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Energy Services: The key to optimising Hybrid Mini Grid System Design

Bhupendra Shakya[1], Anna Bruce[1], Iain MacGill[2]

[1] *School of Photovoltaics and Renewable Energy Engineering,*
[2]*Centre for Energy and Environmental Markets and School of Electrical Engineering and Telecommunications,*
University of New South Wales (UNSW), Sydney, NSW 2052, Australia
E-mail: b.shakya@student.unsw.edu.au

ABSTRACT

Mini Grids for rural electrification, are expected to play a key role in meeting the energy access goals of the UN's Sustainable Energy for All (SE4ALL) initiative. Current practices for providing electrification mostly focus on the supply side with emphasis on ensuring reliability, affordability and security of supply. While in developed countries, there is an expectation of extremely high levels of reliability for all customers who are almost all supplied through a centralised gird, consumers in developing countries can have far simpler energy service needs, widely varying willingness and ability to pay and hence quite different preferences when trading off reliability and costs. A supply side focus on electricity provision does not capture some important aspects of energy service delivery from the consumer side, such as the different relative value placed on, and expectations from, energy services such as hot water, food cooking and space heating. In addition, some energy services have characteristics such as flexibility and storability, which may provide opportunities to better optimise their delivery given cost, reliability and environmental objectives, particularly in systems integrating variable renewable energy. Accessing these opportunities requires a better understanding of both the potential flexibility of different energy services, and their relative value to consumers.

This paper presents a potential framework for energy services characterised based on flexibility, storability and consumer value, using existing survey data from a Mini Grid in Nepal and other secondary data. These insights are applied to a modelling study using the HOMER Pro software package and optimisation analysis. Preliminary findings indicate that a focus on energy services may provide opportunities to improve the design of Hybrid Mini Grid system that reduces operational and capital cost of the electricity supply system, while still ensuring energy services meet consumer preferences.

Keywords: Energy Service, Hybrid Mini Grid, Rural Electrification, HOMER

1. Introduction

Energy services play a key role in meeting basic needs and enabling productive activities. Access to affordable, reliable, sustainable and modern energy to deliver these services is therefore seen as an essential requirement for meeting sustainable development goals (UNSD, 2015). For this reason, the United Nations has launched Sustainable Energy for All (SE4ALL) with the goal of providing modern energy services to all by 2030.

As distinct from energy itself, energy services are the services, processes and commodities from which consumers ultimately derive value through energy (Pedrasa, *et al.*, 2009). Examples of energy services include cooking, space heating, water heating, lighting, cooling, refrigeration and outputs from using other appliances (Howells, *et al.*, 2005). Many of these services, such as clean lighting, computing and communication, and those derived through motor-driven loads, can only or are best provided by electricity.

Grid electricity has not reached many parts of developing countries, particularly rural and remote areas (Practical Action, 2010). While many governments have set targets to extend the main grid to most or all of these communities, it has been recognised that a number of other options are now more cost effective in many cases (IRENA, 2016), particularly because those areas still without access to electricity tend to be the most remote, requiring grid extensions to cover large distances, often over rough terrain, to provide small amounts of electricity to dispersed customers. It has also been recognised that households are often counted as having access to electricity when the grid passes through the village, but often cannot afford either to extend the grid to their house or purchase grid electricity (Bhattacharyya and Palit, 2014). In addition, in many countries, reliability of the grid is poor, and, particularly in rural areas and poor communities, electricity is available infrequently (Bhattacharyya and Palit, 2014).

Because of the high costs, poor reliability and challenges associated with grid extensions, distributed energy options are expected to play an important role in providing energy access to these communities and households (Deshmukh, 2014). In particular, hybrid renewable energy mini grids (HMG) can provide more energy and power to serve a wider range of energy services than Solar Home Systems (SHS) can, but reduce the costs and risks associated with diesel use in a diesel-only mini grid or battery use in a RE-only mini grid. Many studies have suggested that HMG may be an increasingly appropriate option for rural areas in terms of cost, service and environmental objectives (Bhandari, *et al.*, 2014, Bhattacharyya, 2012, Deshmukh, 2014, IRENA, 2016).

However, there are a number of challenges associated with the design and operation of RE mini grids in developing countries (Hazelton, *et al.*, 2014). Firstly, balancing demand and supply is more challenging in very small isolated systems, due to less diverse loads and generation options, and the high cost of dispatchable or storable energy, typically in the form of diesel or battery storage systems (IEA, 2015). The design of these systems is also challenging, partly due to a lack of data about energy service demand where communities have been previously unelectrified, difficulties predicting load growth and a general lack of understanding about demand for, and the characteristics of energy services in rural areas. However, even the most thoughtful rural electrification efforts to date have been largely focused on the supply side of electricity systems (Sovacool, 2011) in particular on cost effective, clean electricity generation, with high levels of availability (hours/day) via a suitable choice of generation technology and system architecture (ESMAP, 2007).

This paper is a preliminary exploration of opportunities to improve HMG energy service delivery, first through a better understanding of energy service needs and their associated characteristics in rural communities including their perceived value and possibility flexibility in delivery. This provides a basis for designing HMG configurations that better meet these community needs. The paper uses energy service data collected from a case study village in Nepal, and the HOMER Pro HMG design tool.

The remainder of this paper is organised as follows. In Section 2, a description of the current status of rural energy access understanding in Nepal, and approaches for demand estimation and rural electricity planning and system design are reviewed, highlighting the potential value of an energy services approach. The methodology for a preliminary case-study investigation of the value of an energy services approach is described in Section 3. Preliminary analysis of flexible services and their potential value is presented in Section 4, followed by conclusions in the final Section.

2. Current Energy Access Planning and Design in Nepal

In Nepal, only around 74% of the population have electricity access, and in rural areas, where the country's poorest mostly live, access is lower still at around 70% (CBS, 2012). The most common means of rural electrification include extension of central grid and the use of distributed renewable energy technologies including Solar Home Systems (SHSs), Solar Mini Grids and Micro Hydro Mini Grids (World Bank, 2015). The most appropriate means depends on the available resources, distance from the grid, dispersion of the population and size of demand. Many rural and remote locations in Nepal are very unlikely to gain access to the central grid in the short to medium term, so alternative options should be explored to expedite electricity access to these communities (Shakya, *et al.*, 2015). There are significant challenges in providing modern energy services to these people and a likely significant role for Mini Grids.

Energy Access Understanding

Under current practice, energy access is typically measured from a supply-side perspective, using metrics such as whether an electricity connection or a modern cook stove exists. A range of issues related to not only lack of availability, but also poor power quality and reliability of electricity supply affect rural areas of Nepal. Even in dense urban areas of Nepal's cities, the grid is unreliable, with load shedding of 14 hours common in the dry season due to inadequate generation capacity. This is, of course, typical of many utilities in the developing world given the challenges faced (Bhattacharyya and Palit, 2014). In this context, connection statistics are an incomplete indicator of energy access.

While energy access is relatively easy to measure via connection status, such metrics provide a limited view, and a range of factors on the demand-side are critical in determining whether consumers can successfully access energy services (Groh, *et al.*, 2016, Practical Action (2013)) For instance, it has been recognised that in addition to availability of energy, affordability determines whether the consumer can take advantage of the connection, while sufficient capacity, quality and reliability to meet the requirements of specific loads are key factors in determining access to energy services.

The Energy Sector Management Assistance programme (ESMAP)'s Multi-Tier Framework (MTF) considers energy access as a process of transition up through energy tiers, rather than a binary measure of connection status (SE4All, 2013). Within the MTF, access is measured using 7 attributes (capacity, duration, reliability, quality, affordability, legality and health and safety). This broader view of the factors that comprise energy access could provide a more useful basis to understand energy access status in Nepal, however it still maintains a supply- and consumption focus. Groh et al. (Groh, *et al.*, 2016) have argued that the MTF needs to be updated to measure the services provided from electricity. In particular, in order to understand whether consumer requirements are being met, a more detailed understanding of the demand side, the characteristics of loads, how consumers prefer to own and operate them, and at what price, will be required to understand requirements for capacity, duration, reliability and quality and whether they are being satisfied.

Electricity Demand Estimation

Electricity demand estimation is a crucial part of rural electrification planning and electricity system design, facilitating appropriate sizing and choice of supply options. Demand at a household level is determined by a range of factors, such as the availability and affordability of energy, household characteristics (Jain and CHENG, 2015) and climatic conditions.

The current demand estimation method used in Nepal for Micro-Hydro Mini-Grid (MHMG) sizing has been influenced by a Government subsidy policy that was based initially on an 'allowance' of 100W per household, designed primarily to meet lighting loads, and which has recently been increased to 200W per household (World Bank, 2015). Beyond this rule of thumb, there is typically a lack of detailed demand or energy service assessment during the feasibility study phase for new MHMG projects in Nepal, which has led to inadequate planning, and created problems of both underutilisation and overutilization of MHMGs in different contexts. Underutilisation, particularly during off peak times, has resulted in an average Capacity Factor (CF) of around 20% for some MHMGs, and as a result, many of these plants have difficulty generating sufficient revenue to meet even their operating costs (Shakya, 2012). In some areas, demand has instead increased, as income growth, gradual urbanisation and increase in education level increase willingness to pay for a wider range of energy services from electricity (such as cooking, entertainment and heating). In many cases, this demand cannot be satisfied by a system designed to supply 200W per household.

The latent demand for energy services in rural areas is believed to be high, but a better and more detailed understanding of this demand from an energy service perspective, including appliance ownership and use, daily and seasonal patterns of demand, the factors that influence demand, and how demand might evolve over time as household and community characteristics change, and as they gain access to energy at potentially lower cost, is critical to ensuring adequate, cost-effective and reliable energy access. There is an increasing consensus that traditional supply focussed planning approaches are inadequate and a new approach is needed, with consideration of energy services.

Planning, System Design and Operation

Most thoughtful rural electrification efforts to date have been largely focused on the supply side of electricity systems - in particular on cost effective, clean electricity generation, with high levels of availability (hours/day) through appropriate generation technology and system architecture choices. While ESMAP's MTF framework retains a focus on the characteristics of supply, an energy service perspective (Groh, *et al.*, 2016) would allow for a better understanding of the value that consumers place on different energy services, the extent to which they are flexible about their operation, as well as their willingness and ability to pay for different services at different levels of reliability.

Overloading and underutilisation of MHMGs is common, due to strong alignment of residential loads, which dominate the overall demand profile. In response, rural electrification system demand management is typically focussed on diversification of residential and commercial loads, and the use of discretionary commercial loads during off peak times to reduce peak load and required capacity. However, taking an energy service perspective, consumers may be somewhat flexible about the timing of some energy services, or whether or not they run at all, while other energy services have some inherent storage (e.g. water pumping or heating/cooling applications), or alternative supply options (e.g. cooking). These characteristics may provide opportunities to optimise cost and reliability, particularly in systems integrating non-dispatchable renewable energy. Examining both the value and potential flexibility of energy services, may provide opportunities to shift loads to reduce costs, while still providing energy services in accordance with consumer preferences.

In resource constrained areas where there is low willingness and ability to pay for electricity, many consumers may prefer cheaper energy over higher availability and reliability of energy services (Lee, *et al.*, 2014). An energy service oriented approach has the potential to better account for consumer preferences, alternate sources of energy and load characteristics (power requirements, flexibility) in decision making, potentially allowing a wider range of opportunities for reducing peak demand to be identified, and improved optimisation in energy source selection and system design across factors such as affordability, adequacy, quality and reliability

3. Method

To better understand energy service demand characteristics and therefore the potential to improve design and operation of rural HMG systems, energy services data from consumers in the Urja Uptyaka Micro Hydro Interconnected Mini Grid (MHIMG) region in Baglung Nepal, which was previously collected for a techno-socio-economic report for the Alternative Energy promotion Centre (AEPC) (ECoCoDE, 2013), was analysed. The survey data included detailed appliance ownership from 185 out total of an 1184 households, along with some commercial and community loads in the community. The data comprised appliance ownership, mini-grid system level data, and consumer willingness to pay. Operating hours and duration, capacity of typical appliances and consumer prioritisation of energy services was estimated with reference to survey data from other parts of Nepal and the lead author's field experiences during the construction and monitoring of the Urja Uptyaka MHIMG project from 2010 to 2014, when working for the Renewable Energy for Rural Livelihood (RERL) Programme.

The energy service analysis included categorising each appliance according to the delivered energy service such as lighting, cooking, water heating, refrigeration, space heating, cooling, information and communication (IC) and entertainment, and then assessing each in terms of:

- consumer priority placed on each energy service,
- flexibility available in terms of when each load might be operated, and whether or not inherent storage exists in each appliance.

For the purposes of this study, consumer priority is an indicator of how highly the consumer values the service compared to other services. In the absence of survey data, for this study, the percentage ownership of different appliances is an indicator of consumer preferences and has been used to estimate the value placed on services from that appliance. An indicative 1-3 ranking has been applied on the basis of appliance ownership and operation, and the author's field experience. Future work in this area will include collection of survey data on consumer priority.

Flexibility is defined as the possibility to shift energy services to another time, for instance to offset the peak demand. Factors influencing flexibility include consumer flexibility about when the energy service is provided, the relationship between timing of electricity consumption and service use (i.e. storage such as stored heat in hot water), and the potential use of an alternative source of energy to supply the service. Again for flexibility, an indicative 1-3 ranking has been applied for the purposes of this study, but more detailed data will be collected for future work.

A representative load profile for one weekday and one weekend day for each of winter and summer, disaggregated by appliance type, were constructed in 30 minute intervals, based on the survey, additional sources and personal experiences. These were then repeated as appropriate to create a full year profile. A PV-battery-diesel HMG[1] was then modelled using the HOMER Pro software tool to meet the estimated electricity demand profile constructed above. Different architectures with a combination of generic flat plate solar PV, 100 kW Diesel Generators and generic lead acid batteries were considered in the analysis. The system design was optimised for levelised cost per kilowatt hour of electricity. The cost of capital and operation and maintenance (O&M) cost of the components considered in HOMER Pro is shown in Table 1.

Table 1: Cost of the system components

Components	Capital Cost, AUD	Unit	O&M Cost, AUD
Solar PV Panel	300	1 kW	3/ year
	250,000	100 kW	2,500/year
Generic Lead Acid Battery, 12 V	350	1 kWh	3.50/ year
	30,000	100 kWh	300/ year
Converter	750.00	kW	7.50/year
Diesel Generator	800	1 kW	0.03/ hr
	42,500	100 kW	3/hr
Diesel	1.20	Lit	

Source: Compiled from solar PV project in Nepal, Australia and HOMER inbuilt data

Using the consumer priority, flexibility and inherent storage characteristics, optimisation can be performed on the load side as well as the supply side. For this study, the example of a rice cooker, which has some flexibility and inherent storage of the energy used to cook the rice, was used to explore the opportunity for optimisation of system design via load shifting without endangering energy service delivery. To understand the characteristics of the rice cooker load, the author tested a locally available 450 W rice cooker and found that it consumes a constant rated power of 450 W throughout the cooking period of 27 minutes, after which, it consumes 40 Watts in warm mode.

4. Results

Energy Service characterisation

The share of the load from different appliances amongst the households in the survey sample is shown in figure 1. In addition to residential load, a number of commercial and government service loads were also included in the modelling.

[1] While the data collected was from a MHIMG system, this research considers the particular value of an energy services approach to HMG systems.

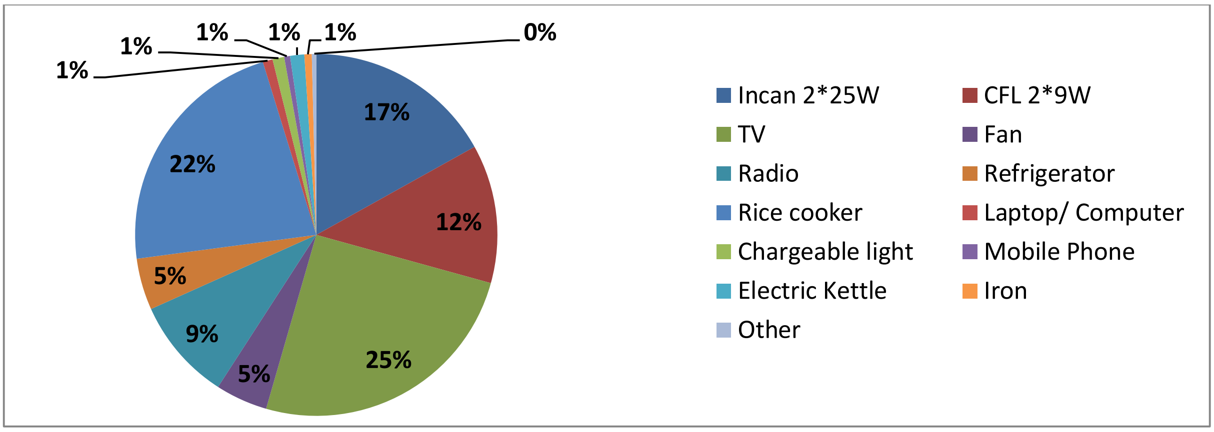

Figure 1: Energy consumption in residential sector

Source: Based on Survey data from (ECoCoDE, 2013), Pandey (2010) with additional load and its ownership such as fan, DVD based on informal conversations with local people.

Table 2 shows the ownership of different appliances in the residential sector, categorised by energy service supplied. Indicative metrics for flexibility and consumer priority have been applied for each appliance, higher numbers reflect greater flexibility and higher priorities respectively.

Table 2: Ownership of electrical load and energy services characterisation

Energy services	Appliances	Ownership HHs %	Flexibility*	Consumer Priority*
Lighting	Incandescent Bulb	78%	1	3
	CFL	77%	1	3
	Chargeable light	99%	3	3
Cooking	Rice cooker	33%	2	2
Hot Water	Electric kettle	2%	2	1
Refrigeration	Refrigerator	4%	2	1
Information and Communication	Phone/ mobile phone	100%	3	3
	Computer/ Laptop	5%	3	2
Entertainment	Television	57%	1	2
	Radio	83%	1	2
Others	Iron	8%	2	1
	Blender	3%	2	1
	Printer	2%	2	1
	Bread making	<< 1%	1	1

Source: Techno-socio-economic study of Urja Upatyaka MHIMG (ECoCoDE, 2013), (Pandey, 2010)

* 1 represents low flexibility or low priority and 3 represents highly flexible or high priority

Table 2 indicates that lighting and mobile phone charging are fundamental energy services used in almost all households. Similarly, radios televisions and rice cookers are commonly owned. Note that a range of different appliances with non-electrical energy sources are not mentioned in the table, but are also expected to be utilised in these households.

Rice cooker as a Flexible load

33% of the HHs owned a rice cooker and, surprisingly, an additional 41% of HHs wish to have a rice cooker in near future (ECoCoDE, 2013). Rice is the staple food and usually people cook rice twice a day in the Urja Uptyaka area. As mentioned by Pedrasa (Pedrasa, *et al.*, 2009) it is comfortable, convenient and clean to cook rice in a rice cooker rather than using fuelwood. Considering the consumer priority, high energy consumption and inherent storage, the rice cooker has been selected as a valuable but potentially flexible load that has an opportunity to contribute to improve HMG design and operation via demand response. It is conservative to assume that rice cookers can be safely maintained in warm mode for several hours, as they store food above 60 degrees Celsius (Ahamad, *et al.*, 2014), which is sufficient to maintain food hygiene[2]. This is also consistent with manufacturer claims that warm mode can be used safely for 5 or more hours[3].

For modelling purposes, a generic rice cooker of 2.2 L capacity and 800 Watt rated power consumption and 40 Watt warm mode was characterised. It was conservatively assumed that 25% of residential consumers own a rice cooker and they use it twice every day. In the base case scenario, it was assumed that rice cooker usage occurs at the following times in the morning: 8 am (15% of total rice cooker operation), 8.30 am (70%) and 9 am (15%). Similarly, winter evening usage was assumed to occur at: 6 pm (15% of total rice cooker operation), 6.30 pm (70%) and 7 pm (15%) and the same pattern was followed for summer evenings, but delayed by half an hour i.e. 6.30 pm (15%), 7 pm (70%) and 7.30 pm (15%). As a demand response measure, the rice cooker use in the evening is shifted earlier as follows: 4 pm (10% of total rice cooker operation), 4.30 pm (10%), 5 pm (30%), 5.30 pm (40%), 6 pm (5%), and 6.30 pm (5%). In practice, this might be incentivised as a response to price or via direct load control. The shifting will not hamper the service provided (hot rice) as the cooker was then modelled as remaining in warm mode until the evening meal time.

The daily load curve of the entire system is shown in Figure 2. The rice cooker contributes to a peak load in the morning and evening of around 210 and 292 kW respectively. The shifting of rice cooker use, when distributed to different times in the evening helps to smooth the load curve and reduces the evening peak from 292 to 147 kW, as shown in Figure 3.

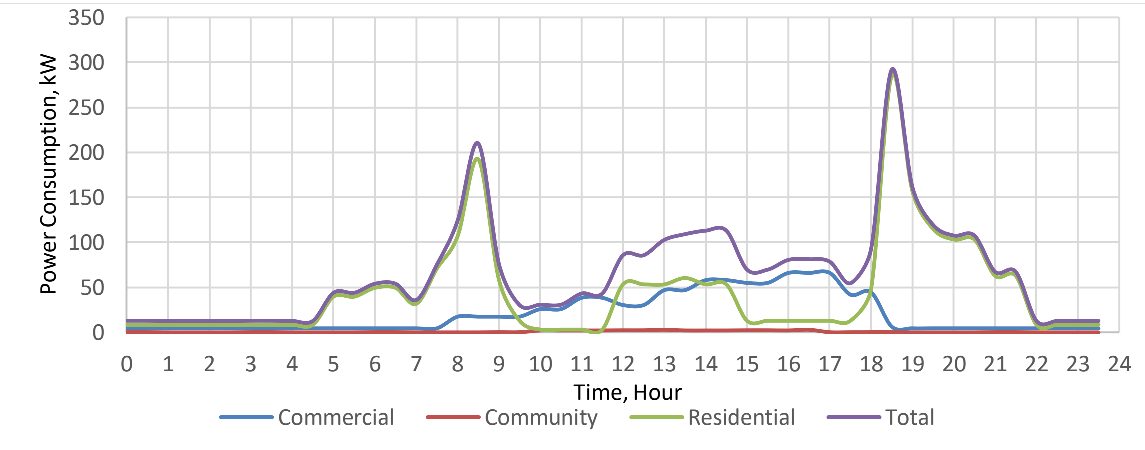

Figure 2: Daily load profile weekdays-Winter

[2] http://healthywa.wa.gov.au/Articles/S_T/Safe-cooling-of-cooked-rice
[3] http://www.manualsdir.com/manuals/181505/philips-hd4728-hd4723-hd4738-hd4733.html?page=9

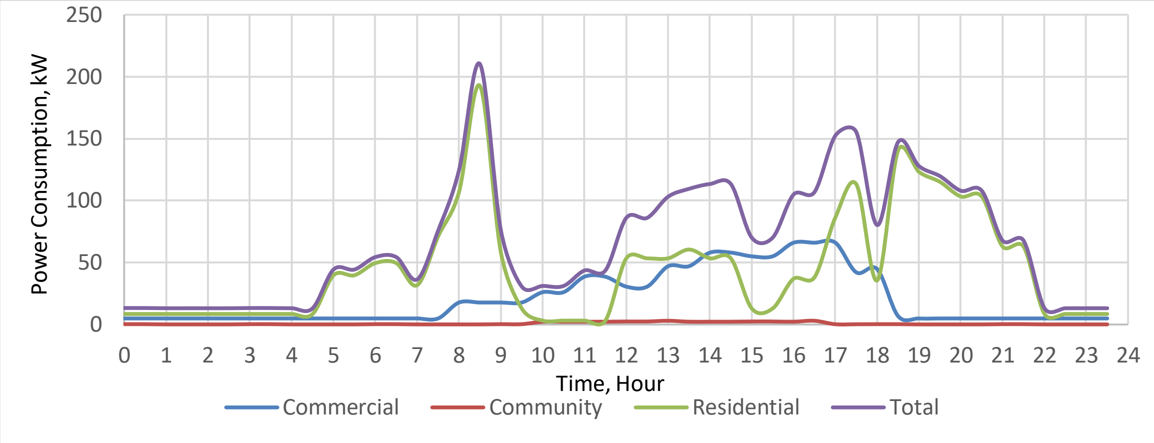

Figure 3: Daily load profile - Rice cooker shifted in evening

System design was carried out using HOMER Pro for the base case load profile and again for the profile with shifted evening rice cooker load. Of the different architectures with a combination of generic flat plate solar PV, 100 kW Diesel Generators and generic lead acid batteries considered in the analysis, a hybrid PV, diesel and battery combination was found to be most optimal.

The 'optimal' system designed by HOMER Pro, and the cost of energy from operating the system both before and after shifting the rice cooker use is shown in Table 3. The size of the system components: solar PV, diesel generator, battery and converter have been reduced significantly and the levelised cost of the electricity reduced from $0.56/kWh to $0.49/kWh.

Table 3: System Designed to Meet Load and Cost of Energy Before and After Rice Cooker Shift (HOMER Output)

	PV (kW)	Diesel Gen100 (kW)	Battery 1kWh LA	Converter (kW)	Levelised Cost of Electricity Cent/ kWh	Cost/ NPC ($)
Homer Output before Rice Cooker shift	300	300	975	175	56	4,378,689
Homer Output after Rice Cooker shift	250	200	350	125	49	3,923,737

Source: Author

5. Conclusions

An energy service approach provides a consumer perspective that can help to better understand the characteristics of energy services and how consumers use and prioritise them. Detailed assessment of energy services may provide an opportunity to optimise HMG systems. This paper has outlined an approach for categorising energy services that can be used to model the opportunity for optimisation of the demand side as well as the supply side in HMG system design. The rice cooker was taken as a preliminary example load, and the effect of shifting this load on HMG system design was modelled. A resultant reduction in the cost of electricity and a significant reduction in systems components are evident. More detailed exploration of the potential of an energy services approach to improve understanding about, planning and system design and operation for rural electrification systems will be undertaken in future work.

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