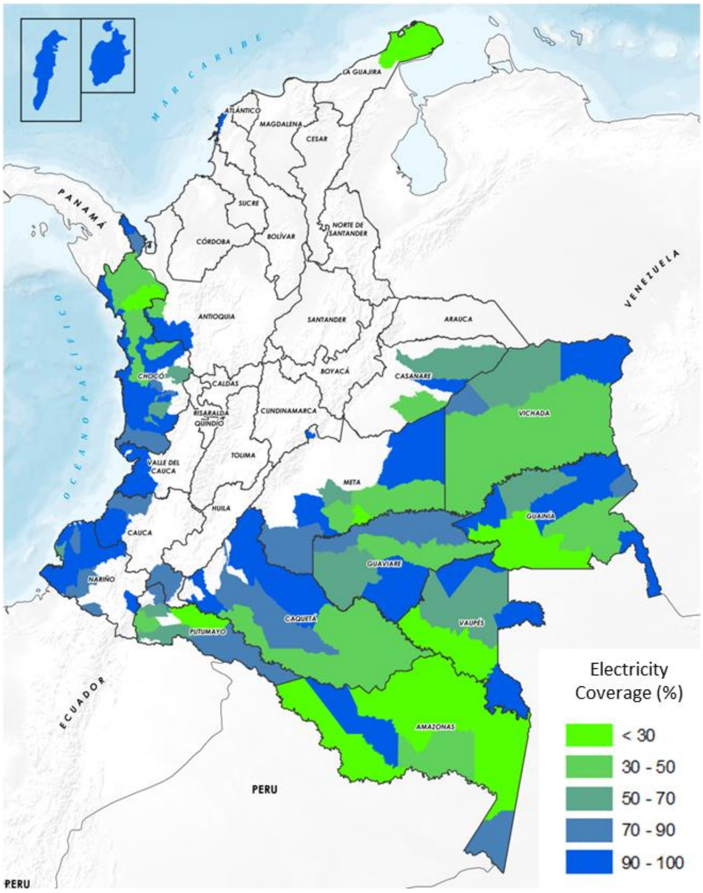

Figure 1. Coverage of the national electricity grid, Colombia (2015). *Source:* IPSE-CNM [24]. Shaded blue and green regions are not connected to the grid, with percentage of electricity access. White areas are covered by the national grid, although not all households living in these areas are connected.

The Ministry of Energy and Mines leads and coordinates energy policy making and regulation in Colombia. It is supported by other government agencies, including the Mining and Energy Planning Unit (UPME) and the Institute for Planning and Promotion of Energy Solutions in ZNI (IPSE). Two pieces of national legislation support the roll out of distributed renewable energy technologies to ZNI and aim to drive development and address inequalities in the process. The first, Article 185 of the National Development Plan (2014-2018) (Ley 1753 (2015)), sets up a fund for the development of the Pacific Coast, one of Colombia's most impoverished and energy poor regions, and where the field research for this paper took place. This fund supports activities under a regional development plan '*Todos somos PAZcífico*', which places access to services – including electricity – at the core of its activities [25]. The second, Law 1715 (2014), aims to promote the development and use of renewable energy in Colombia, including in ZNI [26]. The law provides for the creation of a fund to finance renewable energy projects which target low income households in particular, and to substitute the use of diesel in order to reduce the costs to the end user. Although it was ratified in 2014, the government has not yet developed the necessary regulations and, as a result, Law 1715 has yet to deliver on its promises. Further, Law 1715 does little to address the numerous barriers to renewable energy in ZNI. These include: a lack of data on local energy resources; low awareness of renewable energy; dispersed rural populations; the low running costs of diesel plants; corruption; and low profitability [27]. Addressing these barriers requires a concerted effort to understand how communities currently use, buy and think about energy, and how this changes with access.

In addition to this national legislation, Colombia has several funds which provide dedicated finance for off-grid electrification projects, including the Financial Support Fund for the energisation of ZNI, which is managed by IPSE. Although the government is incentivising the use of renewable energy technologies through Law 1715, efforts to electrify ZNI have to date typically relied on diesel generators. The use of diesel in ZNI is subsidised through a Solidarity Fund. However, the provision of electricity through diesel generators entails a number of disbenefits, including risks to human health and environment due to noxious emissions [28].

1.4 Forgotten Areas?

In 2014, there were nearly 1 million people living in off-grid areas in Colombia, most of whom were located in the eastern Pacific region i.e. the departments of Nariño, Cauca and Chocó [23]. The Southern and Pacific zones of the country are characterised by sparsely inhabited tropical rainforest and are amongst those most affected by Colombia's long-running civil conflict. Chocó is one of the country's most underdeveloped regions, which faces pressing social, environmental and economic issues [29]. Located on the Pacific coast of Colombia it is the wettest region in the country, with an average rainfall of 7,000 – 13,000 mm per annum [30, 31]. Known for its Afro-Colombian population, the region is densely forested, rich in deposits of gold and platinum, and highly biodiverse. Despite its natural and cultural wealth, the region has been largely overlooked by the Colombian Government [29]. Poverty indices are high and 63% of the region's half a million people live in poverty, with 37% living in extreme poverty[1] [32]. Infrastructure is limited; just one highway passes through the capital, Quibdó, and large sections of the interior lack access to roads. Access to basic services is also lacking in much of the region: in 2015, 23% had access to drinking water, 79% to electricity, and 0.4% to the internet [21, 33]. Much of the region is a ZNI; while 52% of the population of Chocó have access to the national grid, grid access is largely restricted to Quibdó and areas located near to the neighbouring department of Antioquia. Expansion of the grid within Chocó is hindered by a highly dispersed rural population, dense forest, weak institutions and poor governance. These characteristics mean that small-scale distributed renewable energy technologies, including wind, solar, bioenergy and micro-hydro, have the potential to deliver affordable, reliable and sustainable energy access for communities in ZNI in Chocó.

This study focuses on the municipality of Bahia Solano, which is comprised of a municipal capital (or *cabecera*) and five small villages (Huina, Mecana, Huaca, Playa Potes and Nabugá) dotted along the coastline (Figure 2). Between 2004 and 2017, a programme of electrification, funded by IPSE, was implemented in the municipality to sequentially connect the villages to the municipal grid. This study examines the process of electrification and its outcomes between 2016 and 2018 for this geographically remote and neglected post-conflict setting.

[1] In 2015, the poverty line in Colombia was 224,000 COP (76 USD) per capita per month, and for extreme poverty was 102,000 (35 USD) per capita per month [34].

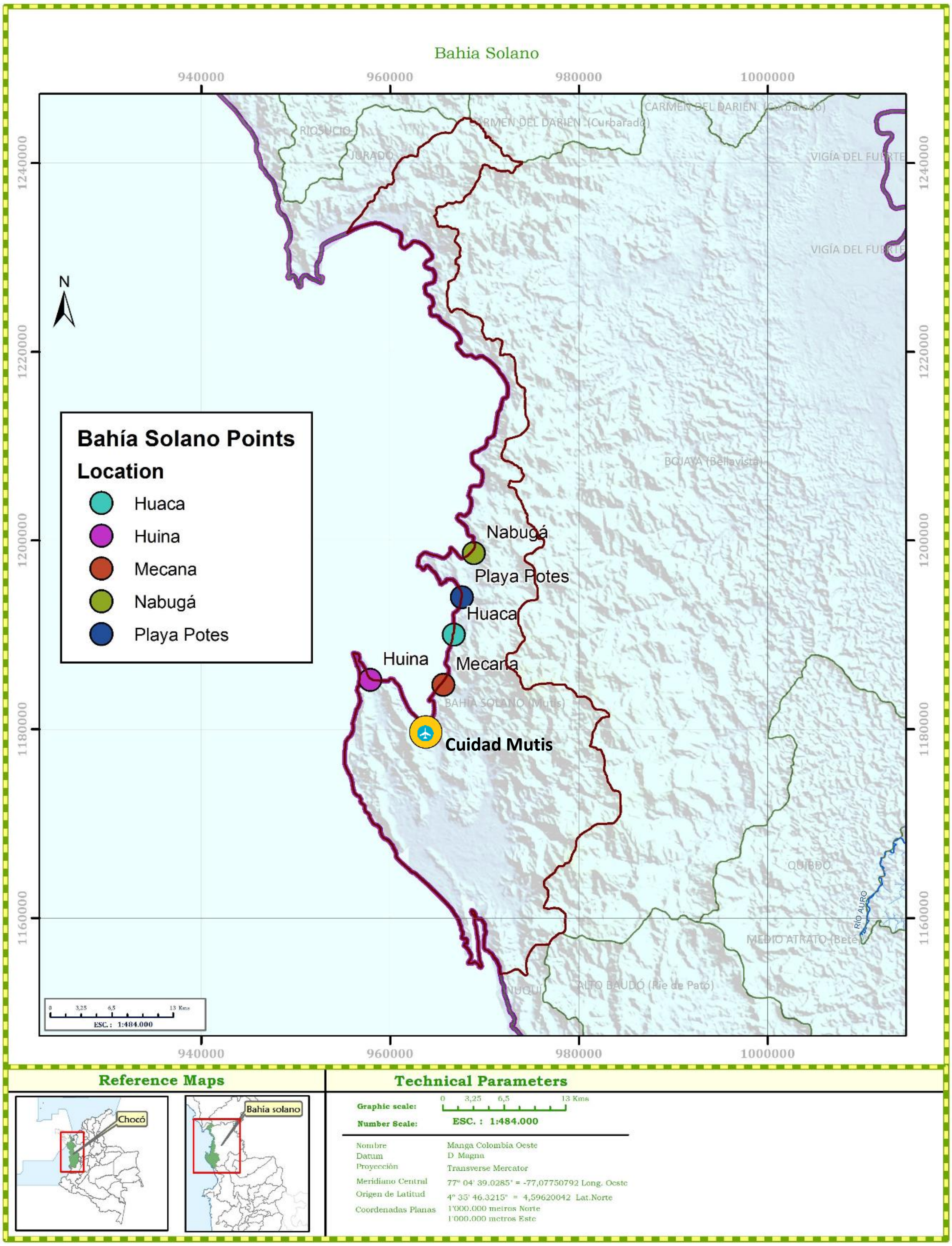

Figure 2. Study area: Bahía Solano, Chocó, Colombia. *Source*: Authors' own.

2 Methodology

This study adopts a mixed method approach, combining field research with techno-economic modelling, to investigate last-mile energy access in Bahía Solano. First, a longitudinal field study tracked the outcomes of electrification with repeated data collection. The MTF method was applied for the case study villages pre- and post-electrification and used to inform the selection of parameters and data for a simple energy system model. Finally, the social and technical research methods were balanced in order to evaluate possible electrification alternatives from both perspectives. As such, we present a descriptive exploratory study grounded in data [35].

2.1 Field research

The primary data were obtained from field research undertaken in five coastal fishing communities of Bahia Solano between 2016 and 2018. Table 2 shows the characteristics of the five communities and number of households surveyed in each. The five villages represent an electrification spectrum, with those villages located closest to the *cabecera* having access to electricity and those located furthest without. This was also reflected in other services, with Huina having the greatest access. Repeated field visits enabled the study of the electrification process as the first field visit was undertaken in November 2016, prior to the extension of the municipal grid to the two more remote villages of Playa Potes and Nabugá. During this visit, a total of 76 face-to-face surveys were carried out in the five communities.

Village	Approx. number of households	Households surveyed		Access to basic services			
		N	%	Electricity 2016	Electricity 2018	Drinking water	Sanitation
Huina	105	16	15	Yes[1]	Yes	No	Partial
Mecana	25	13	52	Yes[1]	Yes	No	No
Huaca	70	15	21	Yes[1]	Yes	No	No
Playa Potes	29	15	52	Partial[2]	Yes	No	No
Nabugá	35	17	49	Partial[2]	Yes	No	No
Total	**264**	**76**	**29**				

Table 2. Characteristics of the case study communities, 2016-2018. *Notes:* 1 = electricity connection via the municipal grid; 2 = some households have electricity via a diesel generator. This is sometimes shared between neighbours.

The questionnaire was based on the SURE-DSS survey [36], and contained modules on household characteristics, primary and secondary fuel use, ownership of appliances, energy expenditure and community characteristics. The data were entered into an Excel database, and descriptive statistical analysis undertaken. Also during this visit, semi-structured interviews were undertaken with one or two leaders in each community, as well as eight interviews with local government, academics and the private sector. The interviews aimed to provide greater context for the field research; interviews focused on energy and other challenges facing the communities and the department of Chocó. Finally, participant observation enabled the researchers to learn more about the day-to-day lives of the communities, experiences of energy interventions and responses when access to electricity was interrupted.

A second field visit was undertaken in February 2018 after the extension of the municipal grid to the two more remote villages. On this occasion, a follow-up survey with 15 households was undertaken in one of the newly electrified villages, Playa Potes, to analyse the impacts on energy use of electrification. The same survey was used, with some additional questions focused on the process and experience of electrification. Follow-up interviews were also carried out with two community leaders and a member of local government, which focused on perceptions of the grid extension process.

2.2 Applying the MTF

Based on the 2016 survey, households in the five villages were characterised according to their tier of electricity access, which was repeated for Playa Potes in 2018. Noting their mode of access (i.e. whether municipal grid, a stand-alone solution or no access) and drawing on [15, 16], each household was classified according to its highest-powered appliance:

- Tier (T) 0: no electricity access
- T1: household has access to electricity, plus lighting and/or a phone charger
- T2: household has a small appliance, such as a fan, TV and/or stereo
- T3: household has a washing machine
- T4: household has a refrigerator, iron and/ or water pump
- T5: household has electric cooking and/ or air conditioning.

This method assumes that ownership of a high-power appliance means that: (a) the electricity supply is of sufficient quality to support it; and (b) that lower appliances were not purchased either because there was no need or they were unaffordable. For example, a household that has lighting, owns a mobile phone and an iron, but not a washing machine or refrigerator would be classified here as T4. While it is recognised that this approach could be positively biased, the data do not enable an understanding of why households own particular appliances. The availability and reliability attributes of the MTF were not appropriate for these communities for reasons that will be discussed. The applicability of the MTF to regions such as the Chocó, which face unscheduled and enduring outages, will be discussed in Section 4.

2.3 Modelling future demands and a renewable micro-grid

To examine the potential of distributed renewable energy technologies to meet the energy needs of these villages, scenarios of future energy demand were developed and the energy system optimisation model OSeMOSYS [37] was used to design a least-cost renewable micro-grid for each scenario. Levelised costs of electricity were calculated for these systems and compared with the grid cost of electricity in Bahia Solano. The OSeMOSYS model was selected as it performs cost-optimisation over a long time-scale and so allows us the examination of supply options with gradually increasing demands, rather than a one-off snapshot. It is an open source model, meaning the method can be easily replicated elsewhere.

Demand scenarios were modelled representing the villages reaching three electrification levels by 2030 (Table 3) based on the survey results and the World Bank MTF [15]. The three scenarios are strongly rooted in the research conducted in the communities: the 2016 demand was calculated from the appliance ownership and hours of use indicated in the household survey results from 2016, and the three electrification levels represent development scenarios which are thought to be realistic possibilities in the timescale of this study. Realistic scenarios were constructed so that the findings can be considered by planners and companies looking to supply electrification to last-mile communities. The demand of households in Huina were chosen for the first scenario, as this is the most developed community in the study area and in 2016 had been connected to the municipal grid for over ten years. The availability of appliances and further productive uses of energy are limited due to the remote location and a lack of infrastructure, such as roads or a market. Scenarios of higher energy demand would likely require significant additional development of infrastructure and economic opportunities.

D1 "Huina"	In 2030, each house in Playa Potes reaches the electrification level of Huina in 2016 (i.e. the same average number of appliances and the same average number of working hours per day).
D2 "MTF 5"	In 2030, each house in Playa Potes has one of each appliance plus 8 lights, 2 mobile chargers, 2 fans and an air conditioning unit. The average number of working hours per day are taken from the Huina survey, as this was considered a better representation of local cultural norms than the typical hours given in the MTF document.
D3 "MTF 5+"	Demand is defined as in D2, with additional community lights along the beach and 4 extra houses for tourist accommodation in each village, which are occupied during the whale-watching season which takes place from May-October.

Table 3. Demand Scenarios

Demands for the years between 2016 and 2030 (in kW) were linearly interpolated rather than projected from appliance ownership explicitly, as the survey results indicated that households in these communities do not tend to buy appliances in the order suggested by the MTF sequential tiers (see Section 3.3). In each scenario, full electrification of cooking is assumed by 2030; the number of hours of use per house is taken from the average daily use of electric cookers indicated in the survey (i.e. 1.5). Electricity demand was modelled with three time-slices per day: day (6am-6pm), evening (6pm-10pm) and night (10pm-6am). Appliances were assigned to each time slice as appropriate (for example, televisions are used in the day and evening, while fridges are used throughout the 24 hours). A constant population was assumed for each village, as any population increase is expected to be balanced by migration towards the municipal capital.

The understanding generated during field research were also used to inform the generation technology options for the model. Diesel generators are not considered desirable due to the high fluctuating price of diesel and air quality and other environmental impacts, so a fully renewable micro-grid is modelled. Biomass-gasification and anaerobic digestion are unlikely to be practical in the near future due to high maintenance requirements. Small-scale hydro has potential in this region, though its suitability is highly site-specific so is not considered here. Small wind and solar generation with battery storage were considered feasible, as long as sufficient clear space is available for each – these technologies are relatively easy to source in the region and could be maintained by trained community members.

Capacity factors (CF) for the wind turbine for each timeslice were derived from hourly MERRA data for 2016 at each village location from the Renewables Ninja tool [38] and the power curve for a standard 4.5kW Enair E70 wind turbine [39] with 20m hub height[2]. Capacity factors for the solar generation were derived for each time slice based on hourly PV generation data from the Renewables Ninja tool [38] – the derived solar PV capacity factors are independent of the PV panel model. For both technologies, an indicative 5% energy loss was applied in the CF calculation to represent downtime for maintenance. Wind and PV generation with battery storage are modelled as combined technologies. For the PV-battery system, it is assumed that 50% of the day's generation is used to charge the batteries which discharge during the evening and night; for the wind-battery system, it is assumed the night's generation is used to charge the batteries, which discharge during the day and evening periods. The CFs for the charging periods were calculated assuming the stored energy is unavailable to meet demand; the CFs for the discharging periods assume the stored energy is available in proportion to the time slice lengths, with an additional 5% energy loss applied to represent efficiency of the battery system. Capital costs for each technology were derived from data from similarly remote ZNI rural electrification projects in Colombia [40], and cost trends [41]. These are shown in Table 4, along with the CF for each technology and time slice.

Technology	**Capital cost**		**Capacity factors (%)**		
	2016 USD /kW	**Yearly reduction factor**	**Day**	**Evening**	**Night**
PV	1690	0.85	26.9	0	0
PV with batteries	3332	0.85	13.4	12.8	12.8
Wind turbine	4021	0.97	2.6	1.7	1.9
Wind turbine with batteries	6767	0.97	3.6	2.6	0

Table 4. Key Model Inputs.

3 Analysis

3.1 Community characteristics

The municipality of Bahía Solano has a population of around 9,000, of whom 87% are Afro-Colombian, 9% are indigenous and 4% are mestizo [42]. At the time of this research, the municipality was accessible only by air or boat, and there were no roads connecting Bahía Solano to other parts of Chocó. All goods, including diesel and LPG, entered the municipality via sea or small aircraft. The municipality was largely self-sufficient in food, but additional goods, including fuel, arrived by boat from Buenaventura, Colombia's principal port. There was a small airport which linked Bahia Solano to the cities of Quibdó and Medellín. Two of the villages had shops which sold basic goods, but to

[2] This turbine model was selected as an example was installed in Playa Potes in 2017

purchase most food and other goods villagers had to travel to the *cabecera*. There were no roads connecting the villages, which were only accessible by boat or on foot through dense forest.

In general, the closer a village was to the *cabecera*, the greater its access to basic services (see Table 2). All of the villages had a school, which catered for children aged between 6 and 11, while older children travelled to the *cabecera* to attend school. In the villages, 60% of surveyed households were educated to primary level, 30% had a secondary education, while 3% had no formal education and 7% had a university education. None of the communities had a health centre. All villages were served by a municipal aqueduct, but none had a treatment system for drinking water. There was a sewage system in Huina, but this reached just 9 of the 16 households surveyed. A minority of households (10%) had a septic tank, but most households did not have access to sanitation services.

Throughout the municipality, the principal economic activities were fishing, forestry and agriculture. Both fishing and agriculture were primarily for subsistence, with families selling additional produce in local markets. Many respondents found it difficult to estimate household income, which fluctuated from month to month. However, 84% of households indicated that they earned less than the national minimum wage of COP 689,454 (USD 230) per month. Ecotourism represented a growing economic opportunity due to the municipality's ecological wealth, such as whale watching. There was a 12-room hotel in Huina, while in the other villages some families rented out rooms to tourists. The opportunities for ecotourism were however complicated by ongoing insecurity, specifically the continued presence of guerrilla groups and narco-traffickers.

3.2 Provision of electricity in Bahia Solano

According to UPME, in 2015 the electrification rate in Bahía Solano was 100% [43]. Electricity was supplied to the municipality by a small hydroelectric plant located in Utría National Park, some 30km from the *cabecera*. Developed by IPSE, and opened in 2000, the plant consisted of five small hydroelectric turbines each with a generation capacity of 375 kW, totalling 1,875 kW [44,45]. The plant was connected to the municipal grid and supplied 2,013 households in the *cabecera*, the small town of El Valle, the communities of Huina, Mecana and Huaca, and three indigenous reserves which are located in Utría National Park [42, 44]. In 2003, the management, maintenance and operation of the plant was transferred from IPSE to GENSA – a private-public company – although the administration remained the responsibility of IPSE[3]. The communities were connected to the grid via overhead lines passing through dense forest and over agricultural land. The communities have been connected sequentially to this municipal grid: Mecana in 2004, Huina in 2005, Huaca in 2011, then Playa Potes and Nabugá in late 2017.

In early 2017, heavy flooding caused damage to the hydropower plant. Repairs were delayed as key components had to be imported from Germany. To supply the grid, a 1,800 kW diesel generator was installed in the *cabecera* [46] and has powered the municipal grid ever since. In early 2019, the hydropower plant remained out of commission and the newly expanded municipal grid continued to run on diesel. The municipality was therefore highly dependent on diesel, which was imported from Buenaventura – a seven-hour journey by boat.

[3] IPSE, personal communication, November 2016.

In the villages that were not connected to the municipal grid in 2016 (Nabugá and Playa Potes), households had sought alternative energy access solutions. One half of the community of Nabugá had access to electricity via a shared diesel generator, and several other households were connected via the police commissioner's generator. The village of Playa Potes had a shared diesel generator, which had broken down some years earlier and never been fixed. Some households had their own diesel generator and also provided electricity to neighbouring households. A local university had installed a hybrid solar-wind system (2kW/ 7.5kW) in the village school in Playa Potes. This provided the school with lighting services and the capacity to charge and use the laptops that had been donated by the Colombian government some years earlier. Community members also used the electricity provided by the system for phone charging and had developed other micro-enterprises, including a barber shop.

3.3 Household use of energy: affordability, reliability and satisfaction

Drawing on the 2016 household surveys, this section describes the use of energy (both electricity and other fuels e.g. for cooking and transport) in the five villages.

In 2012, the generation cost of electricity per kWh in Bahía Solano was approximately 1,160 COP (USD 0.40) without subsidy [46], which was greater than the contract or spot price in Colombia. To make electricity affordable, electricity for domestic consumers in the municipality – who belong to the lowest socio-economic stratum in Colombia – was heavily subsidised[4] [47]. The median expenditure on household energy – both electricity and other fuels – was 85,000 COP (30 USD) per month (Figure 3). Given that the vast majority of households earned less than 700,000 COP per month, this represented a substantial proportion of monthly income. For most households, LPG for cooking represented the greatest energy expenditure, without which expenditure on energy would have been 30,000 COP (10 USD) per month. In 2016, a 40-pound cylinder of LPG cost 65,000 COP (22 USD), and the discrete nature of the volumetric unit of sale meant that households tended to ration energy use to one cylinder per month.

[4] Alcaldía de Bahía Solano, personal communication, November 2016.

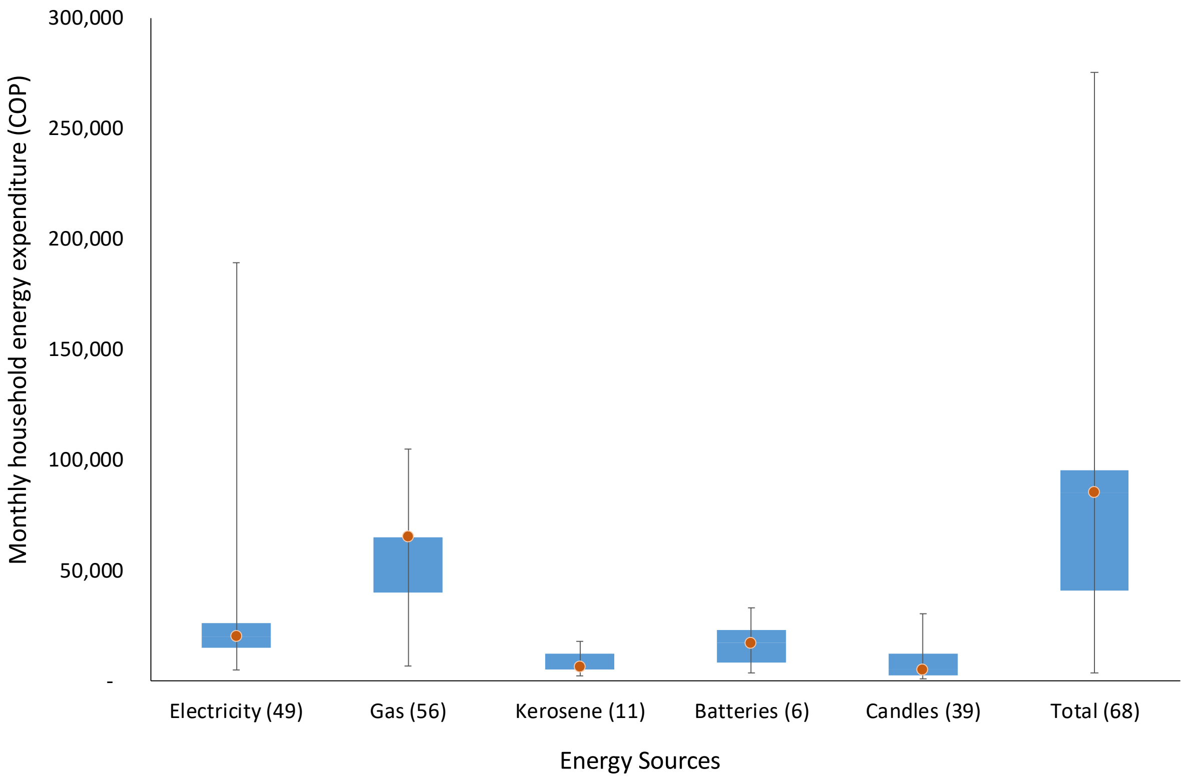

Figure 3. Estimated monthly expenditure on household energy in 2016. *Note:* Numbers in parentheses equal sample size. Total does not equal 76 as not all households answered this set of questions.

However, household use of LPG was contingent on affordability and availability. In 2017, just a few months after the initial field research, a general strike in Buenaventura reduced the supply of goods, including LPG, to the municipality resulting in price increases. Between 2016 and 2018, the cost of a cylinder increased from 65,000 to 80,000 COP (22.4 to 27.6 USD), a considerable price increase for these low-income households. To hedge against such situations, all households practised fuel stacking [48]; a lack of reliability of modern energy sources meant that households in the municipality used a variety of fuels to ensure energy security [3]. Households had not, therefore, fully displaced the use of traditional biomass in cooking, but rather supplemented LPG with firewood due to unreliable access and the high and variable cost of LPG. In addition, 25% of households indicated that they also purchased gasoline for their boats, spending a median of 220,000 COP (73 USD) per month. Boat was the only form of transportation for these communities, and the costs would often be divided amongst those who travelled. In Nabugá, for instance, the community would spend 130,000 COP (43 USD) on gasoline travelling to the *cabecera* to collect diesel for the generator; this cost would be shared amongst those households that had access to the generator.

Although electricity in Bahía Solano was subsidised by the state [47], 53% of respondents thought electricity was expensive. Respondents were asked if they would be willing to pay to improve the service, and 64% indicated that they would be willing to pay (an average of 20,000 COP (7 USD)); however, several respondents indicated that the amount would depend on household resources and/ or the quality of the service provided. In the two villages that were electrified in 2017 households did not yet pay for electricity as, unlike the communities of Huina, Huaca and Mecana, no electricity meters had been installed and it was unclear if they would be. For households, the lack of meters meant households had no baseline against which to judge electricity prices and so found it difficult to say how much they would be willing to pay.

In those villages which had access to electricity via the municipal grid, many respondents indicated that when they had electricity it was reliable (i.e. available 24 hours a day), but that they were routinely without electricity. Chocó's climate meant that heavy rains and falling trees would frequently bring down transmission lines, cutting electricity supply (and communication) to the villages. When electricity supply was interrupted, a community leader explained that a designated individual from the community was responsible for walking the length of the lines to identify where the fault lay; this would then be communicated to the local energy company who would send engineers to fix the fault. Respondents commented that the energy company was often slow to respond, leaving villagers without electricity for as much as two weeks per month. One respondent in Playa Potes argued that because they did not pay for electricity, the energy company felt no urgency to resolve faults. As a result of the frequent outages, several households continued to use a diesel generator as back-up during supply shortfalls. Respondents also discussed having purchased fridges that were no longer usable due to prolonged blackouts. Indeed, at the time of the initial field research, the communities of Huaca and Mecana had been without electricity for several days due to heavy rains. The lack of reliability of electricity also constrained productive activities [3] such as cold storage for fish – an important option for isolated communities with limited access to infrastructure and markets.

Respondents were asked about their priorities for further increasing energy use and the barriers to an improved energy service in their community. A majority of respondents indicated that they prioritised the use of energy in households (64%), as opposed to for community (23%) or productive (13%) activities. When asked why households were the priority, the need for lighting and food storage were commonly cited. As one respondent commented, "without electricity, it's not possible to live" (Male, 44, Nabugá). In terms of basic services, while electricity was considered important for the community, water was the priority for 47% of respondents. A community leader in Playa Potes explained that a long, dry summer had reduced water supply from the aqueduct, leaving households dependent on local streams for water. Overwhelmingly, respondents perceived the key barriers to be a lack of support from the state and/ or local government (71%). Indeed, many individuals spoke of their sense of abandonment by the state - particularly in Nabugá, a community which had been displaced twice in the past decade due to paramilitary activities.

Finally, respondents indicated that they were mostly satisfied with their electricity supply. One woman described how her family were now able to enjoy cold drinks, while another commented that she no longer had to go to sleep early. However, with regard to the electrification process, community leaders in Playa Potes expressed their dissatisfaction. They described how, in the run-up to the expansion of the municipal grid, meetings had been held in the *cabecera* but no transportation had been provided, meaning few people were able to attend. Trees had also been cut down to make way for the transmission lines, but IPSE had not consulted with or compensated landowners for this loss. For some, this process had deepened feelings of mistrust towards outside actors. This highlights how the process of electrification is important for (dis)empowering communities and may further embed a sense of neglect by the state and other actors [5].

3.4 Tiers of energy access: pre- and post-electrification

The MTF analysis revealed an energy access transition across the five villages (see Table 4) wherein the number of high-tier households in a village was related to the time since connection to the grid; Huina had the highest proportion of T4 and T5 households. Also, for villages that had had access for longer, households were more firmly classified as belonging to the higher tiers; the higher tier households in Huina and Mecana were more likely to own a full range of appliances such as a radio, washing machine and electric cooker, whereas the T4 houses in Nabugá owned a mobile phone and fridge only. Furthermore, the availability and affordability of appliances in the five villages was an important factor. The municipality is dependent on imported goods, which raises the price of appliances available in the *cabecera* and affects what is available. This is exacerbated for villages away from the *cabecera* which face the additional barriers of transportation, further increasing the cost and risk of damage. This highlights that while the MTF categorisation primarily focuses on the attributes of electricity supply, the demand side is equally important. Even if electricity supply is reliable and affordable, households' use of that supply may be constrained by other factors such as infrastructure, preferences and economic opportunities (see also [18]).

Village	Number of households surveyed	Tier of energy access					
		0	1	2	3	4	5
Huina	16	6%	0%	0%	0%	81%	13%
Mecana	25	0%	8%	8%	8%	77%	0%
Huaca	15	0%	7%	33%	0%	40%	20%
Playa Potes	15	40%	27%	13%	0%	13%	7%
Nabugá	17	41%	41%	0%	0%	18%	0%

Table 4. Tracking electricity access with a Multi-Tier Framework: Bahía Solano, Colombia, 2016. Number of surveyed households and percentages in each tier of energy access.

Table 4 also highlights the disparities within the villages themselves. Even Huina, which was connected to the municipal grid first, continued to have some households without access to electricity. In addition, some households owned many appliances, while others owned very few; again highlighting that access is about more than just electricity supply. This points to the importance of understanding energy access and use at the household and the community level when designing energy interventions if they are to meet a range of capabilities, needs and aspirations [3,19]

It is important to note that even those households considered here to have T5 access, used very low levels of electricity. For example, while the average per capita electric power consumption in Colombia was 1,289 kWh per annum [49], the average per capita electricity consumption in T5 households in Bahia Solano was 1,089 kWh per annum. This highlights the energy inequalities that continue to exist in Colombia.

In 2017, the municipal grid was upgraded and extended to the most remote villages of Playa Potes and Nabugá. Table 5 shows the change in tier of electricity access pre- and post-electrification for the village of Playa Potes.

Playa Potes	Number of households surveyed	Tier of energy access					
		0	1	2	3	4	5
Pre-electrification	15	40%	27%	13%	0%	13%	7%
Post-electrification	15	0%	7%	33%	0%	60%	0%

Table 5. Tracking electricity access with the Multi-Tier Framework: Playa Potes pre- and post-electrification.

Table 5 shows that the extension of the municipal grid provided all households in Playa Potes with electricity, but that the uptake was uneven. Pre-electrification, 40% of households had no access to electricity (T0), while 60% had some access via an individual or shared diesel generator. One household was already at T5. Post-electrification, access increased to 100% and the majority of households (60%) transitioned to T4, gaining lighting plus small appliances and a refrigerator. This may be considered a rapid transition, particularly given many households live on low incomes. However, and as indicated above, prior to electrification, some households already owned appliances but were unable to use them. Here, extension of the municipal grid enabled these households to make use of these previously idle appliances. This reinforces the notion that, in many instances, access to electricity should not be represented with a binary indicator as it can be a 'step wise' progression through different levels and forms of electricity provision (see also [17]).

3.5 Electrification options

As outlined in the previous sections, the empirical research indicated that using household diesel generators exposed residents in remote villages to high and fluctuating fuel prices, as well as poor air quality. Connection to the municipal grid has provided households in all five villages with an electricity supply, however, the supply is subject to significant periods of downtime due to vulnerable infrastructure and insufficient maintenance systems, so that several have kept diesel generators for back-up. This section examines the current energy demand and scenarios of future demand in order to consider the feasibility of micro-grids powered by renewable energy as an alternative electrification option the municipal government could have considered.

In 2016, the average household energy demand across the five villages was 1.40 MWh per year, with 49-56% occurring in the day, 24-35% in the evening and 16-20% during the night. Projections of the energy demand for the three levels of increased energy access up to 2030 shows that, as households purchase appliances associated with higher access tiers, the demand shifts slightly, with 59%, 28% and 13% occurring in the day, evening and night respectively in the MTF Tier 5 scenario. The OSeMOSYS optimisation models constructed for the four villages indicate a combination of solar PV generation with batteries is cost-preferable in order to meet the increasing energy demands of the villages up to 2030. PV generation is more suitable than wind turbines for these villages due to the very low wind resource in this area. Considering the PV resource in this region, 111 - 546 kW installed PV capacity is required to meet the growing energy demands in each village (Table 6). Across the villages, to meet demand scenario D3, the installed capacity must increase by a factor of approximately 1.75 compared to D1. The model recommends an incremental installation of this capacity over the modelled period, indicating a modular approach could be cost optimal.

Scenario	Total PV capacity (kW)			
	Playa Potes	Nabugá	Mecana	Huaca
D1 “Huina”	129	155	111	314
D2 “MTF 5”	185	224	160	448
D3 “MTF 5+”	226	264	201	546

Table 6. Total installed PV capacity required

The total capital cost of the four village PV-battery systems required to meet demand scenario D3 was 1,683,966 USD (2016). In comparison, the total cost of the grid extension from Cuidad Mutis to Huaca, Mecana, Nabugá and Playa Potes was 782,961 USD (2,395,039,015 COP [23]) indicating that the renewable micro-grid option would have been more capital intensive compared to the extension of the municipal grid. However, considering the generation over the lifetime of the systems, the cost comparison is more favourable towards the PV micro-grid. This is shown by the average levelised costs of electricity for each village and demand scenario given in Table 7, which range between 0.28 and 0.35 USD/kWh. The average cost of electricity at the point of delivery in Bahia Solano during January to June 2017 was 0.60 USD/kWh (1,766 COP/kWh) [50]. This comparison shows PV-battery micro-grids could have provided a cost-viable alternative to municipal grid connections for these villages. Sensitivity tests showed this conclusion is robust even if the cost reductions rates were halved, or if the 2016 cost were multiplied by a factor of 1.5. We also note that if the costs were increased, it would most likely be due to a difficulty of transportation, in which case the cost of diesel and/or O&M for the municipal grid would also be increased and so raise the price of grid electricity accordingly. Notably, the LCOE does not simply increase for micro-grids meeting higher demand levels.

Scenario	Micro-grid LCOE (USD 2016/kWh)			
	Playa Potes	Nabugá	Mecana	Huaca
D1 “Huina”	0.33	0.31	0.35	0.33
D2 “MTF 5”	0.29	0.28	0.32	0.30
D3 “MTF 5+”	0.32	0.30	0.34	0.29

Table 7. Average levelised cost of electricity (LCOE)

This price comparison reveals that cost should not prohibit consideration of renewable micro-grids for remote communities, as the technologies are cost-comparable, even before incorporating the benefits of a cleaner, more reliable and empowering system. Importantly, village-level micro-grids offer several potential advantages compared to extensions via larger grids. In the Bahia Solano area, they would remove the need for transmission lines from a centralised generation plant through dense forest, which are vulnerable to landslides and falling trees, making maintenance challenging and resulting in intermittent supply. Furthermore, such micro-grids would reduce the local air quality and health impacts of using diesel generators and reduce residents’ exposure to the high and fluctuating cost of fuels. Due to the nature of the system, sufficient land area for the PV panels would need to be provided in each village, which could either be a barrier to the success of these projects or alternatively an opportunity to ensure community participation. Whereas high-voltage power lines must be maintained by specialist engineers, which has previously led to delays in repairs, training could be provided for local people to maintain the low voltage PV-battery systems, presenting another opportunity to empower local people. The success of micro-grid systems in villages such as these would be contingent on the provision of high-quality training and long-term support, just as the success of the municipal grid connections is contingent on good communication with and continued maintenance by the operating company.

4 Discussion

Four key findings emerge from the paper, relating to the research objectives, which have implications for research, policy and practice on energy access and the delivery of SDG7 in Colombia and beyond.

First, the research revealed that electricity access in Bahia Solano was not a one-step intervention that could simply be delivered to communities. Rather, it was a 'precarious accomplishment' that required ongoing work (see also [17]). Community leaders explained that the electricity grid had been delivered without sufficient consultation or consideration of environmental and economic impacts and ongoing reliability of supply. This appeared to entrench the feeling of disconnect between the villages and the state. Lack of engagement with the communities by the service providers had led to poor maintenance, unreliable electricity supply, and thus a failure to realise the full benefits of electrification. During the first field visit in 2016, for example, many households in Playa Potes and Nabugá did not have access to electricity, despite being considered 'electrified' by local and national government [43]. This contributed to the communities' sense of neglect by the Colombian government, demonstrating that electrification requires ongoing involvement of energy providers whether this be the state, private companies or NGOs. In post-conflict settings, such as the Chocó, where populations are marginalised, additional consideration should be given to how the process of electrification is carried out. This relates to both the technical design of the electricity infrastructure and the manner in which it is delivered. Community participation in the electrification process had been minimal, leading to dissatisfaction and worsening the sense of neglect by the state.

Second, the opportunities to realise the benefits of electrification, such as income generation, health and education, were constrained by three key factors. First, household use of energy did not dramatically increase after electrification due to limited availability and affordability of appliances. Second, the usefulness of some appliances, e.g. fridges, which require a stable and reliable electricity supply was limited by the unreliability of the supply. Third, the remote and isolated location of the municipality meant that infrastructure, basic services and access to markets were restricted. These factors had important consequences for the ability to generate income. Fishing, for example, was an important source of household income; however, increasing this activity requires cold storage (i.e. a stable electricity supply) and access to markets. Neither of these conditions were met in the municipality.

Third, recognising that binary measures of 'have/ have not' got access to electricity are too simplistic to capture complex energy access transitions, a research objective was to use the MTF to characterise households according to their tier of access. Operationalising the framework in this setting was complicated by several, interrelated factors. As discussed in Section 3.2, while most of the time electricity was available 24/7, supply was often interrupted due to tree fall and landslides and, as a result, villages could be without electricity for as long as two weeks. This meant that for long periods, households could be classified as T5 and be reduced to T0 during an outage. Surveys to assess reliability of electricity supply should ask questions to estimate outages over longer periods. In addition, the research revealed that households did not buy appliances in a sequential manner. Rather, some households had a washing machine (a T3 appliance), but no radio, TV or fan (T2), while others had an electric cooker (T5) but no fridge (T4). The lack of sequential purchasing of appliances makes it clear that basing the tier of access on the lowest tier appliance owned is not appropriate. Households purchase different appliances at different times, depending on their needs, aspirations and/ or access to finance. Categorising a household according to the MTF should be combined with social research to gather information on the reasons for appliance ownership patterns. These include social and cultural preferences, affordability, availability or reliability of the electricity supply, which are difficult to capture in the linear MTF and impossible to capture in national statistics. The MTF could include alternative indicators of supply reliability, such as longer-term outages and voltage fluctuations, which can damage appliances and therefore disincentivise their uptake. In addition, input data into the MTF should not come from a single data source or point in time. The technical information may be more accurate when provided by the energy suppliers, while information on the impacts of these supply issues will need to come from the households themselves.

Finally, simple energy system modelling indicated that PV-micro grids with battery storage in each village could provide households with more reliable electricity in a way that is cost-favourable over the lifetime of the project, compared to extension of the municipal electricity grid. Village-scale micro-grids powered by renewable energy could offer a solution that meets these requirements, provided there is sufficient renewable resource, their levelised costs are comparable to or lower than those of the grid connections, and there is suitable provision for operations and maintenance. While factors such as land requirements and battery replacement must be considered, these systems offer an opportunity for increased engagement with local communities, lower costs to the users, and more reliable supply, with lower local and global environmental impacts. As described in section 1.3, Article 185 of the National Development Plan, Law 1715 and several national funds provide an opportunity to finance renewable energy projects for communities in ZNI including in Chocó. Understanding the cost-competitiveness and significant potential benefits of renewable micro-grids should incentivise concerted efforts to consider them as an alternative to grid expansion or diesel generators for future electrification projects. Further work could explore scenarios for larger increases in productive uses of energy, or an uptake of efficient appliances. These changes would likely require additional transport infrastructure so the energy system solutions for those scenarios should be considered in that context of wider regional development.

5 Conclusions

This paper has examined the process, outcomes and alternatives to an electrification programme in Chocó, Colombia, using a mixed methods approach that combined social research and energy system modelling. It has shown how social science research can be used alongside simple tools for energy system design to enable an understanding of the social, cultural and economic impacts of electrification, and how this should guide the design of more appropriate access solutions. This wider understanding of the requirements and practicalities of energy use is vital for grounding techno-economic evaluations of potential solutions in a real-life context. Our continuing engagement with the villages will enable a deeper understanding of the changing nature of access as people purchase different appliances, experience fluctuations in supply, as incomes increase and decrease, and as individuals move through different stages of life.

This research has also shown that the benefits of electrification cannot be assumed, particularly where programmes to deliver access have a narrow focus on the delivery of energy infrastructure alone. Here, the lack of engagement with communities led to an inappropriate and inadequate electrification solution for the setting. Connection to the grid is not always the best solution, especially when environmental conditions make reliable supply challenging. Village-scale micro-grids, based on renewable energy sources, can provide a more appropriate solution. The cost-competitiveness of this option, even considering the challenges of sourcing equipment in a geographically remote region, showed this should be considered for future projects in Colombia and elsewhere.

The current legal framework in Colombia, particularly Law 1715, provides a mechanism to promote more locally appropriate energy solutions in ZNI. However, it should not be forgotten that energy is an enabler and lack of access to electricity may be just one of the challenges faced by geographically, economically and politically isolated communities. In Colombia, the peace process offers an opportunity to design and deliver rural development programmes that address people's multiple needs – beyond energy. These findings have relevance for policymakers, practitioners, researchers and planners working to deliver last-mile energy access everywhere. It cannot be assumed that access to energy alone can drive sustainable development in isolated settings. A more holistic approach to (energy) planning, which engages with local communities and considers the broader context and constraints under which people live, could deliver energy services that create greater social value. While access to modern energy services can open the door to other benefits, a focus on electrification alone is insufficient – it should always be considered a means to an end rather than the goal itself.

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References

[1] Fuso-Nerini, F., Tomei, J., To, L.S., Bisaga, I., Parikh, P., Black, M., Borrion, A. and Castan-Broto, V. Anandarajah, G., Milligan, B. and Mulugetta, Y. (2018). Mapping synergies and trade-offs between energy and the Sustainable Development Goals. *Nature Energy* **3**: 10-15.

[2] UN (2014). Sustainable Energy 'Gold Thread' connecting economy growth, increased social equity, Secretary-General tells Ministerial Meeting. Press Release, United Nations, Washington DC. Available from: https://www.un.org/press/en/2014/sgsm15839.doc.htm [Accessed June 2018].

[3] Reddy, B.S. (2015). Access to modern energy services: an economic and policy framework. *Renewable and Sustainable Energy Reviews* **47**: 198-212.

[4] Huber, M. (2015). Theorising energy geographies. *Geography Compass* **9**(6): 327-338.

[5] Cloke, J., Mohr, A. and Brown, E. (2017). Imagining renewable energy: towards a social energy systems approach to community renewable energy projects in the Global South. *Energy Research & Social Science* **31**: 263-272.

[6] Leopold, A., Stevens, L. and Gallagher, M. (2014). *Poor People's Energy Outlook.* Practical Action Publishing, Rugby. Available from: https://policy.practicalaction.org/resources/publications/item/poor-people-s-energy-outlook-2014 [Accessed August 2018].

[7] Boamah, F., Rothfuß, E. (2018). From technical innovations towards social practices and socio-technical transition? Re-thinking the transition to decentralised solar PV electrification in Africa. *Energy Research & Social Science* **42:** 1-10

[8] Geall, S., Shen, W., Gongbuzeren (2018). Solar energy for poverty alleviation in China: State ambitions, bureaucratic interests, and local realities. *Energy Research & Social Science* **41:** 238-248.

[9] Ulsrud, K., Rohracher H., Winther T., Muchunku C., Palit D. (2018). Pathways to electricity for all: What makes village-scale solar power successful? *Energy Research & Social Science* **44**: 32-40.

[10] Mentis, D., Welsch, M., Fuso Nerini, F., Broad, O., Howells, M., Bazilian, M., Rogner, H. (2015). A GIS-based approach for electrification planning—A case study on Nigeria *Energy for Sustainable Development* **29**: 142-150

[11] Lee, K., Brewer, E., Christiano, C., Meyo, F., Miguel, E., Podolsky, M., Rosa, J., Wolfram C. (2016). Electrification for "Under Grid" households in Rural Kenya. *Development Engineering* **1**: 26-35

[12] Schers, J., van Vuuren D.P. (2012). Model-based scenarios for rural electrification in developing countries, *Energy* **38**: 386-397

[13] Francesco Fuso Nerini, F., Howells, M., Bazilian, M., Gomez, M.F. (2014). Rural electrification options in the Brazilian Amazon: A multi-criteria analysis *Energy for Sustainable Development* **20**: 36-48.

[14] UN (2017). *Progress towards the Sustainable Development Goals: report of the Secretary General*. UN Economic and Social Council, New York. Available from: http://www.un.org/ga/search/view_doc.asp?symbol=E/2017/66&Lang=E [Accessed January 2019].

[15] ESMAP (2015). *Beyond connections: energy access redefined.* Energy Sector Management Assistance Programme (ESMAP) and SE4All, World Bank, Washington DC.

[16] Fuso-Nerini, F., Dargaville, R., Howells, M. and Bazilian, M. (2015). Estimating the cost of energy access: The case of the village of Suro Craic in Timor Leste. *Energy* **79**: 385-397

[17] Kumar, A., Ferdous, R., Luque-Ayala, A., McEwan, C., Power, M., Turner, B. and Bulkeley, H. (2019). Solar energy for all? Understanding the successes and shortfalls through a critical comparative assessment of Bangladesh, Brazil, India, Mozambique, Sri Lanka and South Africa. *Energy Research & Social Science* **48**: 166-176.

[18] Cook, P. (2011). Infrastructure, rural electrification and development. *Energy for Sustainable Development* **15**: 304-313.

[19] Sovacool, B.K. (2012) Design principles for renewable energy programs in developing countries. *Energy & Environmental Science* **5**: 9157-9162.

[20] Yépez, A., Levy, A. and Valencia, A.M. (2016). *The Energy Sector: opportunities and challenges*. IDB Technical Note No. 967, Inter-American Development Bank, Washington D.C. Available from: https://publications.iadb.org/bitstream/handle/11319/7801/The-Energy-Sector-Opportunities-and-Challenges.pdf?sequence=1&isAllowed=y [Accessed November 2017].

[21] SIEL (2016). *Cobertura de Energía Eléctrica a 2015*. Sistema de Información Eléctrico Colombiano, Bogotá. Available from: http://www.siel.gov.co/Inicio/CoberturadelSistemaIntercontecadoNacional/ConsultasEstadisticas/tabid/81/Default.aspx [Accessed November 2016].

[22] IEA (2017). *World Energy Outlook 2017 – energy access database*. International Energy Agency, Paris. Available from: http://www.iea.org/energyaccess/database/ [Accessed August 2018].

[23] IPSE (2015). *Mejoramiento y ampliación de la infraestructura eléctrica de la cabecera municipal de Bahía Solano*. IPSE, Ministerio de Energía y Minas, Bogotá.

[24] IPSE-CNM (2015). *Mapa de cobertura de electricidad en Zonas No Interconectadas*. Centro Nacional de Monitoreo, IPSE, Ministerio de Energía y Minas, Bogotá.

[25] CONPES (2015). *Plan Todos Somos PAZcífico*. Consejo Nacional de Política Económica y Social, Departamento Nacional de Planeación, Bogotá.

[26] Congreso de Colombia (2014). *Ley No. 1715: por medio de la cual se regula la integración de las energías renovables no convencionales al sistema energético nacional.* Congreso de Colombia, Bogotá.

[27] Meurig, C. (2016). *How successful will Law 1715 be in promoting the deployment of renewable energy technologies – both on and off grid in Colombia?* MSc thesis, Centre for Environmental Policy, Imperial College London, London.

[28] Awofeso, N. (2011). Generator diesel exhaust: a major hazard to health and the environment in Nigeria. *American Journal of Respiratory and Critical Care Medicine* **183**: 1437.

[29] Bonet, J. (2007). *¿Por qué es pobre el Chocó?* Centro de Estudios Económicos Regionales, Banco de la República, Cartagena.

[30] Eslava Ramírez, J. (1994). *Climatología del Pacífico Colombiano*. Colección Eratóstenes, Academia Colombiana de Ciencias Geofísicas, Bogotá.

[31] Poveda, G. and Mesa, O. (2000). On the existence of Lloró (the rainiest locality on Earth): enhanced ocean-land-atmosphere interaction by a low level jet. *Geophysical Research Letters* **27**: 1675-1678.

[32] DANE (2015). *Pobreza Monetaria 2015: Chocó*. Departamento Administrativo Nacional de Estadística, Bogotá.

[33] PERS Chocó (2016). *Planes de Energización Rural Sostenible del Departamento del Chocó*. Sistema de Electrificación Eléctrico Colombiano Zonas No Interconectadas, Bogotá.

[34] DANE (2016). *Pobreza monetaria y multidimensional en Colombia 2015*. Boletín Técnico, Departamento Administrativo Nacional de Estadística, Bogotá DC.

[35] Sovacool, B.K., Axsen, J., Sorrell, S. (2018). Promoting novelty, rigor, and style in energy social science: Towards codes of practice for appropriate methods and research design. *Energy Research & Social Science* **45:** 12-42.

[36] Cherni, J.A., Dyner, I., Henao, F., Jaramillo, P., Smith R. and Olalde Font, R. (2007). Energy supply for sustainable rural livelihoods. A Multi-Criteria Decision-Support System. *Energy Policy* **35**: 1493-1504.

[37] Howells, M., HolgerRogner, H., Strachan, N., Heaps, C., Huntington, H., Kypreos, S., Hughes. A., Silveira, S., De Carolis, J., Bazillian, M., Roehrl, A. (2011). OSeMOSYS: The Open Source Energy Modeling System. An introduction to its ethos, structure and development. *Energy Policy* **39**: 5850–5870.

[38] Staffell, I. and Pfenniger, S. (2016). Using bias-corrected reanalysis to simulate current and future wind power output. *Energy* **114**: 1224-1239.

[39] Enair (2019). Small wind turbine Enair 70Pro. Available from: https://www.enair.es/en/small-wind-turbines/e70pro [Accessed January 2019].

[40] Gaona, E. E., Trujillo, C. L., Guacaneme, J. A. (2015). Rural microgrids and its potential application in Colombia. *Renewable and Sustainable Energy Reviews* **51**: 125-137

[41] IRENA (2019), Renewable Power Generation Costs in 2018, International Renewable Energy Agency, Abu Dhabi

[42] Alcaldía de Bahía Solano (2016). *Plan de desarrollo 2016-2019: cambiando para mejorar*. Ciudad Mútis, Bahía Solano.

[43] SIEL (2019). *Cobertura de Energía Eléctrica a 2016*. Sistema de Información Eléctrico Colombiano, UPME, Bogotá. Available from: http://www.siel.gov.co/Inicio/CoberturadelSistemaIntercontecadoNacional/ConsultasEstadisticas/tabid/81/Default.aspx [Accessed February 2019]

[44] IPSE (2014). *Análisis general de la Ley 1715 y su impacto en las ZNI de Colombia*. IPSE, Ministerio de Energía y Minas, Bogotá.

[45] IPSE (2018). *Informe mensual de telemetría*. IPSE, Ministerio de Energía y Minas, Bogotá.

[46] EdBS (2012). *Informe de Gestión*. Empresa de Servicios Públicos de Bahía Solano, Bogotá.

[47] DANE (2016). *Estratificación socioeconómica para servicios públicos domiciliares*. Departamento Administrativo Nacional de Estadística, Bogotá.

[48] van der Kroon, B., Brouwer, R. and van Beukering P.J.H. (2013). The energy ladder: theoretical myth or empirical truth? Results from a meta-analysis. *Renewable and Sustainable Energy Reviews* **20**: 504-513.

[49] World Bank (2018). DataBank: electric power consumption. World Bank, Washington DC. Available from: https://data.worldbank.org/indicator/EG.USE.ELEC.KH.PC?locations=CO [Accessed December 2018].

[50] UPME (no date). *Empresa De Servicios Públicos de Bahía Solano*. Sistema Único de Información, SuperIntendencia de Servicios Públicos, UPME, Bogotá. Available from: http://www.sui.gov.co/web/ [Accessed January 2019].