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The cost and emissions advantages of incorporating anchor loads into solar mini-grids in India

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ABSTRACT

Renewables-based mini-grids have the potential to improve electricity access with lower emissions and better reliability than national grids. However, these systems have a challenging cost to revenue ratio, hindering their implementation. Combining residential loads with an anchor load, a relatively large non-domestic user, can help to improve mini-grid economics. Using measured electricity demand data from India and energy modelling, we assess the cost and emissions advantages of integrating health clinics as anchor loads within domestic solar mini-grids. For comparison, we also assess the ability of the national grid to meet our demand scenarios using monitored grid data. We apply a scenario-based approach, using separate domestic and anchor load demand profiles, and both in combination; we test meeting two levels of energy demand, 95% and 100%; and compare systems using PV and batteries, diesel, and hybrid generation. We find that the national grid has poor availability, at just over 50% at the most comparable monitoring site; and that it would meet a lower fraction of energy demand for our anchor load scenarios than the domestic only ones. For the off-grid systems, we find substantial cost and emissions reductions with anchor loads relative to demand scenarios without anchor loads. At 95% of demand met, we find PV and battery systems are 14-22% cheaper than diesel-only systems, with 10 times lower carbon intensity. Our findings illustrate the role off-grid systems can play in the provision of reliable low-carbon electricity and highlight the advantages of incorporating anchor loads like health centres into such systems.

1. Introduction

Almost 800 million people globally have no access to electricity [1], and it is estimated that a further one billion people suffer from a chronically unreliable or poor-quality supply [2]. Lack of electricity access holds back human development, preventing improved educational outcomes [3,4], health outcomes [5] and livelihood opportunities [6]. India has achieved rapid progress in meeting its target of electrification for all, but one third of households still without grid connections live in one state, Uttar Pradesh, and those that do have them suffer frequent and long outages which are most acutely experienced in rural areas [7,8].

Electricity access challenges are accompanied by an increasing urgency to decarbonise the global energy system: anthropogenic global warming of 1 degree Celsius has already occurred since pre-industrial times, the majority of which can be attributed to emissions from advanced economies [9]. Nevertheless, utilising low-carbon generation technologies to increase electricity access in emerging economies is a key route to minimising additional greenhouse gas (GHG) emissions and future carbon lock-in of polluting generating capacity [10–12] and thus aids progress towards Sustainable Development Goal (SDG) 13: taking urgent action to combat climate change [13].

Three main electricity supply options are available for meeting unserved populations: national grid extension, local or mini-grids and stand-alone systems; with the density of the population and household demand level important factors in determining which is most suitable for a given household or community [14]. The International Energy Agency (IEA) estimates that achieving universal access to electricity by 2030 (SDG 7) would need 70% of new connections in rural areas to come from mini-grids or stand-alone systems [15]. Moreover, it is considered that mini-grids are now the least-cost electrification solution for 490 million currently unserved people [16]. Despite grid extension being the favoured option for rural electrification historically, the reliability and decreasing costs of mini-grids have led policymakers, developers and national grid representatives to view mini-grids and a viable alternative to the centralised network [17]. Furthermore, a recent study in

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Uttar Pradesh and Bihar found that rural communities adopt mini-grids even in grid-connected villages owing to the improved service reliability that the decentralised systems offer [18].

Renewables based mini-grids have demonstrated the potential to offer reliable electricity to off-grid communities, yet significant upfront capital expenditure requirements may necessitate subsidies for viable operation [19]. High capital cost remains a challenge for developers despite reductions of 50% over the last decade [20,21]. These high costs are coupled with low average revenues per user and many off-grid rural customers have a low ability to pay for electricity [16]. In the poorest 40% of households in half of the countries with lowest access, the cost of obtaining an electricity connection is greater than an entire month's income [16], and a basic level of consumption (30 kWh/month) is considered unaffordable [22]. Furthermore, the cost of acquiring electric appliances can be unaffordable, holding back consumer demand [23]. General uncertainty in the consumer demand levels of newly connected customers is a significant financial risk for developers [24].

One route to improving the financial viability of mini-grids is to incorporate anchor loads to mini-grids supplying domestic customers. Anchor loads are larger, consistent consumers of electricity with greater capacity to make reliable payments, reducing the risk of connecting smaller consumers with low ability to pay. Anchor loads can also perform important social and economic functions for a community, which makes this model additionally attractive [25]. In India, telecommunication towers are the anchor load in some mini-grids with the surrounding community using surplus electricity [26]. Using hypothetical demand data, techno-economic analysis has found a 48% reduction in the unit cost of electricity when anchor loads constitute 30% of the load in PV and battery mini-grids [27]. Another techno-economic study, using estimated demand and willingness to pay data, suggests that a business model for a mini-grid operator using PV and batteries with anchor loads offers improved viability, but still requires subsidies [25]. Rural health centres acting as an anchor load may provide additional benefits since, as well as improving the viability of off-grid systems, they enable the supply of electricity for healthcare needs [28,29]. Other options for additional loads in rural India are often agricultural and seasonal, meaning they cannot provide consistent demand and payment year-round [30]. Health centres do not experience seasonality in the same way and therefore may present a more suitable alternative.

Access to electricity for rural unserved health facilities has been demonstrated to improve patient outcomes [5] and therefore enables further progress towards SDG3: ensuring healthy lives and promoting wellbeing for all [13]. Electricity can extend the hours of service through the provision of lighting, allow the use of life-saving electrical medical equipment and improve staff recruitment and retention [29]. Additionally, electricity is needed for maintaining the cold chain that allows for storing blood and temperature-sensitive medicines such as vaccines [31,32]. A lack of electricity supply has serious consequences for healthcare provision in low-income countries. For example, at night in the absence of electric lighting practitioners are forced to perform surgery or child delivery using candles or mobile phone torches, significantly increasing patient risk [33,34]. The reliability of any supply is of vital importance. Good quality electricity supplies result in health centres using energy services more widely in their care provision, improving outcomes [35]. Further, blackouts and voltage drops – that cause life-support equipment such as ventilators to cease functioning – lead to a higher incidence of patient mortality [36].

Despite its importance for boosting human health outcomes, electricity access for healthcare remains a significant challenge. Roughly a billion people globally are reliant on health facilities that lack access to electricity; in India, 50% of primary health centres (PHCs) still have no reliable access, with a further 38 million people dependent on a PHC with no electricity at all [37]. In India's most populous state Uttar Pradesh, where this research is focused, access is amongst the lowest across states: 30% of PHCs have no access to electricity at all, and only 10% have a reliable supply [38].

This paper contributes novelty in that it is the first techno-economic assessment of rural health facilities acting as anchor loads in domestic mini-grids. Differing from previous studies, this work also exploits high-resolution monitored demand data and detailed cost data from an existing domestic solar mini-grid site in its exploration of anchor loads. Further novelty arises from the use of granular, monitored grid availability data from close to the case-study site to estimate the ability of the national grid to meet various demand scenarios and thus give a comparison of different electrification options. It uses energy system modelling to investigate the hypothetical impact on the unit cost and emissions intensity of electricity of integrating rural health facilities into solar and battery mini-grids powering domestic demand. In addition to a comparison with the national grid, it compares these results to diesel-only and solar-diesel hybrid mini-grids.

2. Methodology

To investigate the use of health centres acting as anchor loads in mini-grids, we created 5 different demand profiles consisting of demand data from two health centres and a rural village located in Northern India. These demand profiles were used in energy system modellling to find least-cost and least-emission electricity system configurations. In addition, we created three national grid electricity profiles and assessed their ability to meet the demand of the 5 demand profiles.

The methodology is depicted in Figure 1 and described in more detail in the following sections:

- Section 2.1: Description of the construction of five hourly energy demand profiles incorporating domestic and health centre demand used for this study. We use a mixture of monitored demand data and energy use survey data.
- Section 2.2: Explanation of the use of monitored grid data to select and construct three hourly national grid profiles with varying levels of availability. We use the demand profiles and grid availability profiles to assess the ability of the grid to meet this hypothetical demand.
- Section 2.3: Using the demand profiles and additional financial, emissions and technical data, we use energy system modelling to find the cost and emissions optimal mini-grid system sizes capable of supplying 95% and 100% of energy demand to each demand scenario.

2.1. Demand scenarios

2.1.1. Domestic

For the domestic demand profile, we used power usage data monitored from households connected to a direct current (DC) solar and battery mini-grid in the village of Sarvantara located in the district of Bahraich, Uttar Pradesh, India. The system has been operational since June 2017 and supplies approximately half of the 100 households in the village with electricity for USB phone charging, LED lighting and fans. The national grid is present in the village with the mini-grid operating alongside it.

At the time of data collection, 45 households were connected to the mini-grid, 29 of which were being monitored by smart meters (BBOXX Ltd, UK), providing minute-by-minute load data which we aggregated to give hourly energy for one-year from 1.12.2017 – 30.11.2018. To represent the load of all households connected at the time, we synthesised 16 additional household profiles from the existing data of the 29 monitored households to represent the total community size of 45 households. We assumed the data followed a normal distribution and used the hourly mean and standard deviation of the existing data to produce randomised values for every hour in the year, to be used for the additional household profiles. Where gaps in the datasets existed for other households, such as periods where data were missing due to meter faults, these were synthesised using the same procedure.

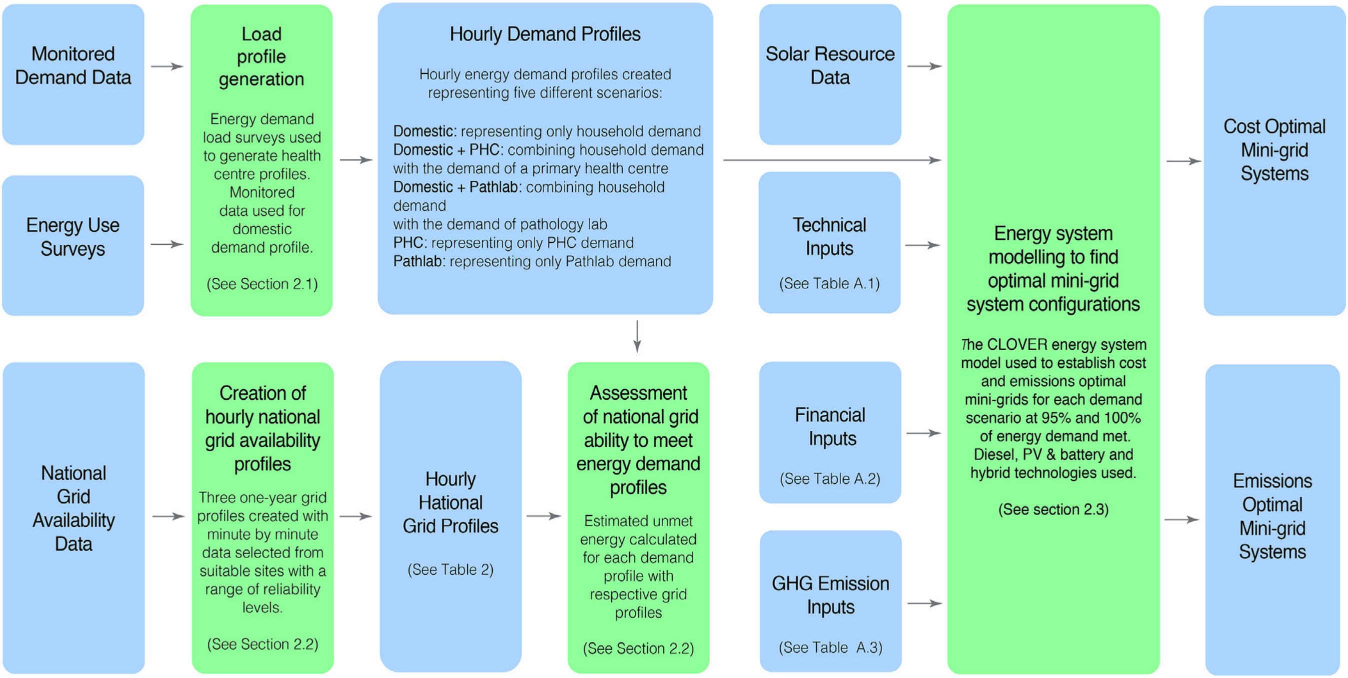

Fig. 1. Showing outline of the methodological process. Inputs and outputs are shown in blue, with processes in green.

Table 1
Summary information about the two health facilities used for this study

Clinic	Location	Opening Hours	Devices
PHC	Navapur, Maharashtra	09:00 – 17:00	Lights, fans[*], ILR, freezer, nebulizer, suction machine, shadowless lamp, fetal monitor
Pathlab	Bahraich, Uttar Pradesh	07:00 – 20:00	LED lights, fans[*], analyser, blood mixer, cell counter, centrifuge, exhaust fans, fridge, incubator, laptop, microscope, nebulizer, spectrophotometer, printer, X-ray machine

[*] Fans only in use in the summer months

2.1.2. Healthcare facilities

For the health centre demand profiles, we used data from two facilities: a pathology lab located 50 km from the village of Sarvantara, and a primary health centre, located in the state of Maharashtra. The data for the two health centres were gathered via correspondence with local organisations Oorja Development Solutions & Gram Oorja. These organisations carried out quantitative load surveys that detailed existing electrical devices in use with their daily usage pattern and respective power rating. The usage hours were converted into probability profiles that indicate the likelihood that a given device would be in use in a given hour of the day, to meet the model input requirements. For a detailed explanation of the health centre load profile generation see Supplementary Information S1.

The PHC used for this study is broadly typical of those in rural India in terms of services offered, and with opening hours from 9:00 to 17:00. The devices used at the facility are listed in Table 1. The data obtained from the PHC were supplemented with data from other appropriate sources where incomplete: for further details see Supplementary Information S1.

The pathology lab (Pathlab) is a larger facility than the PHC but is also located in a rural area. The main activity performed in the Pathlab is the analysis of medical samples of patients, which is why it has a greater a greater range of devices in use (see Table 1). It therefore represents a health centre that is larger and has a higher electricity consumption than the PHC, but is still critical to a rural community. It has opening hours of 7:00 to 20:00, when patients can arrive to give samples and receive results. The probability profiles for most devices were calculated by dividing the total device usage hours by the number of opening hours as it was reported that they only consumed energy during opening hours. Some exceptions exist: LED lights were reported to be used beyond normal opening hours and had different usage patterns depending on whether it was summer or winter. The fridge was expected to have a constant electricity demand across all hours of the day, and outside opening hours. We assumed the X-ray machine had a constant power requirement of 0.6 kW during the opening hours of the Pathlab, which is an often-cited wattage for the standby mode [39–41].

2.2. Indian national grid

Before calculating the implications of use of mini-grids to meet domestic and health centre loads, monitored grid availability data is used to assess the reliability with which the national grid, as it currently operates, could meet these loads. Grid data are publicly available from monitoring locations across India from the Prayas Energy Supply Monitoring Initiative (ESMI) database [42]. We examined the data availability and the grid service level for the months between November 2017 and March 2019, across nine monitoring locations ranging between 4 and 37 km from the Sarvantara mini-grid site. From these, we selected three monitoring locations with a range of service levels and settlement types that had adequate data availability to construct three one-year profiles using data from February 2018 to January 2019. The profiles represent high, medium and low availability from a city, a small town and a village, respectively (see Table 2). In this instance, availability is defined as the percentage of minutes during which electricity supply is available in the time period examined.

Table 2

Summarising the locations used for the grid comparison

Location Name	Grid Strength	Availability (% of time)	Availability (hours per day)	Settlement type	Distance from mini-grid site
Bhavaniyapur, Bahraich	Weak	52.2%	12.5	Village	4km
Nanpara, Bahraich	Moderate	71.0%	17.0	Small town	8km
Nazipura, Bahraich	Strong	95.5%	22.9	City	37km

The data for monitoring locations in the ESMI database has some hours where no data is recorded. This occurs when the recording device is turned off, for example, due to device maintenance [43]. To fill these gaps, we used the mean values for that hour of the day in the relevant month to give a complete profile.

We used the grid profiles to compute the unmet energy for each of our demand scenarios. Our load profiles are comprised of total energy demanded for each hour $E_D(t)$; the demand is assumed constant within each time-step. The unmet energy in each timestep $E_U(t)$ is the product of the fraction of the hour where supply is unavailable $U(t)$ and the demand in that hour $E_D(t)$:

$$E_U(t) = U(t)\circ E_D(t) \tag{1}$$

The unmet energy fraction E_{UF} calculated for each grid profile and demand scenario is therefore described as:

$$E_{UF} = \sum_{t=0}^{t_{max}} \frac{E_U(t)}{E_D(t)} \tag{2}$$

This method assumes that unmet energy demand caused by a blackout would not be shifted to other hours with higher availability. The unmet energy fraction E_{UF} calculated for each demand profile on an hourly basis from each grid location provides a truer indication of the suitability of the local grid to supply each demand scenario than assuming that the overall percentage of time where supply is unavailable is equal to the fraction of energy unmet. The results of this for each demand scenario are shown in Section 3.2.

2.3. Energy system modelling

We used the open-source energy model CLOVER ("Continuous Lifetime Optimisation of Variable Energy Resources") to optimise mini-grid systems with the minimum unit cost and emissions intensity of electricity for each scenario over a system lifetime of 20 years. CLOVER was developed by [44], written in Python and is freely available on Github.

We investigated the use of electricity supply systems using the following technologies:

a) PV and battery storage
b) Diesel generation
c) A hybrid system using PV, batteries and diesel

We examined two levels of energy demand met. For meeting 95% of energy demand we compared (a) and (b), and for meeting 100% of demanded energy we compared (a), (b) and (c). We chose to use 95% of demanded energy met as our base case as this is the highest level of energy demand met offered by the grid in the region (see Table 4 in the Results section), and we test 100% of demanded energy to understand the cost and emissions of full reliability. In our description of energy demand met, there is no consideration of outages that may occur due to system failings not related to energy deficits, or due to maintenance requirements.

A full mathematical description of the CLOVER model is available in [45] and [46]; however, we describe in a simplified form how the model simulates systems below. We made minor changes to the model for this research, also outlined below.

2.3.1. System simulation

CLOVER simulates energy systems that comprise any combination of solar PV, energy storage and diesel generation over a multi-year time horizon; it can also incorporate power supplied from a national grid network with a defined availability profile. For systems incorporating PV, CLOVER directly extracts hourly estimated generation data for the co-ordinates of the site from the renewables.ninja API, which uses the MERRA-2 global dataset of historical solar resource [47].

The model operates with an hourly resolution, and in the first simulation function calculates an energy balance profile. In any given timestep it uses the energy demand $E_D(t)$ and the available energy from the PV array $E_{PV}(t)$ to calculate the energy balance $E_{Ba}(t)$:

$$E_{Ba}(t) = E_{PV}(t) - E_D(t) \tag{3}$$

Next, the model uses the hourly energy balance profile $E_{Ba}(t)$ and technical specifications of the system (see Table A.1) to simulate how it will operate over its lifetime. The energy that flows in and out of the storage capacity, S, in any given hour t, referred to as $E_F(t)$, is limited by the charging and discharging C-rates, C_{in} and C_{out}. For any given hour, the storage energy flow $E_F(t)$ is therefore given by

$$E_F(t)\begin{cases} (S)(C_{in}) \text{ for } E_{Ba}(t) > (S)(C_{out}) \\ -(S)(C_{out}) \text{ for } E_{Ba}(t) < -(S)(C_{out}) \\ E_{Ba}(t) \text{ Otherwise} \end{cases} \tag{4}$$

The storage energy flow $E_F(t)$ is added to the storage energy level in the previous timestep $E_S(t-1)$, to provide a storage level for the current timestep $E_S(t)$:

$$E_S(t) = E_S(t-1) + E_F(t) \tag{5}$$

The model ensures that the hourly storage energy $E_S(t)$ is within the maximum and minimum storage bounds, S_{max} and S_{min}, as defined by the user. If $E_S(t) > S_{max}$ then the surplus energy is dumped and $E_S(t)$ is set to S_{max} and the unmet energy for the hour $E_U(t)$ is zero. If $E_S(t) < S_{min}$ then unmet energy for the timestep $E_U(t)$ is greater than zero:

$$E_U(t) = S_{min} - E_S(t) \tag{6}$$

When the value of $E_S(t)$ would otherwise fall below the minimum permitted, the storage level for the hour $E_S(t)$ is instead set to the minimum, S_{min}.

In hours with unmet energy, the model records a blackout in a binary blackout profile, $B(t) = 1$. For hours where unmet energy is zero, $B(t) = 0$. Following this simulation function, the blackout rate B_r is calculated:

$$B_r = \sum_{t=0}^{t_{max}} \frac{B(t)}{t_{max}} \tag{7}$$

If the system is set to incorporate diesel generation, the model will use the system blackout rate B_r and a user defined threshold of the fraction of permitted blackout hours B_{Th} to meet unmet demand E_U with diesel energy E_{DL}. When the blackout rate $B_r > 0$ and the permitted $B_{Th} = 0$ (i.e. the system must meet all demand), in all hours where $B(t) = 1$, diesel backup is used to meet unmet demand, $E_{DL}(t) = E_U(t)$.

When $B_r > 0$ and the $B_{Th} > 0$, (i.e. some blackouts are permitted) the model fills in blackout hours that have the greatest unmet energy demand $E_U(t)$ first, until the blackout rate B_r for the simulation has reached the desired blackout threshold B_{Th}. To do this it assigns a binary value to the required number of hours to reach the blackout threshold B_{Th} using a profile $M(t)$: where demand is to be met $M(t) = 1$, and for the remaining hours $M(t) = 0$ meaning demand is not to be met. Diesel energy thus fills in the unmet energy for the required hours:

$$E_{DL}(t) = E_U(t)\circ M(t) \tag{8}$$

To simulate the diesel-only micro-grid systems we included no PV or battery storage capacity in the model and therefore the diesel back-up acted as the only source of generation meeting the resulting unmet energy from the initial parts of the system simulation.

The model allows the user to define the technical characteristics an energy system in detail, including conversion and transmission efficiencies, the degradation of PV capacity, and degradation of battery storage capacity as a function of time and energy throughput, over the lifetime of the system. The values we used are, where possible, based on the existing mini-grid at Sarvantara and are provided in Table A.1.

2.3.2. Model modifications

2.3.2.1. Battery replacement. Given the simulated time horizon of 20 years, it is a likely requirement during the project life for the storage capacity to be replaced if it degrades beyond a certain point. To do so we added a condition in the model, the storage replacement capacity S_{rc}. For each hour, the value of the usable storage capacity $S_u(t)$ is calculated from the installed storage capacity S and the factor by which the storage has degraded $S_{deg}(t)$:

$$S_u(t) = S \circ S_{deg}(t) \tag{9}$$

If $S_u(t) \leq \ S_{rc}$ then $S_u(t) = S$ and this timestep in the simulation is recorded so that the discounted costs and associated emissions are taken into account when these are calculated for a given system in the optimisation process described below.

2.3.2.2. Hybrid AC and DC distribution. Due to the demand data sourced, we assumed hybrid AC and DC distribution. The model was adapted to tolerate this, treating each load segment with differing relative conversion and loss factors, and sizing the inverter or rectifier within the model only for the components of demand that would be fed through them.

2.3.3. System optimisation

2.3.3.1. Optimisation criteria. We used the CLOVER model to optimise systems for both cost of and emissions intensity of electricity for each of our demand scenarios. Similarly to [44] our metric for economic assessment is the levelised cost of used electricity (LCUE) in $/kWh. This metric explicitly accounts for only the useful energy consumed by the users, relevant in situations with overgeneration or shortfalls in demand satisfaction, as is the case in the scenarios modelled here. The LCUE will be greater than or equal to the levelised cost of generated electricity (LCOE), a more commonly used metric. As off-grid PV systems often dump a significant fraction of the electricity generated due to an imperfect match between supply and demand, LCUE is therefore is a more appropriate metric in this context.

The LCUE is the discounted sum of all capital investment I_n, operation and maintenance M_n, and fuel costs F_n in every year n, divided by the sum of the discounted energy E_n that is *used* in each year:

$$LCUE \ = \frac{\sum_{n=1}^{N} \frac{I_n \ + \ M_n \ + \ F_n}{(1+r)^n}}{\sum_{n=1}^{N} \frac{E_n}{(1+r)^n}} \tag{10}$$

The same approach applies to the emissions intensity of used electricity (EIUE) electricity generated but dumped is not considered. The emissions intensity is the sum of embedded emissions $G_{e,n}$ in installed equipment and operating emissions $G_{o,n}$ from the electricity system in every year over the lifetime of the project divided the sum of all energy used:

$$EIUE = \frac{\sum_{n=1}^{N} G_{e,\ n} + \ G_{o,n}}{\sum_{n=1}^{N} E_n} \tag{11}$$

For a full description of the cost and greenhouse gas emissions model inputs see appendix Tables A.2 and A.3.

2.3.3.2. Optimisation process. CLOVER uses a form of exhaustive search optimisation, described fully in [45] and (33), to identify the combination of component sizes that meet the requirements that the user has defined. The model performs simulations for systems (as described in Section 2.3.1) with incrementally increasing PV and storage sizes to find the optimum system (defined as that which minimises the optimisation criterion, LCUE or EIUE in this study). It steps through a predefined set of PV and battery sizes but has a mechanism to ensure when an edge case occurs, the model will simulate further systems to ensure the optimum is found.

The sizes of PV and battery units considered by the model are defined by the user; we chose 0.3 kWp as our PV module sizes, and 1kWh for storage, as these represent real component sizes used (see appendix Table A.1). The hourly output of the resulting simulations combined with the financial and cost data are used to compute the LCUE and EIUE of the systems. For a system to be considered as a potential optimum, either with the lowest LCUE or EIUE from the set of simulated systems, it must meet a defined sufficiency threshold. The sufficiency threshold in our case is a maximum fraction of unmet energy that is permitted over simulation period. Figure 2 shows a graphical representation of the relationship between these thresholds and the optimal system configuration for an example demand scenario.

3. Results

3.1. Energy demand

The hourly energy demand curves for all the demand scenarios are shown in Figure 3. Table 3 gives the average total daily energy demand for all scenarios and the fraction of demand occurring at night. For the domestic demand, the average daily household consumption is 0.15 kWh.

For both health centres, the demand is highest during their respective opening hours. The required energy for the Pathlab is considerably higher than for the PHC as it uses more electrical equipment. Relatively low and constant demand is observed out of hours due to the use of devices requiring constant supply such as refrigerators. The domestic demand of the village shows a different demand pattern, with the demand lowest during the day, and increasing in the evening, remaining high overnight. The village residents keep their lights on overnight for security reasons, to protect their homes and livestock [48], meaning the domestic scenario has the greatest proportion of demand at night of any scenario. The domestic demand profile and the health centres' demand profiles are complementary and when combined, result in a more balanced demand pattern over the day.

Nonetheless, as shown in Table 3, the *Domestic + PHC* scenario still has most of its demand occurring out of the solar irradiation hours (at 59%, albeit lower than the 76% of the *Domestic only* scenario, as expected). For the *Domestic + Pathlab* scenario, the peak demand occurs in the evening hours after sunset which would be expected to increase the storage requirement of the system compared to the *Pathlab only* scenario.

3.2. National grid unmet energy

For comparison with the alternative electrification option of connection to the national grid, we estimated unmet energy that would arise for each of the demand scenarios from three grid locations close to the mini-grid site. The three locations represent a range of grid availability levels and are from different geographies (see Table 2) with the closest site and most representative of the grid locations being the 'weak' one, from the nearby village of Bhavaniyapur.

Table 4 shows the estimated unmet energy of each of the demand profiles across the three sites. For the *Domestic* demand scenario, for all three grid locations, the unmet energy fraction is lower compared to the percentage of minutes the grid is unavailable. This is due to the

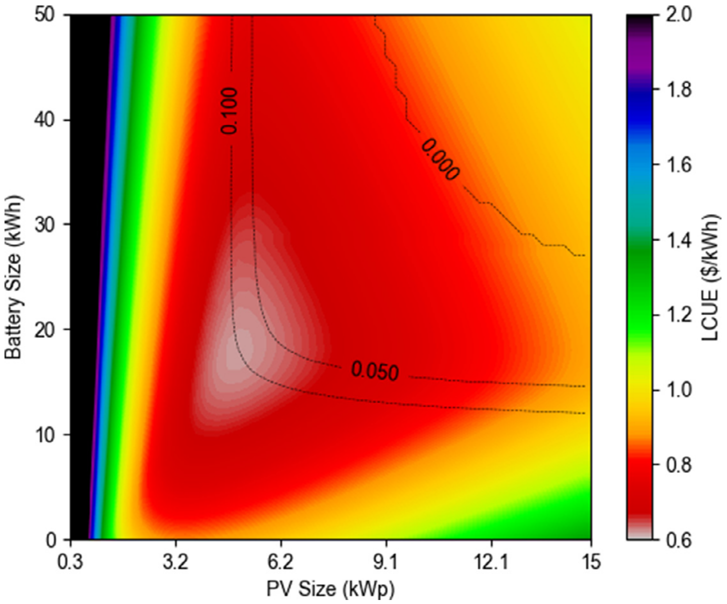

Fig. 2. Showing the LCUE ($/kWh) of 2450 PV (0.3 – 15kWp) and battery systems (0-50kWh) considered for the *Domestic + Pathlab* demand scenario. The heatmap is formed from the LCUE ($/kWh) of each system configuration simulated, with the contour lines marking the unmet energy thresholds for 10%, 5% and 0%; and the sufficient systems. The lowest LCUE systems are at or around 10% unmet energy, with a significant jump in both storage and PV capacity required between 5% and 0% unmet energy. If the sufficiency threshold is set to 5% of unmet energy, only the tested systems above that contour line would be considered.

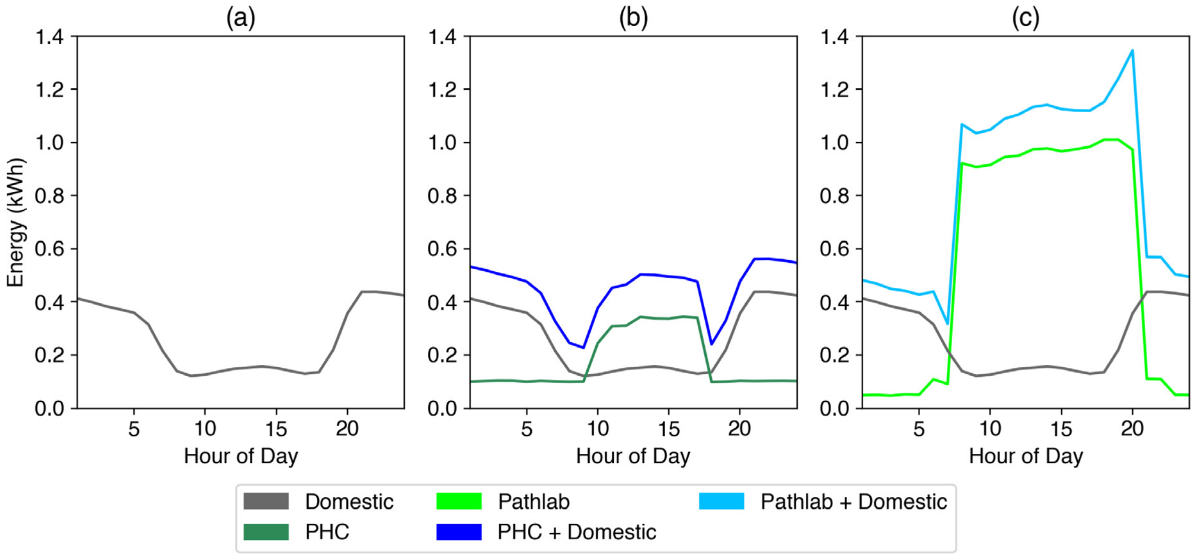

Fig. 3. shows the shape of the daily demand profiles for all scenarios. Panel (a) shows the domestic load curve alone. Panel (b) shows the domestic, PHC and PHC + domestic curves. Panel (c) shows the domestic, Pathlab and Pathlab + domestic curves

Table 3
Energy demand of the five scenarios. The night demand fraction is calculated by assuming that the average daylight hours are from 7:00 to 18:00.

Scenario	Average Daily Demand (kWh)	Average night demand fraction
Domestic	6.9	76%
PHC	4.5	32%
Pathlab	14.4	21%
Domestic + PHC	11.4	59%
Domestic + Pathlab	21.3	39%

majority of demand happening overnight when the average availability of all three grid locations is better (see Figure 4). Critically, for the *PHC* and *Pathlab* scenarios, the unmet energy fraction is substantially higher than the proportion of time the grid is unavailable overall, meaning that blackouts tend to occur during periods of higher demand during daytime hours when the clinics are open.

These results suggest that in rural locations the grid is inadequate, especially for the daytime uses of the health centres. The high levels of unmet demand estimated suggest that for a more reliable supply, in the absence of national grid improvements users may require other forms of generation such as mini-grids or stand-alone systems.

Table 4
showing the results of estimated unmet energy for each demand scenario across three grid profiles. The minutes unavailable for each grid profile can be compared with the amount of unmet energy expected for each demand profile.

	Minutes unavailable:	Bhavaniyapur Bahraich (Weak) 47.8%	Nanpara (Moderate) 29.0%	Nazipura Bahraich (Strong) 4.5%
Scenario	Night Demand	Unmet energy fraction	Unmet energy fraction	Unmet energy fraction
Domestic	74%	46.1%	26.6%	4.3%
Domestic + PHC	58%	48.6%	28.9%	4.8%
Domestic + Pathlab	43%	50.7%	31.9%	5.3%
PHC	32%	52.2%	32.4%	5.5%
Pathlab	28%	52.9%	34.4%	5.7%

Table 5
Results summary for PV and Battery systems optimising for cost with 95% of energy demand met

	PV Size(kWp)	Battery Size(kWh)	Dumped energy fraction	LCUE($/kWh)	Emissions Intensity (gCO2/kWh)
Domestic	2.1	12	15.0%	1.35	120.44
Domestic + PHC	3.3	17	11.7%	0.95	113.68
Domestic + Pathlab	6	20	10.5%	0.63	97.23
PHC	1.2	5	9.6%	1.45	93.23
Pathlab	3.9	10	9.1%	0.65	92.38

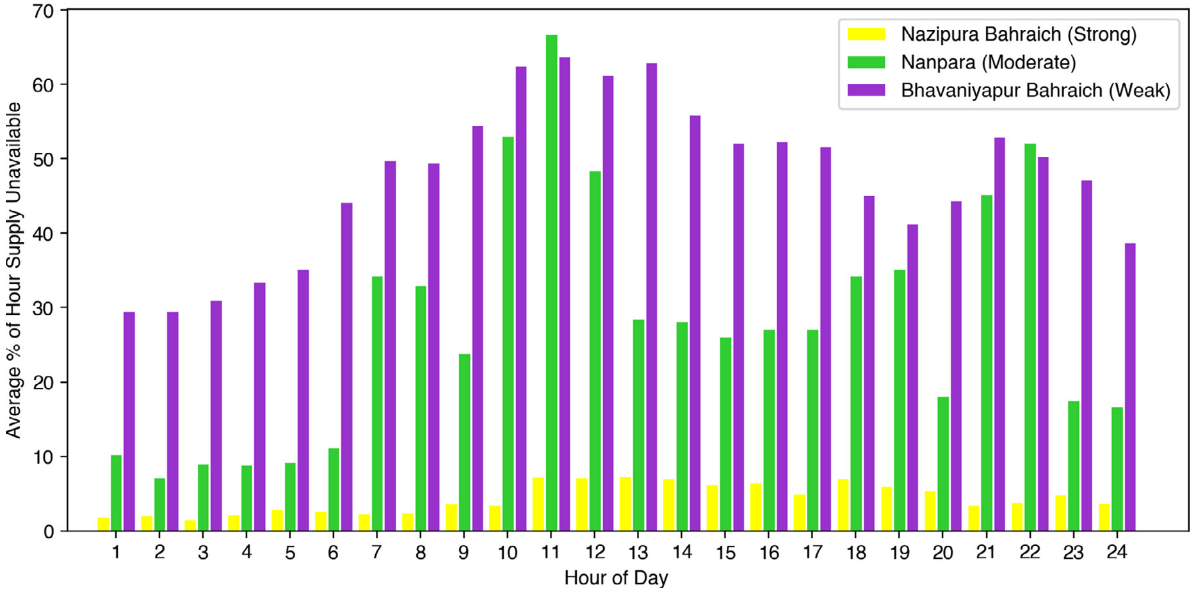

Fig. 4. Average proportion of each hour of the day where electricity supply is unavailable for each of the three grid locations. For all three locations, a peak towards the middle of the day can be observed, with a further clear evening peak for the Moderate and Weak locations.

3.3. Cost and emissions implications of health centre anchor loads

This section outlines the findings on cost and emissions of electricity for PV with battery systems as well as diesel only systems that meet 95% of energy demand (see Figure 5).

3.3.1. PV and battery systems

This section compares characteristics of optimised microgrid systems incorporating solar PV and batteries (without diesel backup) to meet domestic and health centre loads alone and in combination. Relative to the *Domestic* scenario, the *Domestic + PHC* and *Domestic + Pathlab* scenarios achieve a 30% and 53% reduction in LCUE, respectively. When comparing the individual health centre scenarios (*PHC or Pathlab*) to the scenarios combined with domestic demand (*Domestic + PHC* or *Domestic + Pathlab*), the results are mixed. There is a substantial reduction in the LCUE of 35% for the PHC, but a smaller reduction of 2.5% for the Pathlab. This may be explained by the increased fraction of dumped energy that the *Domestic + Pathlab* scenario has compared to the *Pathlab* scenario due to the higher fraction of night demand, which offsets some of the cost savings from the economies of scale of larger systems. Additionally, the health centre-only scenarios are considered without the distribution network for domestic users, and therefore have a reduced capital equipment cost which subsequently reduces their LCUE.

The emissions intensity of energy is lower for the *Domestic + PHC* (by 5.6%) and *Domestic + Pathlab* (by 19.3%) scenarios compared with the *Domestic* only scenario. However, when comparing the respective combined scenarios with the *PHC* or *Pathlab* only scenarios, there are greater emissions intensities (of 21.9% and 5.3% respectively). There is an association of increased fraction of dumped electricity with greater emissions intensity, which indicates why the health centre-only scenarios have lower emissions intensities.

In addition to LCUE, we optimised the PV and battery systems for emissions intensity of used electricity (EIUE). For all but the *PHC* scenario, the systems had larger battery capacities but identical or slightly

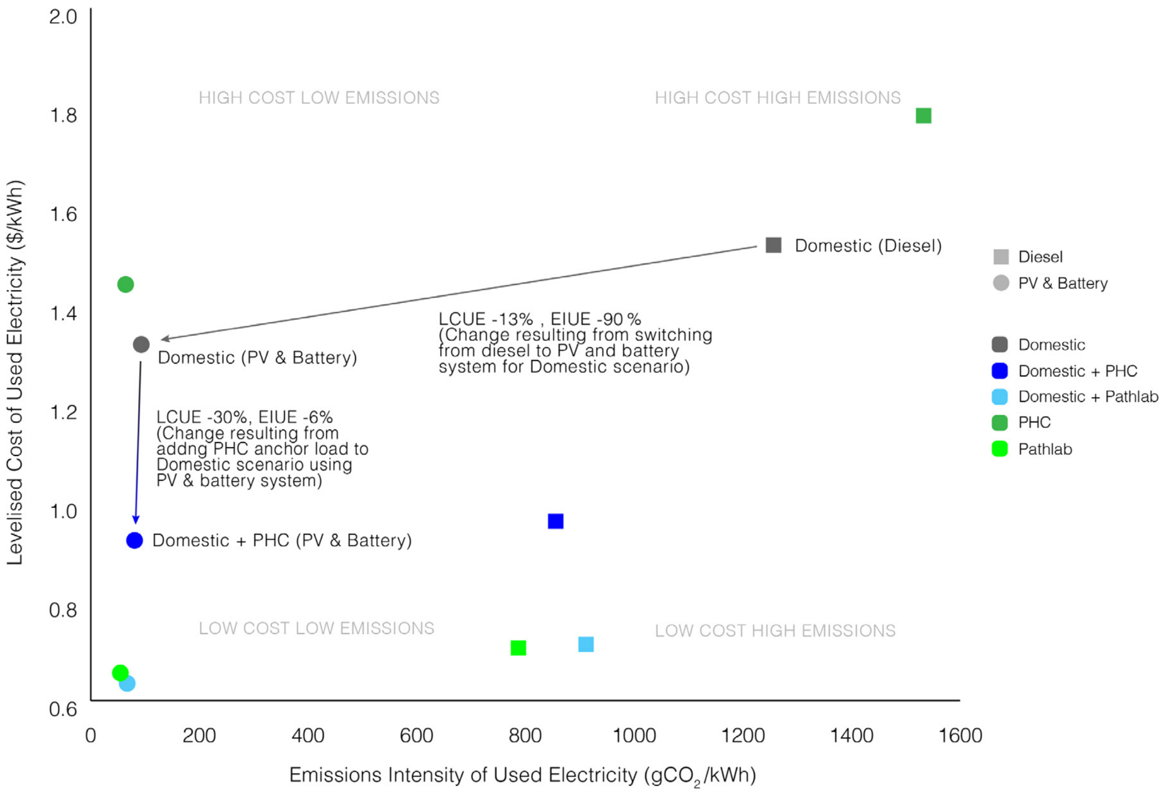

Fig. 5. compares the levelised cost of used electricity ($/kWh) and emissions intensity of used electricity for PV and diesel systems for each demand scenario at 95% of energy met. The figure highlights the change in LCUE and EIUE from switching from diesel to PV for the domestic scenario, and from integrating the PHC as an additional load to the domestic mini-grid.

Table 6
Results summary for diesel-only systems optimising for cost with 95% of energy demand met

Scenario	Diesel Capacity (kW)	Average capacity utilisation	Diesel efficiency (litres/kWh)	*LCUE ($/kWh)* (% change from cost optimal PV & battery)	Emissions Intensity (gCO2/kWh) (% change from cost optimal PV & battery)
Domestic	2	18.5%	0.46	1.55 (+14.3%)	1259.96 (+946.1%)
Domestic + PHC	2	30.5%	0.32	0.97 (+2.1%)	858.92 (+655.6%)
Domestic + Pathlab	4	27.6%	0.34	0.75 (+18.3%)	917.55 (+820.3%)
PHC	2	15.1%	0.56	1.81 (+20.2%)	1539.47 (+1446.5%)
Pathlab	3	39.9%	0.29	0.74 (+14.6%)	794.35 (+759.9%)

smaller PV sizes and with a reduced fraction of energy dumped. The EIUE was 12-16% lower and accompanied by increases of ~1-4% in LCUE, representing a small increase in cost for a more substantial reduction in emissions intensity. For detailed results see S2 of the Supplementary Information.

3.3.2. Diesel-only systems

Table 6 shows the results of the different demand scenarios at 95% of demand met solely using diesel generation. Notably, when comparing with the cost optimal PV and battery systems, the diesel-powered systems have 14.3 – 22.1% higher LCUE, and the emissions intensities are in the order of magnitude of ten times higher than the emissions optimal PV and battery systems (see Figure 5).

Apart from the *Pathlab* scenario, the same trend is observed as with the PV and battery scenarios: lower costs for the combined scenarios (*Domestic + PHC*, and *Domestic + Pathlab*) than for the individual scenarios (*Domestic, PHC*). An exception to this rule is the *Domestic + Pathlab* scenario, which is marginally more expensive (<1%) than the *Pathlab* alone. Broadly, for diesel systems, the scenarios with greater overall demand have both higher operating fuel efficiency and higher generator capacity utilisation, which are associated with lower LCUEs and EIUEs.

3.4. Sensitivity of results to increased energy demand met

In a healthcare context, it is particularly important to provide a reliable electricity supply. This section presents the cost and emissions of systems that meet 100% of the energy demanded over the system lifetime (see Figure 6). These are compared to systems already presented meeting 95% of demanded energy.

3.4.1. PV and battery systems

Optimising PV and battery systems for cost which could hypothetically meet 100% of energy demand led to significant increases in the installed capacity of both batteries and PV panels for all scenarios, and

Table 7
Results summary for PV & Battery systems optimising for cost with 100% energy demand met

Scenario	PV Size(kWp)	Battery Size(kWh)	Dumped energy Fraction	LCUE($/kWh) (Change from PV & battery system meeting 95% ofdemanded energy)	Emissions Intensity (gCO2/kWh) (Change from PV & battery system meeting 95% ofdemanded energy)
Domestic	3.9	18	42.6%	1.55 (+14.6%)	158.32 (+31.5%)
Domestic + PHC	6.3	26	41.2%	1.16 (+22.3%)	153.49 (+35.0%)
Domestic + Pathlab	9.9	40	37.2%	0.82 (+30.2%)	132.09 (+35.9%)
PHC	2.1	8	38.2%	1.60 (+10.7%)	142.71 (+53.1%)
Pathlab	6.3	22	35.7%	0.82 (+26.5%)	126.67 (+37.1%)

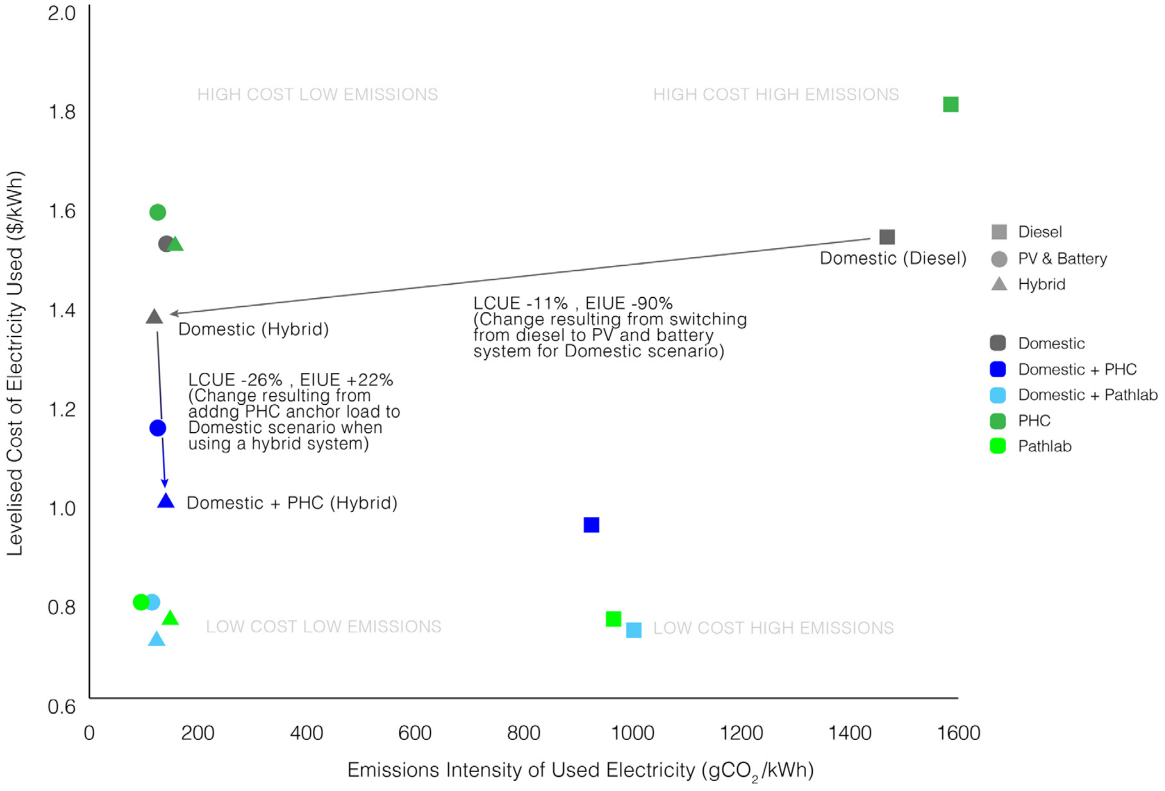

Fig. 6. compares the levelised cost of used electricity ($/kWh) and emissions intensity of used electricity for cost optimal PV and battery, diesel and hybrid PV, battery and diesel systems for each demand scenario at 100% of energy met. The annotations highlight the change in LCUE and EIUE when hybrid technology is used over diesel for the domestic scenario; and when the PHC is added as an anchor load to the domestic scenario for a hybrid system.

LCUE figures that were 10.7 to 30.2% higher than the cost optimal systems meeting 95% of energy demand.

Still, either health centre acting as an anchor load has beneficial cost impacts: the combined scenarios are cheaper in both cases than the domestic-only mini-grid, with lower emissions. The combined *Domestic + PHC* scenario has also lower cost than the PHC alone although with higher emissions. However, the combined *Domestic + Pathlab* scenario sees marginally higher LCUE when compared to the *Pathlab* alone and with a higher EIUE.

Optimising for emissions at 100% energy demand met, again the systems have smaller PV and larger battery capacities relative to the cost optimal ones, and are accompanied by small (0.1-3.3%) increases in LCUE and modest (1.2-6.6%) reduction in EIUE. For more detailed results see S2 of the Supplementary Information.

3.4.2. *Diesel-only systems*

When using solely diesel generation at 100% of demand being met, the LCUE figures are almost the same as for the 95% case. The combined scenarios have the lowest costs of all five scenarios suggesting anchor load benefits with diesel when meeting 100% of energy demand (see Table 8).

The combined scenarios see reductions in emissions against their respective individual scenarios except for a small increase of 3.1% for the combined *Domestic + Pathlab* scenario when compared to the *Pathlab* scenario.

The results are mixed when comparing the LCUE figures with the cost optimal PV and Battery systems for 100% of energy being met (see Figure 6). For the *Domestic*-only scenario and the *PHC* scenario using solely diesel is more expensive, by 0.6% and 13.5%, than the PV mini-grid respectively. These scenarios have the poorest diesel generating capacity utilisation and operating efficiency. For the remaining scenar-

Table 8
Results summary for diesel-only systems optimising for cost with 100% of energy demand met

Scenario	Diesel capacity (kW)	Average capacity utilisation	Diesel efficiency (litres/kWh)	LCUE($/kWh) (Change from 100% reliable cost optimal PV & battery)	Emissions Intensity (gCO2/kWh) (Change from 100% reliable cost optimal PV & battery)
Domestic	2	16.0%	0.53	1.56 (+ 0.6%)	1438.39 (+808.5%)
Domestic + PHC	2	27.5%	0.34	0.96 (- 16.9%)	933.26 (+508.0%)
Domestic + Pathlab	4	25.1%	0.37	0.76 (- 7.9%)	998.56 (+656.0%)
PHC	2	14.6%	0.58	1.82 (+ 13.5%)	1587.54 (+1012.4%)
Pathlab	3	28.4%	0.36	0.78 (-4.0%)	968.77 (+664.8%)

Table 9
Results summary for hybrid systems optimising for cost with 100% of energy demand met

Scenario	PV Size (kWp)*	Battery Size (kWh)*	Diesel Capacity (kW)	Average diesel capacity utilisation	Diesel efficiency (litres/kWh)	Dumped energy fraction*	LCUE ($/kWh)	Emissions Intensity (gCO2/kWh)
Domestic	2.1	12.0	1	34.1%	0.33	15.1%	1.39	142.35
Domestic + PHC	3.3	17.0	2	24.4%	0.38	11.7%	1.03	150.96
Domestic + Pathlab	6.0	20.0	4	14.4%	0.59	10.5%	0.74	173.52
PHC	1.2	5.0	1	18.3%	0.47	9.6%	1.55	164.11
Pathlab	3.9	10.0	3	13.8%	0.63	9.1%	0.78	182.66

*These values are from the 95% energy met cost optimal PV systems

ios, the diesel system is lower cost than the cost optimal PV and battery only systems at 100% energy satisfaction: 16.9% lower for the *Domestic + PHC* scenario, 7.9% lower for the *Domestic + Pathlab* scenario and finally a 4% reduction for the Pathlab scenario. As would be expected, the EIUE values are far greater for all systems using diesel only than PV and battery systems at 100% of energy being met.

3.5. Cost and emissions of 100% reliable hybrid PV, battery and diesel systems

Finally, we investigated using diesel to meet the last 5% of the demand unmet. We did this by taking the cost optimal PV and battery systems that already meet 95% of energy demand, as described in Section 3.3, and added diesel generation for remaining demand.

The results show that for all scenarios the LCUE is lower than exclusively PV and battery system. For three scenarios, *Domestic, Domestic + Pathlab* and *PHC* the hybrid systems are cheaper than exclusively diesel systems for meeting 100% of demanded energy. For the *Pathlab* scenario, the LCUE figures are the same, with a higher figure returned for the *Domestic + PHC* scenario.

In all cases, the combined scenarios are cheaper than the individual ones. The *Domestic + PHC* scenario is 26.2% and 33.8% cheaper than the *Domestic* and *PHC* ones respectively. The *Domestic + Pathlab* scenario is 46.7% than the Domestic scenario and 4.6% than the *Pathlab* scenario.

The results for emissions intensity are mixed, with the hybrid systems having in most cases similar but slightly higher emissions of electricity used than solely the PV and battery systems. The emissions intensities are much lower than for the diesel-only systems.

4. Discussion of results

At a 95% of demand met threshold our results indicate that there are cost and emissions benefits for health centre anchor loads regardless of the generating technology used. The benefits are clearest when comparing a mini-grid meeting only domestic demand to one meeting both domestic and health centre demands: across all the assessed scenarios, LCUE reduces between 23% and 38% when adding the PHC, and between 46% and 53% when adding the Pathlab. When comparing health centre systems with the respective combined domestic and health centre mini-grid, there are significant reductions in LCUE for the PHC but no or only marginal gains for the Pathlab. In other words, our results suggest that whilst it is always beneficial for the domestic mini-grid to integrate with one of the two health centres, there is far less of a cost incentive for the larger health centre (Pathlab) to connect to surrounding domestic loads than the smaller health centre (PHC).

When using PV and batteries without backup generation, the emissions intensity of electricity used across the demand scenarios sits at 92 – 120gCO$_2$/kWh for systems capable of meeting 95% of energy demand. This is substantially lower than that reported for the Indian national grid, which has an emissions intensity of approximately 720gCO$_2$/kWh [49], and diesel generation, which ranges from 794-1540gCO$_2$/kWh. Although it is more likely in practice that a PV system would be optimised for cost rather than emissions, our results suggest that emissions optimisation can achieve noteworthy reductions in the emissions intensity of electricity used (~12-16%) with only small cost increases (~1-4%), when compared to cost-optimal systems.

At 95% of demand met, our analysis finds diesel generation to be between 14.3% and 22.1% more expensive than PV across all scenarios, demonstrating that PV and battery technology can be a lower-cost option than diesel. The diesel price used was the average of one year of daily prices from Delhi, the nearest major city for which reliable price data over a long period of time was available. In reality, the cost of diesel at the mini-grid site may be higher when considering transport costs to a more remote location, therefore possibly making diesel even less competitive at 95% of energy demand met. The LCUE for PV systems are lower than diesel reflecting lower lifetime averaged costs; however, the upfront capital cost of equipment is often the primary challenge for installing off-grid energy infrastructure and this is still lower for diesel.

When testing the sensitivity of the results by changing the threshold to 100% of energy demand met, integrating a health-centre remains broadly beneficial in terms of LCUE reductions, yet costs are 10.7 -

30.2% higher for solar PV and battery systems compared to systems meeting 95% of demand, indicating a significant premium for the final 5% of electricity demand. The dumped energy fraction of the 100% reliable PV systems is roughly three to four times greater than that of the 95% reliable ones, demonstrating the large quantity of poorly utilised capacity required to meet the last 5% of energy demand. A hybrid system where a diesel generator is used to meet the final 5% of demand that the PV and battery capacity does not meet, is the cheapest way to reach 100% of energy demand met for all but one scenario we investigated. This finding is unsurprising, with modern 3rd generation mini-grids typically utilising the same generation combination to achieve high levels of energy demand met and low costs [16]. Critically, when using a hybrid configuration, the anchor load effects are always beneficial in terms of cost, whether comparing from the domestic or the health centre-only scenarios.

The national grid availability data and our results showing the estimated fraction of demand that would be unmet across different locations underline the fact that the grid in the region is far from adequate for supplying rural areas. In the ‘weak’ case, the closest and most representative of the case study site, the unmet energy proportion is at or above 50%, worsening for the scenarios including the health clinics. This demonstrates that to provide reliable high-quality electricity for both healthcare and domestic needs, either drastic improvements to the national grid, or alternatives such as the mini-grid systems are needed.

To improve the service level for rural grid customers to similar levels as seen in the urban or ‘strong’ grid location, investment in improved infrastructure is needed either by strengthening the grid or through alternatives such as mini-grids, as this paper explores. In 2019-20 the grid in Uttar Pradesh suffered from transmission and distribution losses of 22%, and an energy supply shortfall of 7%, up from 5% in the previous year [50]. Improving service levels requires upgrading power lines as well as increasing generating capacity or implementing energy efficiency measures. The remote location of the case-study site and the fact that recent electricity demand increases in the district of Bahraich are among the highest in the state, averaging 27% a year between 2016 and 2019 [50], suggest that fairly significant investment is likely to be needed to improve service levels.

The grid electricity unit cost for metered customers is low, with a tariff at around $0.11/kWh, varying somewhat for the type of consumer and the amount of electricity consumed [51]. However, electricity in India is subsidised: in Uttar Pradesh, there is around a 30% gap between revenue per unit and expenditure per unit, widening to around 50% for domestic customers [50], meaning that the cost of production is higher than the tariff rates paid by many consumers. Adding further complexity, more than half of customers in Uttar Pradesh do not have a meter and are therefore thought to pay a higher equivalent unit cost of up to $1.13/kWh [7].

Whilst even the lowest cost mini-grid systems described here offer a unit cost of electricity considerably higher than the national grid, it is worth considering that the cost premium for more reliable electricity from the mini-grid compared to the grid may be outweighed by increased welfare that could result from the improved quality of electricity supply. For healthcare uses, previous research has demonstrated that a more reliable supply can reduce mortality [36] and boost health centre capabilities [35], potentially resulting in socioeconomic benefits to a host community.

5. Conclusion

This paper quantitatively assesses the impact of integrating health centres as anchor loads into a domestic mini-grid using solar, diesel and hybrid electricity generation. In addition, it explores the suitability of the national grid for meeting demand, to understand the necessity of off-grid systems for more reliable power.

Using monitored demand data, and detailed system and cost data, our modelling demonstrates promising results for rural health centres to act as anchor loads in mini-grids. There are cost and emissions benefits at both levels of reliability that we investigate, and across generating technologies. Additionally, our modelling demonstrates that solar PV and battery technologies used in mini-grids are cost competitive or cheaper than using diesel-only generators. At the highest level of service provision, hybrid systems whereby diesel supplies 5% of electricity are the lowest cost option, concurring with other previous studies. Our findings indicate that for our study area the national grid is not adequate for meeting either domestic or healthcare electricity demand, with poorer service levels for healthcare demand.

We have demonstrated the potential that anchor loads - in this case using the example of health centres - have in improving both the financial and environmental sustainability of mini-grids, through lower unit cost and greenhouse gas emissions intensity of electricity. Improving the economics of solar mini-grids will help to speed up their deployment and ensure they fulfil their potential role in providing high-quality, low carbon access to electricity in countries still facing the persistent challenge of poor access. This paper uses the example of rural health centres acting as anchor loads in northern India; however, the findings have relevance beyond this case: other anchor loads with a similar pattern and share of demand within domestic solar mini-grids may produce similar benefits.

Further analysis, beyond the scope of this study, should focus on the practicalities of implementing mini-grids with anchor loads, and the tariff structures required for feasible operation in different contexts. In addition, the consideration of both growth in domestic electricity demand to more substantial level and more of how mini-grids may interact with the main grid are important areas of future work. If benefits identified in this paper can be realised in practice, the application of such systems has the exciting potential to tackle poor levels of rural electricity access for both households and anchor users in India, as well as in other countries with electricity access challenges.

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Appendix A: Model Data

Model inputs

The model inputs for the energy system, costs and emissions were sourced from the literature and other sources such as suppliers of equipment. Where possible and relevant we used data for India. Where appropriate, all costs include the respective rate of Indian sales tax (GST); an exchange rate of 69 Indian rupees (INR) to 1 US dollar (USD) was used.

Table A.1
Technical Inputs

Item	Value	Unit	Source
Battery Maximum Charge	0.85	State of charge (0.00-1.00)	[52]
Battery Minimum Charge	0.15	State of charge (0.00-1.00)	[53]
Battery Leakage	0.004	Fractional leakage per hour	[54]
Battery Conversion in	0.93	Conversion efficiency (0.00-1.00)	[54]
Battery Conversion out	0.93	Conversion efficiency (0.00-1.00)	[54]
Battery Cycle Lifetime	2500	Expected number of cycles over the lifetime	[55]
Battery Lifetime Loss	0.30	Fractional loss over the lifetime (0.00-1.00)	[53]
Battery C Rate	0.20	Charge/Discharge rate	[56]
Battery Replacement Capacity	0.70	Minimum level of capacity before replacement (0.0-1.0)	
Transmission efficiency DC	0.96	Efficiency of distribution network (0.00-1.00)	[57]
Transmission efficiency AC	0.92	Efficiency of distribution network (0.00-1.00)	[58]
DC to AC conversion	0.97	Conversion efficiency (0.00-1.00)	[59]
DC to DC conversion	0.95	Conversion efficiency (0.00-1.00)	[58]
AC to DC conversion	0.90	Conversion efficiency (0.00-1.00)	[60]
AC to AC conversion	0.98	Conversion efficiency (0.00-1.00)	[61]
PV panel tilt	29	Degrees above horizontal	
PV panel azimuth	180	Degrees from North	
PV panel lifetime	20	years	
PV panel degradation	0.01	Fractional degradation per year	
Diesel generator fuel consumption	0.28	Litres per kW capacity per year	[62]
Diesel minimum load	0.30	Minimum capacity factor (0.00 – 1.00)	

Table A.2
Financial Inputs

Item	Value	Unit	Comments	Source
PV Panels	392.40	$/kWp	*17% efficiency, 300-watt panel*	[63]
Discount Rate	10	%		[62]
PV O&M	7.85	$/kWp p.a.		[64]
Battery Cost	325.61	$/kWh	*Lithium-ion Phosphate battery 1.02kWh*	[65]
Battery O&M	3.26	$/kWh p.a.		[64]
Battery cost reduction	7.5	% p.a.		[66]
Diesel generator cost	426.92	$/kW		[67]
Diesel fuel cost	0.97	$/litre	*Based on one year of daily diesel prices, Delhi, India*	[68]
Diesel O&M	42.69	$/kW p.a.	*10% of capital cost p.a.*	[62]
Balance of System	348.69	$/kWp	*Cables, Racks, Charge controllers*	[69] & Private correspondence, technical employee Oorja Solutions
Connection & Distribution Network	5627.95	$	*Estimate for 45 Households*	Private correspondence with Oorja Solutions and [62]
Connection & Distribution Network (Community + Health centre)	5798.72	$	*Estimate for 45 Households + Health centre*	Private correspondence with Oorja Solutions and [62]
Inverter	170.46	$/kW	*SMA inverter*	[70]
Misc. Costs	1458.76	$ /kW		Private correspondence, technical employee Oorja Solutions
General O&M	1785	$ p.a.	*Costs of spare parts and technician*	Private correspondence, technical employee Oorja Solutions

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rset.2021.100003.

Table A.3
GHG Emission Inputs

Item	Value	Unit	Comments	Source
PV Panels	1520	$kgCO_2/kWp$	*Based on multi-crystalline silicon PV manufactured in China*	[71]
Battery	110	$kgCO_2/kWh$		[72]
Diesel Generator	476	$kgCO_2$-eq/kW		[73]
Diesel Fuel	2.68	$kgCO_2$/litre		[74]
Balance of System	134	$kgCO_2/kW$	*Based on the sum of figures of BOS*	[75]
Inverter	124	$kgCO_2/kW$	*Based on manufacture in China, 0.89 kW inverter/kWp*	[71]

References

[1] IEA, “SDG7: Data and Projections – Analysis - IEA,” 2020.
[2] IEG, “World Bank Group Support to Electricity Access, FY2000-2014,” 2015.
[3] M. Gustavsson, Educational benefits from solar technology—Access to solar electric services and changes in children’s study routines, experiences from eastern province Zambia, Energy Policy 35 (2) (Feb. 2007) 1292–1299.
[4] J. Aguirre, “The Impact of Rural Electrification on Education: A Case Study from Peru,” 2017.
[5] Y.J. Chen, N. Chindarkar, Y. Xiao, Effect of reliable electricity on health facilities, health information, and child and maternal health services utilization: evidence from rural Gujarat, India, J. Health. Popul. Nutr. 38 (1) (2019) 7.
[6] F. Riva, H. Ahlborg, E. Hartvigsson, S. Pachauri, E. Colombo, Electricity access and rural development: Review of complex socio-economic dynamics and causal diagrams for more appropriate energy modelling, Energy Sustain. Dev. 43 (Apr. 2018) 203–223.
[7] S. Agrawal, N. Bali, and J. Urpelainen, “Rural Electrification in India: Customer Behaviour and Demand,” 2019.
[8] S. Agrawal, S. Mani, A. Jain, and K. Ganesan, “State of Electricity Access in India Insights from the India Residential Energy Survey (IRES) 2020.”
[9] IPCC, “Special Report on 1.5 degrees: Summary for Policymakers,” 2018.
[10] S. Pachauri, Household electricity access a trivial contributor to CO 2 emissions growth in India, Nat. Clim. Chang. 4 (12) (Jan. 2014) 1073–1076.
[11] P. Blechinger, M. Köhler, C. Juette, S. Berendes, C. Nettersheim, Off-Grid Renewable Energy for Climate Action – Pathways for change, Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), 2019 published by.
[12] C. Bertram, N. Johnson, G. Luderer, K. Riahi, M. Isaac, J. Eom, Carbon lock-in through capital stock inertia associated with weak near-term climate policies, Technol. Forecast. Soc. Change 90 (Jan. 2015) 62–72.
[13] United Nations, “Transforming our world: The 2030 agenda for sustainable development,” 2015.
[14] N. Narayan, V. Vega-Garita, Z. Qin, J. Popovic-Gerber, P. Bauer, M. Zeman, The Long Road to Universal Electrification: A Critical Look at Present Pathways and Challenges, Energies 13 (3) (Jan. 2020) 508.
[15] IEA, “Energy Access Outlook 2017: From poverty to prosperity,” 2017.
[16] ESMAP, “MINI GRIDS FOR HALF A BILLION PEOPLE Market Outlook and Handbook for Decision Makers,” 2019.
[17] S. Graber, T. Narayanan, J.F. Alfaro, D. Palit, Perceptions towards solar mini-grid systems in India: A multi-stakeholder analysis, Nat. Resour. Forum 43 (4) (Nov. 2019) 253–266.
[18] A. Sharma, S. Agrawal, J. Urpelainen, The adoption and use of solar mini-grids in grid-electrified Indian villages, Energy Sustain. Dev. 55 (Apr. 2020) 139–150.
[19] R. Sen, S.C. Bhattacharyya, Off-grid electricity generation with renewable energy technologies inIndia: An application of HOMER, Renew. Energy 62 (2014) 388–398.
[20] Power for AllPower for All Research Summary: US$220 billion needed to build mini–grids for half a billion people, 2019.
[21] C. Blodgett, E. Moder, L. Kickham, and H. Leaf, “Achieving Mini-Grid Scalability in Kenya: Financing the Future of Rural Electrification,” pp. 1–30, 2017.
[22] ESMAP, “Regulatory Indicators for Sustainable Energy. ESMAP Report.,” Washington, DC, 2018.
[23] S. Mitra and S. Buluswar, “Universal Access to Electricity: Closing the Affordability Gap,” 2015.
[24] C. Blodgett, P. Dauenhauer, H. Louie, L. Kickham, Accuracy of energy-use surveys in predicting rural mini-grid user consumption, Energy Sustain. Dev. 41 (Supplement C) (2017) 88–105.
[25] N. Ramchandran, R. Pai, A.K.S. Parihar, Feasibility assessment of Anchor-Business–Community model for off-grid rural electrification in India, Renew. Energy 97 (Nov. 2016) 197–209.
[26] S.C. Bhattacharyya, D. Palit, Mini-grid based off-grid electrification to enhance electricity access in developing countries: What policies may be required? Energy Policy 94 (Jul. 2016) 166–178.
[27] F.C. Robert, G.S. Sisodia, S. Gopalan, The Critical Role of Anchor Customers in Rural Microgrids, in: 2017 Int. Conf. Comput. Power, Energy, Inf. Commun., 2017, pp. 398–403.
[28] A. Welland, “Electrification of health clinics in rural areas: Challenges and opportunities Smart Villages,” 2017.
[29] WHO, “Access to Modern Energy Services for Health Facilities in Resource-Constrained Settings,” 2015.
[30] S. Mukherjee, R. Symington, Beyond Household Lighting: Promoting Anchor Load Agri-Business to Build Mini-Grids in India, Energy Access Practitioner Network (2018) [Online]. Available: http://energyaccess.org/news/recent-news/mlinda/ . [Accessed: 23-Sep-2019].
[31] C.L. Karp, et al., Evaluating the value proposition for improving vaccine thermostability to increase vaccine impact in low and middle-income countries, Vaccine 33 (30) (Jul. 2015) 3471–3479.
[32] N.S. Ouedraogo, Caroline Schimanski, Energy poverty in healthcare facilities: a ‘silent barrier’ to improved healthcare in sub-Saharan Africa, J. Public Health Policy 39 (2018) 358–371.
[33] H. Essendi, et al., Infrastructural challenges to better health in maternity facilities in rural Kenya: community and healthworker perceptions, Reprod. Health (2015).
[34] J.A. Forrester, N.J. Boyd, J.F. Edward Fitzgerald, I.H. Wilson, A. Bekele, T.G. Weiser, Impact of Surgical Lighting on Intraoperative Safety in Low-Resource Settings: A Cross-Sectional Survey of Surgical Providers, World J. Surg. 41 (2017) 3055–3065.
[35] L. Suhlrie, J. Bartram, J. Burns, L. Joca, J. Tomaro, E. Rehfuess, The role of energy in health facilities: A conceptual framework and complementary data assessment in Malawi, PLoS One 13 (7) (Jul. 2018) e0200261.
[36] B.A. Apenteng, S.T. Opoku, D. Ansong, E.A. Akowuah, E. Afriyie-Gyawu, The effect of power outages on in-facility mortality in healthcare facilities: Evidence from Ghana, Glob. Public Health 13 (5) (May 2018) 545–555.
[37] H.H. Dholakia, Solar powered healthcare in developing countries, Nat. Energy (Jul. 2018) 1.
[38] S. Mani, S. Patnaik, and H. H. Dholakia, “The State of Electricity Access for Primary Health Centres in India Insights from the District Level Household and Facility Survey (DLHS-3 and DLHS-4) Issue Brief |,” 2019.
[39] COCIR, “Status Report 2016. Tech. rep. September. European Coordination Committee of the Radiological, Electromedical and Healthcare IT Industry,” 2017.
[40] Canadian Coalition for Green Health Care, “Assessing Opportunities to Reduce Energy Consumption in the Health Care Sector,” 2017.
[41] A.H. Jensen, P.M. Petersen, Energy Efficiency in Hospitals and Laboratories, ECEE Summer Study Energy Effic. First Found. a Low Carbon Soc. Innov. Build. Appliances (2011) 1513–1520.
[42] Prayas, “Electricity Monitoring Initiative,” 2019.
[43] Prayas, “Private correspondence with Prayas 29.03.19,” 2019.
[44] P. Sandwell, N. Ekins-Daukes, J. Nelson, What are the greatest opportunities for PV to contribute to rural development? Energy Procedia 130 (Sep. 2017) 139–146.
[45] P. R. Sandwell, “The greenhouse gas mitigation potential of photovoltaic technologies,” no. December, 2017.
[46] P. Sandwell, H. Beath, and J. Nelson, “The impacts of using decentralised solar generation and battery storage to improve grid reliability in rural India,” 2020.
[47] S. Pfenninger, I. Staffell, Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data, Energy 114 (Nov. 2016) 1251–1265.
[48] P. Kumar, “Personal Communication 19 March 2019.” 2019.
[49] IEA, “WEO 2018,” 2018.
[50] Uttar Pradesh Power Corporation Limited, “Statistics at a Glance 2019-20,” Lucknow, India, 2020.
[51] Uttar Pradesh Electricity Regulatory Commission, “Tariff for FY 2018-9.” 2018.
[52] DNV GL, “Battery Energy Storage Study for the 2017 IRP,” p. 40, 2017.
[53] DNV GL, “Battery Energy Storage Study for the 2017 IRP,” p. 40, 2017.
[54] IRENAElectricity storage and renewables: Costs and markets to 2030, 2017.
[55] Inverted Energy, “Inverted Energy Lithium Plus Batteries Datasheet,” 2019. [Online]. Available: https://pdf.indiamart.com/pdfim/?url=https://5.imimg.com/data5/JV/AJ/MY-4524498/lithium-plus-battery.pdf&pdfdet=JmRpZD0yMDU1-MTEyOTMzMCZjdGc9MzYmbWNhdD0xNzE5MyZjb21wPUludmVydGVkIEVuZXJ-neSZsb2NhbGl0eT0mY2l0eT1OZXcgRGVsaGkmc3RhdGU9JmNvdW50cnk9SW5ka-WEmcHJvZF9. [Accessed: 23-Aug-2019].
[56] Inverted Energy, “Inverted Energy Lithium Plus Batteries Datasheet,” 2019. .
[57] H. Pang, E. Lo, B. Pong, DC Electrical Distribution Systems in Buildings, in: 2006 2nd International Conference on Power Electronics Systems and Applications, 2006, pp. 115–119.
[58] H. Pang, E. Lo, B. Pong, DC Electrical Distribution Systems in Buildings, in: 2006 2nd International Conference on Power Electronics Systems and Applications, 2006, pp. 115–119.
[59] M. Starke, L.M. Tolbert, B. Ozpineci, AC vs. DC distribution: A loss comparison, in: 2008 IEEE/PES Transmission and Distribution Conference and Exposition, 2008, pp. 1–7.
[60] K. Mikhaylov, J. Tervonen, and D. Fadeev, “Development of Energy Efficiency Aware Applications Using Commercial Low Power Embedded Systems,” 2012.

[61] M. Starke, L.M. Tolbert, B. Ozpineci, AC vs. DC distribution: A loss comparison, in: 2008 IEEE/PES Transmission and Distribution Conference and Exposition, 2008, pp. 1–7.

[62] R. Tongia, "Microgrids in India Myths, Misunderstandings, and the Need for Proper Accounting Acknowledgements," 2018.

[63] Amazon, "PowerHouse 300W 30V Polycrystalline Solar Panel: Amazon.in: Garden & Outdoors," 2019. [Online]. Available: https://www.amazon.in/PowerHouse-300W-Polycrystalline-Solar-Panel/dp/B07GPLBSPG/ref=sr_1_2?s=garden&ie=UTF8&qid=1552822248&sr=1-2&keywords=solar+panel+polycrystalline+300w. [Accessed: 01-Apr-2019].

[64] C.L. Chambon, T. Karia, P. Sandwell, J.P. Hallett, Techno-economic assessment of biomass gasification-based mini-grids for productive energy applications: The case of rural India, Renew. Energy 154 (Jul. 2020) 432–444.

[65] Indiamart, "Lithium Plus Battery, Capacity: 80 Ah, Rs 18000 /piece, Inverted Energy | ID: 20551129330," 2019. [Online]. Available: https://www.indiamart.com/proddetail/lithium-plus-battery-20551129330.html. [Accessed: 01-Apr-2019].

[66] O. Schmidt, A. Hawkes, A. Gambhir, I. Staaell, I. Staffell, The future cost of electrical energy storage based on experience rates, Nat. Energy 2 (8) (Jul. 2017) 17110.

[67] Indiamart, "Kirloskar 10 KVa Koel Chhota Chilli Diesel Genset, Rs 200000 /unit | ID: 20326816897," 2019. [Online]. Available: https://www.indiamart.com/proddetail/10-kva-koel-chhota-chilli-diesel-genset-20326816897.html. [Accessed: 01-Apr-2019].

[68] Indian Oil, "Indian Oil Historical Diesel Prices," 2019. [Online]. Available: https://www.iocl.com/Product_PreviousPrice/DieselPreviousPriceDynamic.aspx. [Accessed: 01-Apr-2019].

[69] Indiamart, "Pre Galvanized Fixed Type Mounting Structures, Thickness: 1.5 Mm To 4.0 Mm, Rs 2300 /kilowatt | ID: 6865551512," 2019. [Online]. Available: https://www.indiamart.com/proddetail/fixed-type-mounting-structures-6865551512.html. [Accessed: 01-Apr-2019].

[70] Indiamart, "140 V SMA Solar Inverter, 7 A, Rs 48000 /piece, Sarth Solar Solutions Private Limited | ID: 19053602488," 2019. [Online]. Available: https://www.indiamart.com/proddetail/sma-solar-inverter-19053602488.html. [Accessed: 01-Apr-2019].

[71] J M., Mariska) de Wild-Scholten, "Energy payback time and carbon footprint of commercial photovoltaic systems, Sol. Energy Mater. Sol. Cells 119 (Dec. 2013) 296–305.

[72] J.F. Peters, M. Baumann, B. Zimmermann, J. Braun, M. Weil, The environmental impact of Li-Ion batteries and the role of key parameters – A review, Renewable and Sustainable Energy Reviews 67 (2017) 491–506 Elsevier Ltd01-Jan-.

[73] C. Smith, et al., Comparative Life Cycle Assessment of a Thai Island's diesel/PV/wind hybrid microgrid, Renew. Energy 80 (Aug. 2015) 85–100.

[74] Biomass Energy Centre, "Carbon emissions of different fuels," *Defra*, 2011. [Online]. Available: http://www.biomassenergycentre.org.uk/portal/page?_pageid=75,163182&_dad=portal&_schema=PORTAL. [Accessed: 07-Apr-2020].

[75] J.E. Mason, V.M. Fthenakis, T. Hansen, H.C. Kim, Energy payback and life-cycle CO2 emissions of the BOS in an optimized 3•5 MW PV installation, Prog. Photovoltaics Res. Appl. 14 (2) (Mar. 2006) 179–190.