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Clements, William P M

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Enabling the transition to electric cooking in rural Nepali micro hydropower mini-grids

Will Clements

A thesis submitted to the University of Bristol in accordance with the requirements of the degree of Doctor of Philosophy in Electrical Engineering.

Department of Electrical and Electronic Engineering
UNIVERSITY OF BRISTOL
Merchant Venturers Building
Woodland Road
Bristol BS8 1UB
UNITED KINGDOM

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Abstract

Globally, 2.6 billion people lack access to clean cooking fuels and technologies, 1.8 billion of whom now have access to electricity. Indoor air pollution from biomass cooking accounts for the premature deaths of almost 4 million people every year. Electric cooking has the potential to improve quality of life, reducing health impacts and firewood collection requirements, thus freeing up time for other activities. In Nepal there are 3,300 communities with micro hydropower (MHP) plants which provide reasonably constant renewable power of 10-100 kW to community members, but much of the generated energy is wasted and tariffs are often low, leading to low plant financial sustainability. Electric cooking could increase the usage of MHP generation and thereby increase plant income but, with electric cookers often drawing 1-2 kW, and in communities with hundreds or thousands of residents connected to the mini-grid, all wanting to cook at the same time, the feasibility of widespread adoption of electric cooking is limited.

Electricity as a primary cooking fuel is an unexplored prospect in MHP communities, with only rice cookers and electric kettles prevalent, while the introduction of electric cooking in similar contexts has failed to take the cultural nature of cooking into account by neglecting to capture data on cooking practices or provide sufficient training. In this thesis, the transition to electric cooking in rural Nepali MHP communities is investigated from social and technical viewpoints, collecting data and insights on how to enable community members to integrate electric cookers into their daily practices as much as possible, and evaluating solutions to increase the potential adoption of electric cooking.

Two electric cooking studies trialling induction cookers were conducted, using cooking diaries and MHP electrical system data collection, finding that induction cookers are well received and compatible with most Nepali dishes, but that a total switch to electric cooking is unrealistic, with some fuel stacking inevitable, while cooking was found to coincide with peak community activity, limiting induction cooking scalability to only 10-15 households. An electric pressure cooker (EPC) trial study was conducted to understand the potential of efficient cooking devices and demand-side management measures to increase electric cooking scalability. EPCs were appreciated by participants but generally used only for rice, although 6 kW load peaks for 30 EPCs compared to 8 kW peaks for 15 induction cookers showed increased scalability for lower EPC usage levels. Demand-side management measures reduced peak loads by 10-20 kW through industrial load scheduling agreements and household electricity demand reduction, chosen for implementation due to their simplicity, requiring no extra hardware or control software. The three cooking trial studies contributed datasets of cooking practices, electric cooking energy consumption, MHP electricity demand and generation, and electric cooking load profiles and their contributions to peak community loads.

A techno-economic model of a case study MHP community was created and used to show that a tariff system based on electricity consumption could increase community income from NPR 50,000 to NPR 200,000, while electric cooking would contribute almost NPR 10,000 with only 56 households with electric cookers in the community. Uninformed tariff setting and low generated energy utilisation often leads to insufficient

income generation in MHP communities, while previous work has not captured the detailed electricity demand data necessary to construct a model which can estimate electricity usage, resulting income, household payments, electric cooking costs, and contributions of key end uses such as electric cookers and industrial machines to the community load profile. The model was tested by comparison against an adjusted version based on lower detail input data, finding that the detailed data collection conducted was necessary to generate load profiles which adhere closely to measured data and therefore create a useful model.

This thesis contributes the techno-economic model, which can be used to determine equitable and profitable tariff structures for community contexts, simulate demand-side management measures, and inform load planning decisions, including evaluation of the scalability of electric cooking. The model can now be adapted to other similar communities and contexts based on limited input data such as typical daily electricity demand patterns, numbers of households and productive end uses and typical appliances owned, and typical usage patterns for industrial machines.

Even with efficient cooking devices and demand-side management measures in place, widespread adoption of electric cooking is unfeasible without energy storage. A model of an MHP mini-grid integrating centralised and distributed battery energy storage systems using reverse droop control was created, as proof of concept. Electronic load controller frequency setpoint adjustment enabled full battery charging and discharging. A power flows model and household battery sizing model were conceived. Central battery capacities of 135 kWh and 201 kWh were calculated for high usage of 400 induction cookers and 800 EPCs respectively, representing approximate scalability limits without oversizing. Household battery capacities of 1.6 kWh and 0.96 kWh were calculated for enabling high induction cooker and EPC usage, with the corresponding scalability of off-peak charging calculated at 134 and 224 HH batteries respectively. This thesis contributes simplified battery storage sizing models for MHP mini-grid integration.

The techno-economic model showed that all solutions would enable increased electric cooking and improve MHP financial sustainability, with the scalability of high usage EPCs compared to induction cookers calculated at 60 and 40 respectively, confirming that EPCs are more scalable, although induction cookers were deemed more versatile and convenient by cooking trial study participants. However, widespread adoption of electric cookers would require expensive battery storage systems, with payback periods of at least three years, comparable to battery lifetimes, reducing feasibility. The models contributed by this thesis can be used to estimate battery storage system requirements for supporting electric cooking adoption, based on realistic electric cooking modelling validated against measured data, and can evaluate the scalability and economic viability of introducing electric cooking in MHP communities and other contexts, with and without battery storage. This thesis supports Nepali government targets on increasing electric cooking adoption to 25% of households by 2030 and increasing per capita energy consumption by contributing models which can be adapted and used by organisations such as the Alternative Energy Promotion Centre for improving MHP community financial sustainability and enabling electric cooking load planning.

To my Nepali friends

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And finally, thank you, Anna, Mum and Dad, for love, and for all you did and do.

Declaration

I declare that the work in this dissertation was carried out in accordance with the requirements of the University's Regulations and Code of Practice for Research Degree Programmes and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, the work is the candidate's own work. Work done in collaboration with, or with the assistance of, others, is indicated as such. Any views expressed in the dissertation are those of the author.

SIGNED: ....[redacted]......... DATE:...24/01/23....

Memorandum

The accompanying thesis “Enabling electric cooking in rural Nepali micro hydropower mini-grids” is based on work carried out by the author in the Department of Electrical and Electronic Engineering of the University of Bristol.

The main contributions claimed by the author are as follows:

1) Implementation and analysis of two induction cooking trial studies in rural Nepali micro hydropower mini-grids (MHPs) which generated cooking diary and electrical system datasets
2) Design, implementation and analysis of an electric pressure cooker trial study which assessed long-term cooker acceptability and collected load profile data as well as cooking diary and MHP system data
3) A techno-economic model of an MHP community for characterising community electricity demand, determining profitable and equitable tariff structures, and load planning including evaluation of the scalability and economic viability of electric cooking and solutions to increase its adoption potential, such as demand-side management measures and energy storage. The model can be adapted to other communities and contexts based on limited input data such as typical daily electricity demand patterns, numbers of households and productive end uses and appliances owned, and usage patterns for industrial machines.
4) Central and household battery storage system sizing models for estimating required capacities and determining the scalability of battery-supported electric cooking in MHP mini-grids, whose results can then be evaluated through the techno-economic model

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W. Clements, "Electric cooking for rural Nepal," at the University of Bristol, for the Mature Student Outreach Programme, 2021.

Posters

W. Clements et al., "Understanding assimilation of electric cooking devices into rural Nepali households," in Energy and Climate Transformations: 3rd International Conference on Energy Research & Social Science, Manchester, UK, 2022.

Datasets

Techno-economic modelling presented in Chapter 5 – Data are available at the University of Bristol data repository, data.bris:

S. Williamson and W. Clements, "RAMP based techno-economic model for Nepali MHP, v1," 2021. https://doi.org/10.5523/bris.lpsryevp8vxk2royoexrh2hvw

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List of Abbreviations

A2EI	Access to Energy Institute
ADMD	After diversity maximum demand
AEPC	Alternative Energy Promotion Centre
AVR	Automatic Voltage Regulator
BESS	Battery energy storage system
BEU	Business end use
CCA	Clean Cooking Alliance
CC CV	Constant current constant voltage
CCT	Controlled cooking test
CEU	Community end use
ComEUs	Commercial plus community end uses
DELC	Distributed electronic load controller
DoD	Depth of discharge
dq0	Direct-quadrature-zero
DSM	Demand-side management
ECO	Electric Cooking Outreach
ELC	Electronic load controller
ESMAP	Energy Sector Management Assistance Program
EPC	Electric pressure cooker
EUF	Energy utilisation factor
f-P	Frequency-active power
FS	Fuel stacking
GHG	Greenhouse gas
HDI	Human Development Index
HH	Household
HP	High power
IAP	Indoor air pollution
ICS	Improved cookstove
IEU	Industrial end use
IGBT	Insulated-gate bipolar transistors
KAPEG	Kathmandu Alternative Power and Energy Group
LPF	Low-pass filter
LPG	Liquid petroleum gas
MECS	Modern Energy Cooking Services
MHP	Micro-hydropower plant
MoEWRI	The Ministry of Energy Water Resources and Irrigation

MP	Medium power
NDCs	Nationally Determined Contributions
NGO	Non-governmental organisation
NiCd	Nickel cadmium
NiMh	Nickel metal hydride
NPR	Nepali rupee
NRMSE	Normalised Root-Mean-Squared Error
PEEDA	People Energy and Environment Development Association
PEU	Productive end use
PH	Powerhouse
PI	Proportional integral
PLL	Phase locked loop
PM2.5	Particulate matter less than 2.5 micrometres in diameter
PWM	Pulse width modulation
RAMP	Remote Areas Multi-energy systems load Profiles
RMS	Root-mean-square
SDG	Sustainable Development Goal
SEforAll	Sustainable Energy for All
SG	Synchronous generator
SSM	Simplified synchronous machine
SoC	State of charge
TEM	Techno-economic model
TRIID	Technology Research for International Development
UN	United Nations
UPS	Uninterruptible power supply
VDC	Village Development Committee
V-Q	Voltage-reactive power
WHO	World Health Organisation

List of Symbols

Symbols

C	Capacity	kWh
C	Capacitance	F
D	Generator damping coefficient	
E	Energy	kWh
f	Frequency	Hz
F	Decay factor for household battery sizing	
i	Current	A
k_p	Frequency-active power droop gradient	kW/Hz
k_q	Voltage-reactive power droop gradient	kVAr/V
J	Generator rotor inertia	kg m^2
L	Inductance	H
P	Active power	kW
Q	Reactive power	kVAr
R	Resistance	Ω
T	Torque	Nm
v	Voltage	V
V	Voltage	V
u	Reference voltage	V
η	Efficiency	
μ	Cable losses	
ω	Rotational speed	rad/s

Subscripts

0	Nominal, setpoint
abc	Three phase
d	Direct axis component
el	Electromagnetic
min	Minimum
q	Quadrature axis component
ref	Reference

Table of Contents

Chapter 1

Introduction

1.1 Access to Sustainable, Modern Energy

Cooking is integral to life. The importance of food, water, shelter and clothing is well recognized, whereas that of energy, which is less visible, is less so [1]. However, energy is the driving force behind our daily lives, and is fundamental to development because it enables people to do more with what they have [1]. Without energy, cooking would be impossible. Therefore, the seventh of the Sustainable Development Goals (SDGs) set out by the United Nations (UN) demands universal *"access to affordable, reliable, sustainable and modern energy"* [2], [3]. Target 7.1 of SDG 7 calls for this universal access by 2030, and is divided into two indicators of achievement, namely the proportion of the population with (7.1.1) access to electricity, and (7.1.2) primary reliance on clean fuels and technology [3]. The UN sees electricity access and clean fuel access as keys to sustainable, modern energy access. This thesis examines both, and their connection.

The world is not currently on track to achieve SDG 7 [4]. As of 2019, 759 million people still lack access to electricity. Of these, 50% live in fragile, conflict zones, and 84% live in rural areas [4]. Under current policies and with the impact of COVID-19, it is projected that 660 million people will still lack access to electricity in 2030. The lack of access is highest in Sub-Saharan Africa, which accounts for 75% of the global deficit [4].

In the past decade, access to electricity through decentralised systems i.e. alternatives to centralised, national grids, such as mini-grids, microgrids and off-grid solutions, has increased significantly. By 2019, there were 11 million mini-grid users [5] and 105 million people with off-grid solar electricity [6]. Furthermore, the International Energy Agency (IEA) predicts that 50% of electricity access gains will come through mini-grids and stand-alone systems [7]. In many situations where communities live in remote, rural settings, extending the national grid is economically unviable, and so decentralized solutions make the most sense, many of which use renewable energy [8], [9].

Even where electricity is available, it is far from the only 'fuel' used to fulfil people's energy needs. Cooking is a key activity of daily life and requires relatively large amounts of energy – in Nepal cooking consumes around three quarters of household (HH) energy

[1]. However, as of 2019, 2.6 billion people worldwide lack access to clean cooking fuels and technologies [4]. A sustainable cooking technology must be environmentally, socially, as well as economically sustainable to be considered truly sustainable in the long term [10], while sustainability is often defined as in the Brundtland report of 1987 as meeting "the needs of the present without compromising the ability of future generations to meet their own needs" [11]. In relation to SDG 7 and Indicator 7.1.2, clean cooking fuels and technologies comprise electric, liquefied petroleum gas (LPG), natural gas, biogas, solar, and alcohol-fuel stoves [4], where clean is defined according to guidelines from the World Health Organisation (WHO) of levels of indoor air pollution (IAP) [12].

Electrification and clean cooking have generally been seen as separate issues, with electric cooking not taken seriously as an option for the Global South and cooking often overlooked in energy and electricity planning due to the perception that it is too expensive and therefore unfeasible [4], [13], [14]. However, approximately 1.8 billion people now have access to electricity but not to clean cooking, presenting an opportunity for the sectors to be considered together and for electricity to become a primary cooking fuel for a quarter of the population who still cook with polluting fuels [4], [13], [14].

1.2 Global cooking context

Figure 1.1 shows how access to clean cooking fuels varies across the world [15]. Without major changes in trends, Sustainable Energy for All (SEforAll) predicts that at least 2.3 billion people will remain without access to clean cooking in 2030 as a result of insufficient action and population growth [10], [16], [17]. Globally, increasing clean cooking access has occurred alongside population growth, causing a stagnation in the number of people lacking clean cooking [4]. In Sub-Saharan Africa, meanwhile, progress in clean cooking has failed to match the growth in population, leading to the lowest levels of clean cooking in the world, as shown in Figure 1.1 [15].

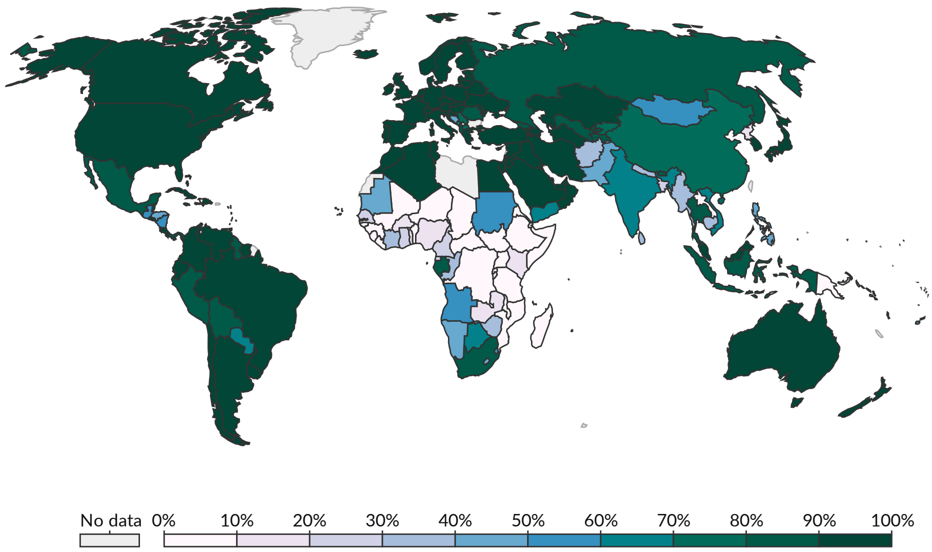

Figure 1.1: Percentage of population with access to clean cooking fuels and technologies by country, 2020 [15]**.**

Biomass cooking refers to the use of traditional, solid fuels such as wood, charcoal, crop wastes, dung and coal, and causes indoor air pollution which leads to negative health impacts for cooks and others [18], [19]. Indoor air pollution from biomass cooking accounts for the premature deaths of over 3.8 million people every year [19], [20]. These deaths are caused by a range of illnesses, with 27% attributable to pneumonia, 27% to ischaemic heart disease, 20% to chronic obstructive pulmonary disease, 18% to strokes, and 8% to lung cancer [10], [19]. Exposure to indoor air pollution doubles the risk of childhood pneumonia and is responsible for 45% of pneumonia deaths in children under the age of five [19]. The WHO has called indoor air pollution the “single most important environmental health risk factor worldwide” [21], [22].

The use of biomass for cooking is also intrinsically related to other development challenges including gender, poverty, climate change and environmental degradation [13]. Generally, biomass cooking disproportionately affects the health of women, who are mostly responsible for cooking, due to their increased exposure to indoor air pollution in kitchens [19]. The burden of firewood collection also falls mainly to women and children, who often have to travel long distances carrying large amounts of wood [10], [18], [19]. In Sudan, refugees had to travel up to 15 kilometres to collect firewood for their cooking needs [23]. Firewood collection increases the risk of musculoskeletal damage and gender-based violence for women and children, as well as limiting their opportunities to go to school, improve their education, engage in income-generating activities, or simply use their time as they please [10], [19], [24].

In addition to health impacts, emissions from biomass cooking are damaging the environment and contribute to climate change. Greenhouse gas (GHG) emissions from biomass cooking amount to approximately a gigaton of carbon dioxide per year, which is around 2% of global emissions [17], [25], [26], while one quarter of emissions of black carbon, a powerful climate change pollutant, is attributed to biomass fuels [19], [25], [26]. Unsustainable deforestation for firewood collection is degrading and depleting forests around the world [27], [28]. As the pressures of global warming, agriculture and timber harvesting increase the rate of deforestation, the availability and cost of biomass fuels are set to pose serious problems for many countries in the Global South [10].

Progress towards achieving SDG 7 has been lacking, especially in cooking, and that widespread, transformative change is required for its achievement. Electric cooking can also support progress across nine of the other SDGs by reducing health and climate impacts associated with biomass cooking and freeing up time for work, education and leisure, especially for women, and is therefore a crucial element of progress towards the SDGs [14]. Although fossil fuels remain significantly resourced by many national electricity grids, renewables will be increasingly employed to generate 'cleaner' electricity, which could then be used to connect billions of people to clean cooking solutions [29].

1.3 Cooking, energy and electricity in Nepal

1.3.1 National context

Nepal is a country in South Asia which already generates around 75% of its electricity from renewable sources but has low access to clean cooking at 31%, as of 2019 [4], [30]. Indoor air pollution from biomass cooking accounts for the premature deaths of around 22,000 people in Nepal every year [31]. Ranked at 142nd in the Human Development Index (HDI), Nepal is a poor, landlocked country with no fossil fuel reserves of its own, but huge renewable potential [32]–[34]. According to a survey in 2016, firewood is the most widely used cooking fuel for Nepal's 29.1 million inhabitants, with 48% of HHs cooking on a traditional wood stove with an enclosed combustion chamber, 15% cooking on an open fire with the pot balanced on stones, and 9% using improved biomass cookstoves, while cow dung and plant residue are other less common sources of biomass cooking fuel [35], [36]. Firewood usage is most prevalent in rural areas, which are home to 79% of the population [37], with 65.8% of HHs using firewood for cooking, compared to 35.4% in urban areas [35].

However, some clean cooking fuels are becoming increasingly common in Nepal, with 33.1% of HHs using LPG and 3.1% using biogas [35]. LPG, a by-product of the extraction of fossil fuels such as petrol, diesel and aviation fuel, is used much more in urban areas (54.1%) than rural (16.5%) [27], [35]. Biogas is a clean fuel produced through anaerobic digestion of a variety of biodegradable organic materials including manure and food waste [38]. However, the use of electricity for cooking in Nepal is very low at less than 1%, and even lower in rural areas [35].

Nepal consumes around 1.5 million tons of LPG annually, all of which is imported, mostly from India [39]. Therefore, LPG stove usage is affected by supply risks and energy security concerns, such as those caused by protests and blockades, and is vulnerable to fluctuating global markets which can cause price surges and resulting social unrest [35], [39], [40]. The Government of Nepal is committed to reducing dependency on LPG imports and making use of its vast hydropower potential by increasing access to electricity for cooking [35].

Access to electricity in Nepal has increased with 71.7% of HHs connected to the national grid, using electricity generated mostly from hydropower, while 23% are connected to off-grid electricity sources [30], [35]. Isolated mini-grids including mini-, micro- and pico-hydropower mini-grids serve 12% of Nepalese HHs, with others connected to solar lighting systems, and around 5% of HHs without electricity access in any form [35]. These HHs depend on dry-cell batteries and solid fuels such as kerosene for lighting [35].

The country has huge renewable energy potential, with 45.6 gigawatts (GW) of hydropower technically feasible, and 3 GW and 2 GW of commercially feasible wind and solar power respectively [33]. However, factors including the April 2015 earthquake, geographical challenges, political unrest and economic weakness have reduced progress in electrification and electricity generation infrastructure [9], [41]. Until 2018, enforced power cuts to prevent electricity demand reaching supply and destabilising the national grid, known as load shedding, were commonplace in Nepal [39], [42]. Although provision of power remains variable in quality, with power cuts and low voltage periods still frequent, the installation of large-scale hydropower projects is set to create a surplus of power generation over the coming years [30], [42]. According to the Nepal Electricity Authority (NEA) Nepal currently has an installed capacity of almost 2,000 megawatts (MW) and a surplus of 400-500 MW in summer monsoon periods already [43].

Therefore, the NEA aims to increase domestic demand through the promotion of electric cooking and electric vehicles, while strengthening national grid infrastructure accordingly

[30]. The Government of Nepal is connecting clean cooking with progress in electricity access in an integrated approach [44]. The Ministry of Energy Water Resources and Irrigation (MoEWRI) White Paper of 2018 centres electric cooking in the country’s long term vision, outlining a program to achieve ‘one electric stove in every HH’ over five years, with further commitments including [44], [45]:

- To reach 5,000 MW installed electricity generation capacity in five years and 15,000 MW installed capacity in 10 years
- To increase the per capita consumption of electricity to 700 kilowatt-hours (kWh) within five years and 1,500 kWh in 10 years

Furthermore, the 2020 Second Nationally Determined Contributions (NDCs) Policy sets a target of 25% of Nepalese HHs using electricity as their primary cooking fuel by 2030 [46]. In 2020/21 the Government of Nepal aimed to enable electric cooking in 100,000 HHs, and encouraged uptake by waiving custom duties on imported induction stoves and introducing a discount of 25% for HHs with high monthly electricity consumption of over 150 units [44], [46].

Electric cooking has the potential to transform the global cooking context, leveraging progress in electrification to drive forward the clean cooking agenda [47]. The Government of Nepal is creating an enabling environment for electric cooking. However, enabling it in rural, off-grid contexts, is much more difficult, due to the remoteness of communities and the often constrained nature of their electrification [48], [49].

1.3.2 Off-grid context

For the last fifty years, micro-hydropower has been a major source of electricity generation in rural areas of Nepal, referring to systems which generate up to 100 kilowatts (kW) [9], [50]. There are now around 3,300 micro-hydropower plants (MHPs) in Nepal, each providing renewable electricity to hundreds or thousands of residents through mini-grids, which are isolated networks where local generation supplies local demand [51]. The MHPs are manufactured and installed by Nepalese enterprises with considerable contributions to the work carried out by local community members [9]. This thesis focusses on MHPs, as opposed to solar mini-grids, due to their prevalence and importance in the Nepali energy context.

The rate of national grid extension is increasing [30]. However, while the government aims to extend grid infrastructure as far as possible to reach rural areas, some MHP communities in Nepal are extremely remote, with inadequate infrastructure and challenging surrounding geography such as mountains, valleys and rivers. These challenges make grid extension to some areas of Nepal uneconomical and unfeasible for the foreseeable future [30], [52]–[54].

Despite access to renewable electricity, MHP community members mostly fulfil their cooking needs with firewood, with MHP electricity used for lighting, phone-charging, other HH appliances, and industrial machines [55]. It is common for HHs to 'fuel stack' between firewood and LPG stoves, using both wood and LPG as cooking fuels, within meals and for different meals. Wood stoves also often provide space heating, essential for keeping warm in cold winters [56]. Although ownership of rice cookers and electric kettles is increasing in rural MHP communities, there is a lack of awareness of the benefits of clean cooking amongst those most affected i.e., women and children in rural areas [17], [56]. Figure 1.2 depicts a woman cooking roti, a flatbread cooked regularly in rural Nepal, on a traditional wood stove.

Figure 1.2: A woman in Solukhumbu. Eastern Nepal, cooking roti using a traditional wood stove. Credit: Sudiksha Uprety.

MHP energy provision varies widely in affordability, reliability and sustainability [55], [57]–[59]. The quality of manufactured MHP equipment can be low, while systems often operate close to full capacity at peak times, causing power instability and outages [9], [60]. Furthermore, insufficient usage of generated electricity during off-peak periods and poor tariff collection can reduce economic viability of MHPs, of which financial sustainability is often not adequately considered past installation [9], [61], [62].

The generating capacity of MHPs is limited by its components and structure such as turbine size and watercourse characteristics [63]. Electric cooking requires high power, often around 1 kW or more for short periods of time, whereas MHP systems have constrained supplies of up to 100 kW for hundreds or thousands of residents [63]. Nepali people living in rural communities often have access to sustainable, modern energy through MHPs, but its sustainability is under threat and it is rarely used for cooking. MHP mini-grids could potentially address both aspects of SDG 7 by providing renewable electricity that can serve HH energy needs across the board, including cooking. This thesis examines whether and how electric cooking could provide a modern, sustainable cooking option for people in rural Nepali MHP communities.

1.4 Research aim and objectives

The aim of this research is to support the transition to electric cooking in rural Nepali MHP mini-grid communities with constrained power capacities. This is the first body of research to focus on electric cooking in this context, in which clean cooking technologies are currently rare and the connection of high-power appliances in HHs to the mini-grid is as yet unexplored. To address this aim, this research focusses on electric cooking trial projects and modelling work. Six objectives were determined to enable achievement of the overarching aim:

1. **Understand and characterise the Nepali cooking context in MHP communities.**

To develop a detailed understanding of current cooking practices and behaviours to understand how best to enable a transition to electric cooking. To the author’s knowledge, this research is the first to include detailed studies of Nepali cooking practices.

2. **Investigate the transition to electric cooking from a social perspective.**

To evaluate the suitability and acceptability of electric cookers for Nepali cooks, the cultural and behavioural challenges involved, and how to improve the transition experience for cooks to enable maximised penetration of electric cooking. The conducted studies are the first to provide rural Nepali cooks with electric cookers and relevant training, and to collect detailed data and feedback on the transition.

3. **Investigate the transition to electric cooking from a technical and operational perspective.**

To assess the effects of different electric cookers on the MHP electrical system and their current scalability in constrained capacity mini-grids. The studies are the first to collect detailed MHP electrical system data and electric cooking load profiles in Nepal.

4. **Explore solutions which could enable increased uptake of electric cooking and improve the financial sustainability of MHPs.**

To explore solutions which could enable increased uptake of electric cooking, such as efficient cooking devices, demand side management and energy storage, using data collection, analysis and modelling approaches, and to understand the potential for income generation from electric cooking to increase the economic viability of MHP communities, through techno-economic modelling. This is the first research work to investigate how the aforementioned solutions could be integrated into MHP mini-grids and to create a detailed techno-economic model of an MHP community.

5. **Investigate how energy storage could enable increased adoption of electric cooking in MHP communities.**

To investigate how battery storage systems could be integrated into MHP mini-grids in different topologies, to reduce peak loads and shift demand, by developing models for battery control and sizing, and to use techno-economic modelling to understand their economic viability.

6. **Identify and compare electric cooking system solutions for enabling widespread uptake of electric cooking through techno-economic modelling**

To evaluate the scalability of electric cooking enabled by identified solutions and their associated costs and income generation potential.

Addressing the research objectives will develop understanding of the Nepali cooking context, social and technical insight on how to transition to electric cooking in rural Nepal, and modelling tools and numerical evaluations for solutions for increasing the potential adoption of electric cooking in MHP communities.

In order to achieve the objectives, the following methods will be employed, supporting methodologies explained in each of the thesis chapters:

- Data gathering: including on the current cooking context, the transition to electric cooking, participant experiences, the MHP electrical system, and electric cooker load profiles, using surveys, energy meters and data loggers. This will be necessary to achieve objectives 1-4, collecting data through electric cooking trial projects on existing cooking practices, electric cooker acceptability and suitability, and solutions to enable increased electric cooking adoption such as efficient electric cooking devices

- Modelling: including techno-economic modelling of an MHP community, MHP mini-grid control system modelling integrating battery storage, and MHP mini-grid power flows and battery capacity estimation modelling, using mathematical modelling, and control system simulation. This will be necessary to achieve objectives 4-6, to assess solutions for enabling increased electric cooking adoption, understand the potential for electric cooking to improve the financial sustainability of MHP communities, and to investigate control and approximate sizing of battery energy storage systems

The thesis produced the following publications, which explored how electric cooking can be supported by MHP mini-grids and how MHP financial sustainability can be improved:

Journal Articles

Clements W, Silwal K, Pandit S, Leary J, Gautam B, Williamson S, et al., "Unlocking electric cooking on Nepali micro-hydropower mini-grids," Energy Sustain. Dev., vol. 57, pp. 119–131, Aug. 2020. Available from: https://doi.org/10.1016/j.esd.2020.05.005

Clements W, Pandit S, Bajracharya P, Butchers J, Williamson S, Gautam B, et al., "Techno-Economic Modelling of Micro-Hydropower Mini-Grids in Nepal to Improve Financial Sustainability and Enable Electric Cooking," Energies, vol. 14, no. 14, p. 4232, Jul. 2021. Available from: https://doi.org/10.3390/en14144232

Reports

Gautam B, Pandit S, Clements W, Williamson S, Silwal K. "Assessing electric cooking potential in micro hydropower microgrids in Nepal". 2020. Available from: https://mecs.org.uk/wp-content/uploads/2020/12/MECS-TRIID-PEEDA_updated-Report.pdf

Williamson S, Gautam B, Clements W, Khanal M, Shrestha M, Bajracharya P, et al. "Understanding the Suitability of Electric Pressure Cookers in Nepali Households". 2022. Available from: https://mecs.org.uk/wp-content/uploads/2022/02/Understanding-the-Suitability-of-Electric-Pressure-Cookers-in-Nepali-Households.pdf

Gautam B, Bajracharya P, Shrestha M, Dangol A, Raimes A, Sieff R, et al. "Nepal eCookbook". Kathmandu, Nepal; 2021. Available from: https://mecs.org.uk/wp-content/uploads/2022/05/Nepal-eCookbook.pdf

1.4.2 Collaboration with partners

The research included important collaborations with local (Nepali) partners. These partners were integral to the projects conducted and provided essential insight, advice and guidance which informed other aspects of the research, improving its direction and quality. The collaborations enabled the researcher to understand their limitations regarding knowledge of the cultural context of Nepal and the case study communities, mitigating impacts on the research. In addition to the work of the supervisors, the key partners involved in the research are described below:

People, Energy and Environment Development Association

The People, Energy and Environment Development Association (PEEDA) is a non-governmental organisation (NGO) focussing on community mobilisation for energy projects, founded in 1997 in Nepal [64]. PEEDA aims to "mobilise both local and external resources to harness Nepal's indigenous resources, thereby promoting activities for economic development and poverty alleviation" [64].

Kathmandu Alternative Power and Energy Group

Kathmandu Alternative Power and Energy Group (KAPEG) is a research-based engineering enterprise working in renewable energy technologies including small wind and pico-hydro systems [65]. KAPEG was founded in Nepal in 2004 [65].

Role of the researcher

Three cooking diary studies underpinned the research presented in this thesis. In the first, the researcher was responsible for the cooking diary data analysis and MHP electrical system data analysis, but none of the project planning or implementation. In the second, the researcher was involved in the conceptualisation, planning, implementation, field work including a week-long site visit, supporting the project partners, MHP electrical system data analysis, and was fully responsible for the cooking diary data analysis and the majority of the report-writing. The researcher collaborated with the project partners in areas such as project strategy, survey creation, and MHP electrical system analysis. In the third study, the researcher was involved in the conceptualisation, planning, supporting the project partners, and was fully responsible for the MHP electrical system data analysis reported in the thesis and the cooking diary data analysis. The report-writing responsibilities were split between the researcher and other members of the research team. The researcher collaborated with the project partners on tasks such as project strategy, survey creation, and MHP electrical system analysis.

In the three studies, PEEDA fulfilled responsibilities such as project initiation, planning, project management, and all field work involving cooking diary study implementation. KAPEG fulfilled responsibilities including planning and management of the technical, electrical system aspects of the projects, including MHP system performance assessment, data logger installation and initial system operation monitoring, transformer load capacity measurement, and HH wiring upgrading.

The work in Chapters 3 and 4 included responsibilities collaboratively fulfilled by project teams which were collaborations between PEEDA, KAPEG and the University of Bristol. Some of the work in Chapter 5, such as conducting surveys on electricity demand, was undertaken by members of PEEDA. Where specific methods, surveys and analyses are reported, it is indicated in the text which party created and conducted the method, analysis or survey. All work outside of Chapters 3-5 was completed by the researcher. Throughout the thesis, the research direction and work conducted were informed by discussion and guidance from colleagues at PEEDA and KAPEG, as well as the researcher's supervisors, as described in the Acknowledgements section.

From the second to the third cooking diary studies, the roles of the researcher and his supervisor changed in relation to project activities implementation changed, most notably from being heavy involved in planning and implementation and providing support and strategic direction during field work in the second study, to being less involved in implementation and field work in the third study, instead providing a more advisory role. This approach happened organically as the project partners grew in confidence and ability to plan and implement project field work activities based on knowledge generation and transfer through the experience of the previous projects, while the approach was also encouraged so that the partners can expand their activities and take ownership of future projects, requiring less support. For example, the project partners are now adept at using the Kobo Toolbox platform for creating and conducting digital surveys and are already using it for new projects.

1.4.3 Ethical considerations

The research conducted followed an ethical approach, which can be defined as avoiding "doing long-term system harm… to individuals, communities and environments" [66]. Ethical approval from the University of Bristol was obtained for all studies, surveys and interviews. Photos were taken with permission of participants. All participants were informed of the purpose of the research and their consent obtained to, firstly, participate, and secondly, for the collected data to be used by the projects and in this research.

1.5 Thesis structure

Chapter 2 reviews the available literature on: the global cooking context; electric cookers; electric cooking studies and interventions; the Nepali cooking context and drive towards clean cooking; MHP mini-grids and their financial sustainability; electricity demand in MHP communities and of electric cookers; and solutions which could enable increased adoption of electric cooking in constrained capacity mini-grids. In reviewing the latter, the potential of a range of solutions is evaluated, leading to the identification of efficient electric cooking devices, demand-side management measures and energy storage as being worth investigation through data collection and modelling methods.

Chapter 3 presents the key lessons from two cooking diary studies which trialled induction cookers in two rural Nepali MHP communities. Socio-cultural, economic and technical insights are reported, revealing the acceptability and scalability of induction cooking in MHPs.

Chapter 4 describes a further, improved cooking diary study which trialled efficient electric cooking devices as a solution for enabling increased adoption of electric cooking in MHP communities, revealing the suitability of the cookers for Nepali cooking, the level of assimilation into daily cooking practices under monitored and unmonitored conditions, and how the cookers contribute to the community electricity demand.

Chapter 5 presents the creation of a techno-economic model of an MHP community which aims to understand the potential of income generation from electric cooking to improve MHP plant financial sustainability, enable evaluation of different tariff structures and provide insight into community electricity demand. The model is used to assess potential economic viability of a case study community under a tariff system based on electricity consumption and demonstrate load planning capability including simulation of demand-side management measures.

Chapter 6 investigates how battery energy storage systems could be integrated into an MHP mini-grid in terms of control and applies the understanding obtained to create a simplified mini-grid power flows model, enabling estimation of battery storage capacity requirements for increased electric cooking adoption using realistic electric cooking load profiles generated using the techno-economic model. HH battery-supported electric cooking is also investigated in terms of battery sizing and the scalability of battery charging.

Chapter 7 evaluates the identified solutions for enabling increased electric cooking adoption in constrained mini-grids in terms of scalability and economic viability, assessing direct electric cooking with different cookers and usage levels, demand-side management measures for spreading out cooking loads, battery energy storage systems in centralised and HH topologies, and electric cooker combinations.

Chapter 8 discusses the key outcomes of the research in terms of applicability and limitations, summarises the main findings, and makes suggestions for further work.

Chapter 2

Literature Review

2.1 Introduction

The literature review considers cooking and MHP communities, including clean cooking technologies and studies/interventions, and MHP mini-grid architecture and sustainability. The introduction of electric cooking into MHPs is explored, including potential measures and innovations for increasing its adoption in constrained grids. The review aims to identify relevant research on electric cooking and mini-grids and generate an understanding of the issues surrounding the introduction of new cooking technologies to households and mini-grid systems. It is found the electric cooking is mostly an unexplored prospect for MHP communities, placing this research as essential for supporting its introduction.

2.2 Cooking and electricity

Cooking is a set of processes, such as boiling, frying, simmering, roasting, grilling, etc, which increase the temperature of food to a desired level and, by continuous energy input and/or insulation, maintain that temperature for enough time that the food becomes 'cooked' [67], [68]. Numerous different fuels are used around the world to provide the energy necessary for cooking, from traditional, biomass fuels such as wood and charcoal to newer, clean fuels such as LPG, biogas and electricity. Clean fuels can be defined according to the WHO guidelines for IAP which state that average annual concentration of particulate matter less than 2.5 micrometres in diameter (PM2.5) should be less than 10 $\mu g/m^3$, and 24-hour exposure to carbon monoxide concentration should be less than 7 $\mu g/m^3$ [12]. Cooking with biomass often leads to IAP exceeding these criteria, while the use of clean fuels can reduce IAP.

2.2.1 Cooking fuels

In Nepal, the prevalent cooking fuels are firewood, LPG and biogas. Firewood has a long history of usage. One recent study on cooking practices in rural Nepal found that, despite the negative health impacts of cooking with firewood, it offers many co-benefits, which make fuel stacking with firewood inevitable, even if HHs own clean cookers [56], [69]. The paper argues that HHs are likely to evaluate clean cooking technologies by the co-benefits that are lost and gained, rather than considering them as replacements for their existing stoves [56]. Figure 2.1 shows a traditional wood stove in a typical kitchen area in rural Nepal [70]. Traditional stoves vary in design, with some simply an open fire with the cooking pot balanced on three stones or a metal stand, as shown in Figure 2.1, and others incorporating an enclosed combustion chamber, but all produce smoke which leads to high levels of IAP [10].

Figure 2.1: Traditional wood stove cooking in rural Nepal. Credit: Biraj Gautam [70]**.**

Health benefits and lower smoke levels are not necessarily priorities for HHs in rural areas [71]. Many HHs use their wood stoves for warmth, while fire and smoke also have other benefits such as offering protection of plants and stored food from pests [56], [72]. Cooking is a deeply cultural phenomenon. Some people perceive food cooked using traditional wood cooking methods to taste better [56]. Food can be kept warm on the side of a wood stove, sometimes for hours after cooking [56]. A cooking fire can serve as an important social centre within a HH around which HH members gather and spend time [72]. Importantly, many HHs collect their own firewood for cooking without direct monetary costs, as depicted in Figure 2.2. Therefore, a transition from traditional wood stove cooking to clean cooking is not straightforward and likely to be partial, at least at first, due to the co-benefits of traditional cookstoves [69].

Figure 2.2: Collecting firewood in a rural Nepali community. Credit: Biraj Gautam [70]**.**

Improved cookstoves (ICS) have focussed on increasing the efficiency of firewood combustion, thereby reducing firewood consumption, and reducing emissions by enclosure and insulation of the combustion chamber and, in some cases, the addition of a chimney to redirect smoke [35]. However, uptake has been limited and, even amongst adopters, health problems often persist [73], [74]. Significant emission reductions have only been demonstrated by the very best ICS and there is doubt over their health benefits in real-world conditions [73], [74]. Up to around 30% of wood fuel can be saved by ICS, meaning that they can reduce IAP and firewood collection time, but many still exceed the exposure recommendations to carbon monoxide and PM2.5, and they still require the collection of large amounts of firewood [10], [25], [34]. Furthermore, while IAP is reduced, chimney smoke can mean that ICS contribute significantly to air pollution in the areas surrounding HHs using them [10]. Regardless of health impacts, ICS design and interventions have often failed to account for the social and cultural aspects of cooking practices, leading to low uptake [72].

LPG produces much lower emissions, improving IAP levels by over 80%, but requires a robust supply chain [25], [75]. Figure 2.3 shows a typical LPG stove in a rural Nepali community. HHs in rural Nepal often use LPG due to its high controllability, for heating tea and cooking snacks, with the gas flame responding quickly to adjustment and able to cook foods in short durations [56], [76]. LPG has enabled access to clean cooking for 80 million HHs in India, where it is a key part of the cooking fuel mix and highly acceptable for consumers [27].

Figure 2.3: An LPG stove with two places, an LPG canister and other cooking equipment. Credit: Sudiksha Uprety.

However, LPG is derived from fossil fuels and therefore non-renewable [10]. Furthermore, it is linked to oil prices and thereby suffers from inherent price volatility [10]. LPG requires robust supply infrastructure and an extensive supply network to ensure availability and sustainability, neither of which are present in Nepal due to total reliance on Indian imports [39]. Distribution to rural areas is inadequate and local access is limited, causing fluctuating supply reliability increased costs [27]. Added to safety concerns over usage, LPG is sometimes seen as only a transition fuel in the move to clean, sustainable cooking [25], [75].

Biogas is carbon neutral, but requires appropriate feedstock, and has high initial capital costs [77]. Biogas digesters convert organic waste and dung into gas, which is piped to the biogas stove. The Biogas Support Program in Nepal, supported by the Government of Nepal, has led to the installation of over 250,000 biogas plants in low-income HHs [78]. Participants reported saving money on energy, reductions of IAP and improvements in sanitation [79]. However, only those with the financial means to run a biogas plant could participate, and other requirements include having cattle for the dung and having enough space for the digester [56]. Biogas plants may not always produce sufficient gas to meet daily cooking needs [80].

Hydrogen is a carbon-free fuel which could be considered for cooking, but is currently most often derived from natural gas, a fossil fuel, and has issues of safety around storage, therefore requiring further development to become a competitive cooking fuel [81], [82]. Clean alternatives to firewood without the supply chain issues of LPG and technical requirements of biogas are necessary for rural Nepal. However, there is a need to understand existing cooking practices and usage of different cooking fuels to determine how best to introduce new cooking technologies to enable maximised adoption [56].

2.2.2 Electric cooking and cookers

Electric cooking presents a clean alternative to biomass cooking, with the potential to: improve health and life expectancy through reduced IAP; save people time thereby improving economic opportunities by reducing firewood collection times; reduce greenhouse gas emissions; and reduce deforestation. Solar electric cooking, which uses energy generated from solar panels directly to power a heating element, has been proposed as a clean, affordable means of cooking [83]–[85]. However, adoption has been limited due to its inconvenience, requiring significant changes in behaviour and strong solar insolation at the time of cooking [84]. A review of solar cooker studies also found that cultural needs are not always sufficiently taken into account and that firewood usage and cooking practices are sometimes seen as barriers rather than included in design thinking [86].

Plug-in electric cookers are analogous to wood and LPG stoves in that they can provide power to cook food continuously and on-demand. Electric stoves include hobs – induction, glass-ceramic, halogen/infrared, solid disk, coil – and insulated cookers – electric pressure cookers (EPCs), rice cookers, slow cookers. Induction cooking, depicted in Figure 2.4, is unique in that heat is generated directly in the pan by electromagnetic induction, providing higher efficiency cooking than the usual hot plate hobs, more than 80%, and reducing the possibility of burns as the hob itself does not need to reach a higher temperature than the pan [68]. This direct heating also means that induction hobs provide greater controllability, as they are quick to respond to changes in input power, similar to gas. Furthermore, as soon as the cooking vessel is removed from an induction hob, heat generation stops as current can no longer be induced [87]. However, specialist ferromagnetic pots and pans are required, increasing the already high cost of a transition to induction cooking for developing communities [18].

Figure 2.4: An induction cooker being used for cooking vegetables in rural Nepal. Credit: Surendra Pandit.

Glass-ceramic and halogen hobs use infrared radiation as their principal heat transfer mechanism. The difference is in the element: glass-ceramic hobs use radiant resistive heating elements whereas halogen hobs use tungsten halogen lamps [88]. Both use glass-ceramic as the hob material to transmit radiation directly to the pan. The hob itself also gets hot in the process and transfers further heat to the pan via conduction [89]. The low thermal conductivity of the glass-ceramic material has the advantages of enabling heat retention in the pan and preventing sideways conduction out of the hob cooking zones, and does not reduce efficiency as transmitting radiation is the main mode of heat transfer to the pan. However, efficiencies are still less than those of induction hobs [90].

Solid disk and coil hobs use conduction as their principal heat transfer mechanism. Both use coiled resistive heating elements encased in insulation and a metal sheath to provide even heating and good heat conduction [88]. Solid disk hobs have a solid metal – often cast iron – disk on top of the coiled elements, whereas coil hobs have the elements exposed and a reflection shield beneath the coils to reflect heat radiating away from the pan. These hobs have the advantage of the coils being in direct contact with the pan, ensuring fast conduction, but are difficult to clean. Solid disk hobs have limited controllability due to the presence of the metal disk slowing conduction but provide gradual, even heating, and good heat retention [88]. They are generally found to be the least efficient of the electric hobs [91] [92]. All electric hobs, except halogen, cycle input power on and off to provide lower power settings, and therefore require a thermal mass between the element and pan to create even heating, such as glass-ceramic, a cast iron disk or ceramic element insulation [93]. The composition, size and shape of the cookware also influence heat transfer, with pans containing highly conductive metals such as copper the most efficient [91].

Insulated cooking devices are another key design, with their insulation decreasing heat losses during cooking thereby reducing input energy requirements. An electric pressure cooker (EPC), depicted in Figure 2.5 can cook a wide variety of meals, perform most essential cooking processes including boiling and frying, and provide significant energy savings, and with one study finding savings of a factor of 5 for certain foods such as beans in Tanzania [94]. EPC cooking of boiling dishes like rice starts with a short preheat phase, during which the devices demands full power and the temperature of the food and water is raised, with the build-up of steam increasing the pressure and therefore elevating the boiling point of water to around 120°C [70], [95]. The insulation of the inner pot reduces heat losses so that little or no extra power input is required during the subsequent cooking phase, with occasional power pulses to maintain cooking temperature [95], [96].

Figure 2.5: An Electric Pressure Cooker, EPC, being used to cook noodles in Nepal. Credit: Biraj Gautam.

An EPC has a resistive heating element controlled by a thermostat [95]. The higher cooking temperature allows boiling dishes to be cooked faster and more efficiently [95]. Once the timer reaches zero, according to preset cooking programmes, the pressure is released, either by a ‘quick release’ mechanism or naturally, the latter of which allows the food to continue to cook as pressure and temperature reduce [96]. For frying, the lid is left off the device and constant power is drawn to keep the oil and food temperature higher, towards 200°C [70]. Generally, EPCs are considered more efficient than other electric cookers, although induction hobs are highly efficient, especially if cookware is well insulated and fits the hob well [10].

Electric rice cookers also reduce the energy requirements for cooking rice can be used to cook a wide range of meals such as soups, stews and omelettes, although they tend to be used mainly for cooking rice [91]. Rice cookers use a resistive heating element and generally demand constant power input during cooking before switching to 'keep warm' mode after around 20 minutes of rice cooking [97]. Slow cookers reduce the power demand of electric cooking by operating over longer periods but require significant behaviour change for people used to cooking in the evening as the food must be prepared earlier in the day [91].

2.3 Electric cooking studies and programmes

Across the Global South the use of electricity for cooking has been gradually increasing over the last decade [27], [35], [55]. However, as of 2018, when the research presented in this thesis began, electric cooking studies and interventions in the Global South were rare. Batchelor et al identified three key factors that have historically inhibited adoption of electricity for cooking: limited grid access, weak grid infrastructure and perception of price [14]. In weak grids, large load changes cause swings in the grid voltage, something that both national power grids and off-grid systems such as mini-grids can suffer from especially in the Global South. This makes the electrical networks susceptible to low voltage events, known as brownouts, and complete system failures, blackouts, at peak load times leading to a lack of consumer confidence that power will be available for cooking. On- and off-grid system peak loads often already exceed the limited grid capacity meaning that many utilities and power providers do not encourage electric cooking [14].

Furthermore, even in places where electricity is the cheapest cooking option, it is often perceived as more expensive [98]. A clean cooking program in rural India introduced induction stoves into almost 4000 HHs, with only 5% adopting them as their primary cooking method due to fear of higher electricity bills and inadequate power supply [99]. Operating costs of the electric cookers were actually comparable to those of LPG but the study found that induction cooking was only adopted as a primary means of cooking where LPG retailers were located far from HHs [99]. A study in a solar mini-grid community in Tanzania found that cost of electricity is a key determinant of EPC usage, which increased during a period when the tariff was reduced [100].

In Ecuador a national energy efficient cooking program launched in 2014 found primary usage of induction stoves among surveyed HHs to be very low at 1%, primarily because of the persistence of LPG as a viable alternative and the high costs of induction stoves, compatible cookware and electricity after adoption [101]. A study of socioeconomic survey data on the choice between electricity, LPG, firewood and kerosene among 709 HHs in five Ethiopian cities found HH economic status and cooking fuel price to be critical [102]. Many rural populations collect their own firewood for cooking, so do not see the costs for this directly [10]. However, when costs for fuels are included, either in time or market value, it has been shown that electric cooking is comparable to other fuels for both on- and off-grid consumers in a variety of contexts [10], [103].

Alongside the economic, technical and policy issues, a successful HH level transition to clean cooking involves changes in behaviour which can include the cooking of different foods, different quantities of foods, and adapting of cooking techniques to suit the new appliance and any new cooking utensils. Furthermore, these may result in real or perceived changes in the size, texture and taste of meals which may influence their desirability [104].

There is a need to foreground the social, rather than the financial or technical, in seeking to transform access to clean cooking technologies [105]. Cooking is a deeply cultural experience, and clean cooking technologies need to be able to fit with, and stretch, existing cooking practices. By this it is meant that it is not enough for electric cooking to fit with a cooking context, it must also offer further benefits such as cost or time savings in order for adoption to be likely [105]. New cooking technologies are likely to be resisted if changes in the taste of food, or processes used for cooking, are perceived, while the cultural significance of cooking means that transitions are more complicated than other innovations such as mobile phones and mobile money [10], [56], [106]. Furthermore, the transition process is fragile due to seasonal changes and no-cost reversal to traditional fuels [104], therefore the support and management of the transition to electric cooking is critical to its long-term adoption.

There are several different methods that have been used to test new stoves. ICS are most commonly tested using the Water Boiling Test, Controlled Cooking Test and Kitchen Performance Test [107]–[109], focussing on stove efficiency, emissions, performance and acceptability. However, none of these provided detailed insight into how people cook and how they adapt their cooking practices to new fuels or appliances.

In Nepal, although there is significant opportunity for electric cooking, when this research began in 2018, little data on Nepali cooking habits existed. In 2002, HH and market surveys were conducted in two municipalities near Kathmandu University alongside experiments to determine the efficiency of different stoves and utensil combinations [110]. The study found that rice, lentils and vegetables, were cooked twice a day and meat cooked once a week due to its higher cost. A number of cooking vessels including pressure cookers and round-bottomed pots were found to be prevalent in the HHs.

A study conducted in 2012 on cooking and lighting habits in Nepal and Uganda used a questionnaire on needs, habits, energy resources, HH economics and aspirations, sampling 360 HHs in rural Nepal from mountainous, hilly and plain regions [111]. The survey aimed to understand how clean technologies could best be promoted. Findings included that income was low with 28% of respondent HHs living on less than $1.2 per day, that the average quantity of firewood used for cooking was 15 kg per person per week, and that respondents wanted a stove that saves fuel, cooks food quickly and is smokeless as priorities [111]. According to 87% of respondents, smoke from biomass cooking was a major problem causing discomfort and illness, and the average HH firewood collection time was 74 hours per month, highlighting the urgency of a transition to clean cooking [111].

A study assessing options for clean energy services in the Pyuthan district, in Western Nepal, found through surveys that the average annual useful cooking energy consumption ranged from 11 to 21.2 kilograms of oil equivalent (128 to 247 kWh) across different Village Development Committees [112]. The majority of surveyed HHs used biomass cookstoves. Pokharel et al found firewood to be the predominant cooking fuel in districts across the three main climatic regions of Nepal, and that it also provides space heating [113]. Bharadwaj et al provided many key insights, including that it is common for HHs to use wood stoves to cook food for livestock, increasing their firewood consumption [56]. However, detailed monitoring of cooking practices and meal energy requirements in rural Nepal is lacking.

2.3.1 Cooking diary studies

In April 2019, the £39.8 million Modern Energy Cooking Services (MECS) programme launched, funded by UK aid, aiming to rapidly accelerate the transition from biomass cooking to modern, clean, low carbon energy-efficient alternative methods [114]. eCook is an electric cooking concept pioneered by MECS researchers in the years leading up to the MECS programme, designed to provide poorer HHs with access to clean cooking and electricity. A cooking appliance is paired with a battery, which can be charged either by solar photovoltaic panels (PV-eCook) or an electrical grid (Grid-eCook) [115] [116]. In 2013, Batchelor proposed that by 2020 the monthly repayments on such a battery-supported cooking system would be comparable to the cost of cooking with charcoal in many developing regions [117]–[120], a hypothesis later confirmed in [121]. PV-eCook and Grid-eCook have different markets, with the former suited to rural, off-grid HHs and the latter targeted at areas where grid infrastructure is weak, such as urban slums or mini-grids. In weak grids, the battery can be charged at off-peak times, reducing peak loads. The eCook concept also includes direct electric cooking from mini-grids or national grids.

The Cooking Diaries Protocols [122], [123] were developed by MECS researchers to provide insight into exactly how cooking is performed in a specific context: what do people cook; which fuels and appliances do they use; and how much energy/time is required to cook their meals. After transitioning to electric cooking, the methodology observes how cooking practices change: how people adapt; and how well suited the new appliance is to the context. The methodology, alongside choice modelling surveys, focus groups and prototyping, was employed during the detailed in-country studies conducted by MECS researchers in a wide range of national contexts, including Tanzania, Kenya, Zambia, Uganda, Ethiopia, Myanmar and Bangladesh, providing insight into culturally distinct cooking practices and their compatibility with electric cooking [95], [115], [116], [124]. The cooking diaries asked HHs to record exactly what, when and how they cooked for six weeks – two weeks cooking as usual followed by four weeks for which they were asked to cook with electricity. This information is key to understanding how successfully electric cooking can be integrated into day-to-day life for families.

Key results of the Tanzania study included energy consumption data for different meals cooked using different electrical appliances which confirm the viability of using batteries for cooking, as well as insight into behaviour change. It had been thought that electric hotplates would be easiest to transition to due to their simplicity and similarity with traditional stoves, but EPCs were accepted and used by HHs, providing energy savings [94]. Batchelor et al showed that it is possible to cook with low power in reasonable timeframes in a study in Bangladesh which include prototyping of a 300 W, heavily insulated electric cooker. Insulation limits heat loss, maintaining high temperature, and it is temperature that cooks food, not heat. The study showed that integration of solar electric cooking with solar home systems by increasing PV panel and battery size can be cost effective compared to usual cooking cost [68].

The eCook concept has evolved during the MECS programme, under which work has shown considerable promise for efficient cooking devices such as EPCs in East and Southern Africa [95], [125]. The automated cooking experience, whereby the device cooks according to a timer and switches off automatically, allowing the user to use their time for other things, was appreciated by cooks [13], [95]. Importantly, the high efficiency of EPCs led to reductions in electricity demand and therefore electricity costs of around 50% across the range of foods they can cook, as compared to other electric cookers [13]. Cooking diary studies have shown that most dishes can be cooked with less than 0.6 kWh in EPCs, with monthly electric cooking consuming 30-60 kWh [13], [63]. Generating datasets of energy requirement including context-specific averages and variation is important for understanding electric cooking feasibility in terms of energy provision and running costs, and the potential of energy storage.

Other key findings of cooking diary studies conducted under the MECS programme include that fuel stacking is common when electric cooking is introduced, increasing energy security for users and enabling them to use the most suitable stove for each dish [13]. Having the option of using another cooking fuel leaves HHs less vulnerable to supply and price fluctuations [35]. Crucially, convenience and cost-savings were the most important drivers for electric cooking adoption, rather than health and environmental benefits, as the ability to save time and money provides tangible benefits for people [13].

The latest round of studies funded through the MECS programme focussed on EPCs, finding that, across a wide variety of contexts, including three studies based in Nepal, EPCs were highly acceptable and appreciated, confirming the findings of previous studies [126]–[128]. Usage levels of the EPCs were generally around 30%, with fuel stacking very common, although firewood consumption reductions were still significant. The studies found that improved power supply reliability, upgraded HH wiring and local after sales services are essential for increased electric cooking adoption [126]–[128]. There is a need for local suppliers and services centres for repair and maintenance so that cooks maintain confidence in their devices [126]–[128]. Generally, recent studies on electric cooking in the Global South have strengthened the evidence base for its feasibility and suitability across different contexts, leading to inclusion in government agendas, particularly in Nepal.

2.3.2 Clean cooking programmes in Nepal

In Nepal, there is a government-led drive for electric cooking adoption across the country, with the latest policy targeting 25% of Nepalese HHs using electricity as their primary cooking fuel by 2030 [46]. Accordingly, a number of large-scale programmes are underway, promoting and providing electric cookers to Nepali HHs. At least seven projects introducing cookers are ongoing as of 2019 [39]. One programme, implemented by the Clean Cooking Alliance (CCA) in peri-urban Nepal, included various educational campaigns on clean cooking, and monitoring through surveys, energy audits and temperature sensors, and led to 170 HHs out of just over 1,500 HHs deciding to purchase induction cookers [129]. Another market-led promotion programme, implemented by Deutsche Gesellschaft für Internationale Zusammenarbeit/Energizing Development Partnership Programme (GIZ/EnDev), led to around 10% of the community purchasing induction stoves [39]. The programme, which included some training and demonstrations on electric cooking techniques, as well as surveys with cooks, found that induction cookers were mostly used for rice and dal, with vegetables generally cooked with LPG [39]. It recommended increased hands-on training and cooking demonstrations.

Therefore, these programmes improved on past electric cooking rollouts, which failed to include guidance or monitoring for users and failed to consider cultural cooking practices sufficiently during project design and implementation [72]. Ongoing programmes include: the Terai Clean Cooking Programme, organised by the AEPC, which aims to replace traditional cooking fuels in 22 districts in Southern Nepal; the Clean Cooking Programme, funded by the Energy Sector Management Assistance Program (ESMAP) and the World Bank, aiming to promote electric cooking across 0.7 million Nepali HHs; and a five-year government clean cooking programme in conjunction with the Green Climate Fund [44]. Overall, there has been a lot of progress, in Nepal and globally, in clean cooking, since 2018, but little work has focussed on Nepali MHP communities.

2.4 Micro-hydropower

Figure 2.6 shows a typical MHP, which is termed 'run-of-the-river' and diverts water from a river to drive turbines and generate electricity, before the water is returned to the river at a later point, downstream [9].

Figure 2.6: A micro-hydropower plant in Ilam, Nepal. Credit: Sam Williamson.

The Alternative Energy Promotion Centre (AEPC), a government agency which promotes and supports renewable energy technologies and clean cooking, supports the development of MHPs with subsidies of around 50% of the overall project cost, and has played a crucial role in the creation of the 3,300 MHPs in Nepal [51], [52]. Community members often provide labour and monetary input during the construction phase of a plant, which often creates a collective sense of ownership in the community, with manufacturing companies conducting the design, manufacture and installation [52]. Privately owned MHPs are run as businesses with the managers responsible for setting tariffs and record keeping, while in community owned MHPs and cooperatives, community members are involved in decision-making and there is an expectation that they provide labour for repairs when necessary [9].

MHPs bring many benefits to communities in rural Nepal, both for HHs and other end uses. HHs have access to electricity for lighting, which can be used during the evening for social activities, education and housework [9], [130]. As well as powering HHs in a community, MHPs provide energy for commercial connections such as shops and mobile phone masts, community services including schools and health posts, and industrial end uses such as flour and grain mills, all of which can be referred to as productive end uses (PEUs) [55], [131]–[134]. Therefore, MHPs can create income-generating opportunities for community members, the diversity of which also supports the economic viability of the plant, increasing the usage of generated energy across the day and therefore creating a range of income sources for the MHP [9]. Figure 2.7 depicts a typical MHP and its constituent sub-systems, with descriptions provided in Table 2.1 [9], [135].

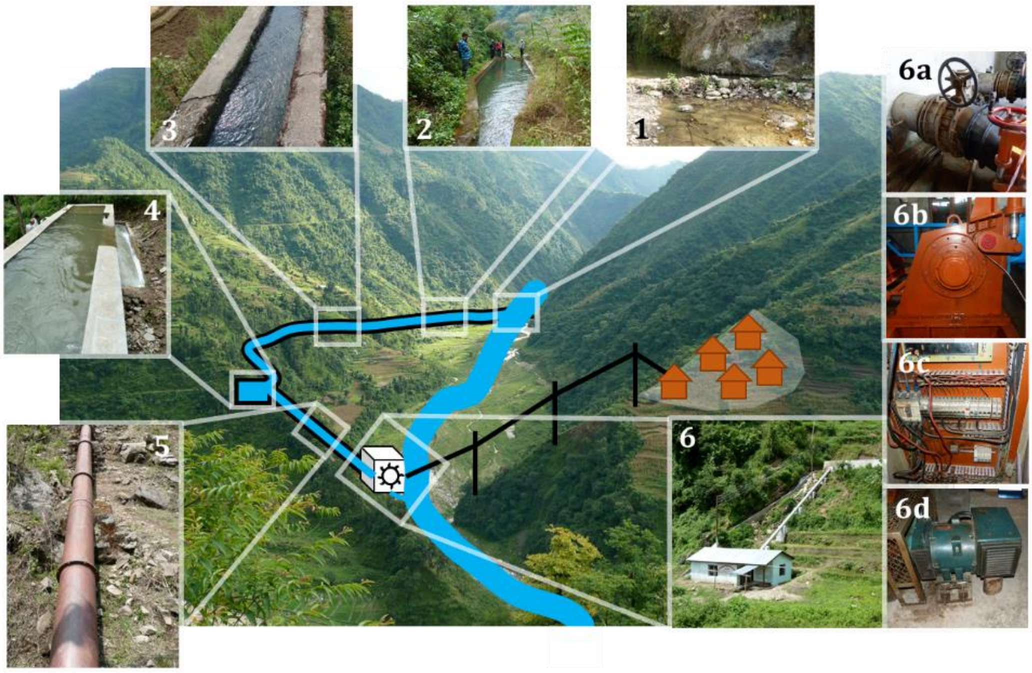

Figure 2.7: Constituent sub-systems of a micro-hydropower plant. Labels indicate the following: 1. Intake, 2. De-silting bay, 3. Canal, 4. Forebay tank, 5. Penstock, 6. Powerhouse, 6a. Internal pipework, 6b. Turbine, 6c. Control panel, 6d. Generator. Taken with permission from [9] **and originally adapted from** [135]**.**

Table 2.1: Sub-systems of a micro-hydropower plant [9], [135]**.**

No.	Sub-system	Description
1	Intake	A structure to divert water from the river into the canal. The intake may include a permanent weir or temporary structure, e.g. large stones arranged to divert the flow.
2	De-silting bay	A settling tank that is used to remove particles of silt and sand from the water. It usually has a gate which can be opened to flush the sediment away.
3	Canal	This is usually an open canal that takes water from the intake to the de-silting bay and from the de-silting bay to the forebay tank. Often made from stones lined with cement although it can be an earthen channel only.
4	Forebay tank	A settling tank which is used to remove silt and sand. A trash rack is used to prevent leaves and any other debris from entering the turbine.
5	Penstock	A closed pipe which transfers the water to the turbine from the forebay tank. Typically made from mild steel or high-density polyethylene (HDPE) pipe.
6	Powerhouse	The building or structure where the turbine and ancillary equipment is stored.

6a	Inlet pipework and valve	Pipework inside the powerhouse connecting the penstock to the turbine. Usually, this includes a butterfly or gate valve which can be used to stop the flow to the turbine.
6b	Turbine	Converts the power available as head and flow into mechanical shaft power. It is often necessary to use a belt drive to transmit the power to the generator.
6c	Generator	Converts the mechanical shaft power into electrical power.
6d	Control panel	Regulates the rotational speed of the generator using an electronic load controller which diverts excess power to a ballast load.
-	Tailrace	A civil structure that returns the water to the river. The environmental conditions determine the form of this sub-system.

In an MHP, pressurised water is converted into mechanical shaft power by a turbine, which drives an electrical generator. MHPs typically operate at near constant output power, as far as possible, generating energy throughout day and night, as the turbine is designed to operate at a certain constant speed to generate the mini-grid frequency. However, community electricity demand varies widely, often from a relatively low level at off-peak times to a high level at peak times in the morning and evening [136], [137]. Three-phase power is generated and distributed to HHs in the community, with each phase roughly balanced so the loads are shared equally across all phases.

An Electronic Load Controller (ELC) is used to balance the load on the system through the use of a dump, or ballast, load; as the consumer load decreases, the ELC diverts more power to the dump load, or vice versa, enabling reasonably constant power generation [138]. The dump load is often resistive heaters in a water tank and is ideally sized to be of the same rated power level as the generated power so that, if required, all of the generated power can be dumped [9]. Usually, the generator uses an Automatic Voltage Regulator (AVR), while a circuit breaker prevents excessive current in overload situations. The ELC and AVR maintain the mini-grid frequency and line voltage within desired ranges, around 50 Hz and 400 V, with maximum steady state deviations of ± 5% i.e. 2.5 Hz and 20 V in Nepal [139].

The ELC measures the mini-grid frequency and uses proportional integral (PI) control on a frequency error signal to control switches used to send power to resistive heaters in a water tank [140]. ELCs can use AC circuits and switches such as thyristors or include rectification and DC components such as insulated-gate bipolar transistors (IGBTs) switched using Pulse Width Modulation (PWM) [138]. The three main ELC control methods are phase-angle, binary-weighted and mark-space ratio [141]. The AVR is designed to maintain a constant terminal voltage by adjustment of the excitation current of the rotor winding in the synchronous generator through PID control [142]–[144].

MHP differs greatly from solar PV and wind power in that it produces constant power throughout the day and night. However, it is subject to seasonal variation due to dry seasons and monsoons which vary the water flow and therefore power generated. MHP grids are a different and unexplored prospect for electric cooking. Unused energy generated by an MHP across the day could be used for electric cooking. However, MHP energy provision varies widely in affordability, reliability and sustainability [55], [57]–[59]. Many MHPs suffer from a low load factor, the ratio between the daily average load and peak load, and a large proportion of generated energy is wasted [58], [145]. However, high peak loads can approach maximum generation capacity and lead to brownouts and blackouts [60], [146]. Low load factors and mini-grid weakness contribute to low financial viability for some MHPs, which are unable to generate sufficient income from consumers and PEUs to cover costs and essential maintenance [55], [145], [147].

Some MHPs have effective management structures and bookkeeping but in many cases there is no record keeping or proper accounting [55], [62], [145], [148]. There is often a lack of understanding on how the addition of new PEUs and appliances would affect the overall electricity demand and generated income. Alongside technical factors, social and cultural influences can reduce plant financial sustainability. MHPs are most often community owned and effectively began as social enterprises, fulfilling the basic need of community members for electricity [145]. This has led to tariffs being set too low to generate healthy profits, with committees reluctant to increase them for fear of social unrest among consumers [145], [147], [149]. Some community members are reluctant to pay for MHP electricity after giving their time during plant construction [145]. Management issues such as difficulty and inefficiency concerning tariff collection further reduce the proportion of paying consumers [55], [147]. Many MHPs charge consumers based on electricity meters installed in their homes, but some charge the same flat rate to all HHs regardless of their electricity usage [55]. Low tariffs, missed payments and management issues contribute to low financial sustainability.

Studies surveying multiple MHPs in Nepal have identified a wide range of plant financial viabilities [55] [145]. In [55] it was found that in most cases, the benefits and quality of service ensured that consumers paid regularly. However, in [145] and [55] several MHPs were operating at a loss and unable to pay for repairs and maintenance. A “vicious” cycle can occur where poor tariff collection leads to insufficient funds, resulting in low quality electricity supply [9], [150]. Component failure is common and manufacturing quality for MHPs in Nepal sometimes of low quality, with plants therefore requiring regular repairs and maintenance [9], [151]. Maintenance schedules are lacking with maintenance approaches more often corrective than preventative [9]. Finally, it is common for young people in rural Nepal to leave their communities, seeking work abroad or in urban areas, including skilled MHP operators, which can have a debilitating effect on the reliability of the plant, reducing its financial sustainability [9].

However, electric cooking and other PEUs can support MHPs, increasing the usage of MHP generation and, as a result, plant income. Overall, electric cooking could help to improve the financial sustainability of failing MHPs, increasing the reliability of the electricity supply, which in turn would provide a better electric cooking experience for consumers. Therefore, electric cooking and MHPs could support each other. The extent to which this is true requires investigation.

2.5 Electric cooking in constrained mini-grids

Mini-grids are broadly either power-limited or energy-limited. Solar mini-grids are energy-limited as peak generation is only attainable during the day, at certain times, while MHPs are power-limited, able to generate energy 24/7 but with a limit to the peak power produced [63]. Electric cooking in off-grid contexts poses a challenge as it is a source of high demand at certain times of day for all HHs. The study on the adoption of induction stoves in rural India highlighted the difficulties of electric cooking on hydro-powered grids, with inadequate power supply one of the main reasons for lack of use [99]. One solution is to upgrade the power generation to increase the capacity of the mini-grid. A study analysing the penetration effects of electric and biogas stoves in Nepal and Thailand found that, in Nepal, successful fuel switching to electricity would increase the use of hydropower resources [152]. However, this is not necessarily possible, especially in the short term, as the cost of hydropower projects or upgrades to them requires significant investment [153]. Furthermore, there may be limits on the head and flow characteristics of the watercourse [63].

Mini-grid infrastructure such as cabling and HH wiring is often inadequate for high-power loads [63], [154]. In some communities the use of high-power devices and appliances is prohibited to conserve power and protect the system [63]. In the CCA programme in peri-urban Nepal, most HHs required upgrades to their electrical wiring to support induction cookers, while the report suggested that many of the transformers serving the area would also need to be upgraded to enable widespread uptake [129]. HHs at large distances from transformers were found to have very low voltage levels, at which electric cooking is very slow or impossible – for illustration, halving the voltage reduces the power level down to a quarter of nominal, so that a 1 kW cooker draws only 250 W [129], [155]. Although the programme covered areas connected to the national grid, the insights into grid infrastructure requirements also apply to MHPs. Therefore, there is a need to understand how electric cooking affects MHP mini-grids.

2.5.1 Loads on MHP mini-grid networks

There is very little measured load data from rural Nepali communities, on community and HH levels. In 2012, the power consumption of a single HH in the Bhanbhane district in Western Nepal was recorded for five days, finding that the HH load varied between around 20 W and 50 W, with peak consumption during the morning and evening due to maximum lighting usage [8]. Figure 2.8 presents the data for one day, reproduced with permission from the author [8]. As the load increased, the line voltage dropped, fluctuating between 120 and 235 V, showing that there was insufficient capacity for a stable power supply, with brownouts occurring [8].

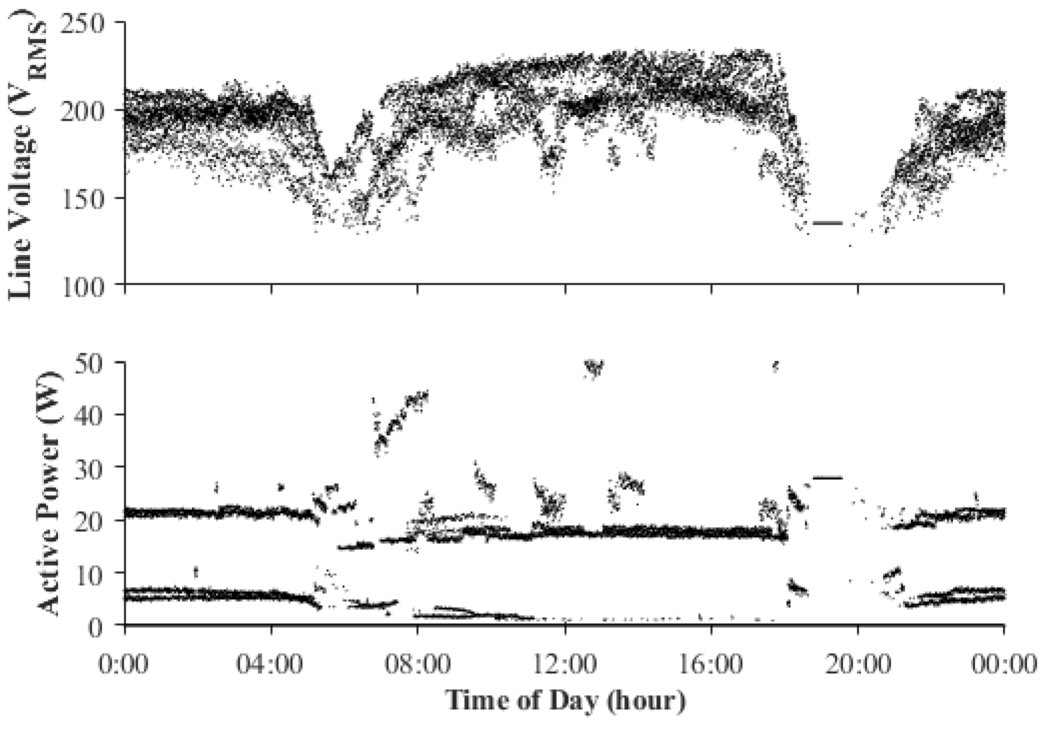

Figure 2.8: Measured line voltage and active power data from a house in Western Nepal [8]**.**

Community-wide demand data is essential to understand the spare power in a mini-grid and therefore the potential for electric cooking adoption. As well as this data, the ability of an MHP to accommodate electric cooking requires understanding of electric cooking loads and their contribution to the community load profile [121]. The initial MECS cooking diary studies included approximation of electric cooking loads using energy consumption and cooking durations data to estimate average power consumption which, while providing useful insight into the timing of cooking and approximate demand, does not reliably reveal peak electric cooking loads [156]. The demand of a number of HHs cooking with electricity depends on the timings of cooking in each HH, which vary between HHs and across days, thus the maximum time-coincident demand is known as the "after diversity maximum demand" (ADMD), an important concept for both cooking and community load profiles [121], [157].

Recent studies have improved on average power consumption profiles by using HH data loggers, such as those provided by the Access to Energy Institute (A2EI), which were used to monitor the electric cooking loads of EPCs in a solar mini-grid in rural Tanzania, enabling understand of voltage levels, energy consumption, cooking durations and load profiles [100], [158]. However, such data has not been captured in rural Nepal. This data would also aid understanding of the effects of electric cooking on MHPs in terms of stability and power quality.

Studies connected to the MECS programme have modelled electric cooking loads in grid systems to evaluate their technical effects on electricity networks, assessing penetration potential, voltage drop at different locations within a network, and voltage unbalance factor [49], [121], [159], [160]. Focussing on solar mini-grids, it was found that power quality issues can generally be addressed by upgrading cables to those with a large cross-sectional area, and that diversity in cooking timings reduces electricity demand, enabling significant electric cooker adoption. However, there is a lack of measured electrical system and load data from MHP communities, which is necessary to understand the effects of introducing electric cooking.

The aforementioned electric cooking and grid network modelling studies used cooking demand modelling to compose load scenarios with different penetrations of electric cooking [49], [121], [159], [160]. Electricity demand modelling is a key area of research for understanding the technical and economic aspects of electricity networks. As identified in Section 2.4, many MHPs suffer from low financial sustainability. Electric cooking and PEUs can support the financial viability of MHPs but their introduction requires understanding of the community load profile to ensure technical viability.

An MHP community is a complex system of consumer behaviours and cultural appliance usage patterns. As explained in [161], many residential load modelling tools have been conceived, employing stochastic approaches to incorporate inherent uncertainties and generate realistic profiles. However, they are usually designed for on-grid contexts in developed countries and reliant on the input of detailed data from activity diaries, detailed time-use surveys, or other available statistical datasets [157], [162]–[166]. In remote communities such as MHPs in Nepal, detailed appliance usage data is often difficult to obtain to a high level of accuracy and demand modelling must be based on surveys and interviews with limited sample sizes which are imprecise and subject to significant uncertainty [161].

ESCoBox is a set of tools including software and hardware designed for off-grid electricity planning and demand-side management [167]. A decision-support tool uses data on hourly usage of end uses to estimate daily load profiles, while the hardware can limit power for PEUs to certain windows of time according to the model outputs. While very useful for certain contexts, it does not disaggregate demand to HH groups or model devices used less than once per day, and produces outputs at an hourly resolution only. Therefore, it lacks the precision required for a detailed monthly breakdown of energy consumption and income. A demand modelling tool implemented in Microsoft Excel has been developed as part of the MECS programme [168], [169]. The model generates HH level load profiles incorporating stochasticity in timings and power ratings of end uses, and includes a model of active occupancy, therefore representing the type of modelling required for a techno-economic model of an MHP community [168], [169].

LoadProGen uses a bottom-up stochastic approach designed for interview and survey data [170]. "Remote-Areas Multi-energy systems load Profiles" (RAMP) builds on this approach by increasing the level of stochasticity and extending its applicability to include loads such as water-heating or cooking, by incorporating random variation of power levels and cycling of power [161]. RAMP applies stochasticity to several parameters related to appliance usage such as windows of use, durations, and frequency of use, to capture uncertainties and variations from relatively low detail input data. Its modelling strategy is flexible and customisable and therefore applicable to a wide range of contexts, and has been employed successfully on a number of projects in [161], [171]–[173]. RAMP and LoadProGen have also been used effectively to model cooking loads in several contexts [103], [172], [174].

2.6 Upscaling electric cooking

Even if there is spare capacity in MHP mini-grids for some HHs to cook with electricity, in communities of hundreds or thousands of HHs, scalability is clearly limited. The studies on electric cooking loads in electrical networks found that there was significant scalability of modelled electric cooking loads in various grid contexts [49], [121], [159], [160]. However, there was a focus on solar mini-grids rather than MHP mini-grids, the latter of which have a clear maximum total load capacity, although the distribution of loads throughout the network and load capabilities of transformers and cables are crucial to the feasibility of increased electric cooking adoption. With limited scalability of direct electric cooking in MHP communities due to constrained capacity, innovative methods of using the generated energy require consideration.

2.6.1 Demand-side management

Demand-side management (DSM) measures can enable increased uptake of electric cooking. DSM has been defined as the “planning, implementation and monitoring of activities to encourage, or sometimes force, customers to alter their electricity consumption habits, in respect to time of use, peak consumption levels and overall energy consumption” [175]. There are a variety of DSM measures which can be implemented in mini-grid contexts. Generally they can be classified into the following categories: peak clipping, for when peak demand exceeds generation capacity; valley filling, for demand troughs, where electricity generation is wasted; load shifting, for when demand peaks do not coincide with peak generation; demand reduction, for when the overall demand generally exceeds supply; and demand stimulation, when the overall demand is generally too low [175].

A simple DSM device, which can represent peak clipping and demand reduction, is a current limiter, such as a circuit breaker, which limits the power drawn by a load, reducing the demand on a network [22]. Although inexpensive and simple to install, they require hardware, are easy to bypass, and restrict electricity usage regardless of the state of the grid [60]. Other demand limiting measures have been implemented, such as HH energy consumption limits enforced utilities through HH meters [176]. Briganti et al implemented a daily energy allowance system on a rural solar microgrid in Santo Antao (Cape Verde) which limited users to an agreed energy usage per day based on the tariff they chose, and protected the solar plant from consumption spikes [177].

There are several approaches to enable weak grids to support electric cooking loads. In Myanmar, a load scheduling community agreement was reached that if the grid voltage dropped below 180 V, the consumers would not be allowed to switch on their cookers [155]. Some users were willing to shift their cooking times to have reliable access to electricity for cooking, although readable voltmeters were required to indicate the grid voltage to the users [155]. Power curtailment of electric cookers is another potential solution, although this could increase cooking times and decrease user satisfaction. Complex technological solutions can enable load scheduling and peak clipping DSM, such as ESCoBox, which includes programmable load controllers that can restrict power for appliances and PEUs to preset times when power is available [167], [178]. Smart control systems such as algorithms for prioritising cooking loads could reduce peak loads but require communications networks, stable power supply and complex control and hardware [22].

In Bhutan, a DSM solution in the form of a device called a GridShare was installed in HHs in an MHP mini-grid community, which regulated usage before severe brownouts occurred and encouraged users to spread their use of high-power appliances such as rice cookers more evenly throughout the day by communicating the state of the grid to them [60]. This approach was successful in reducing the number and duration of severe brownouts. It was particularly appropriate due to the large number of HHs already cooking with electricity and struggling to do so due to brownouts – people were willing to have their power curtailed if it reduced the total number of brownouts. Therefore, in communities where the transition to electric cooking has not yet been made, the potential of such an approach is not yet known [60].

Further innovative research aims to replace dump loads in MHPs, which are often resistive heaters with no useful purpose, with HH water heating or slow cookers, by installing distributed electronic load controllers (DELCs) in HHs [138]. DELCs could enable increased usage of MHP generation through valley filling. A powerhouse ELC is still required in case any DELC units fail or use is discontinued in some HHs, but one study found that the power ratings, cost and weight of the central ELC and dump load can be significantly reduced [138]. Another study also investigated the use of slow cookers as dump loads for DELCs, emphasising that the DELC topology is more reliable than conventional ELC since one DELC unit failure does not significantly impact the entire power network [179]. Slow cookers could reduce peak demand but require significant behaviour change, although they are the only cooking choice for DELC units in grids where the power to each HH is limited. Generally, an issue with DELCs is that HHs are allotted a maximum power consumption, which, in communities of hundreds or thousands of HHs with constrained capacity power generation, is unlikely to be sufficient for high-power electric cooking devices.

Although some measures such as GridShare and the cooking scheduling agreement in Myanmar have shown that cooks can be willing to adapt their cooking practices in certain contexts, cooking is an integral part of daily life which, generally, people may be unwilling to shift, as found in [180]. Efficient cooking devices themselves, such as EPCs, are a form of DSM, reducing peak loads by reducing power and energy consumption, thereby representing a peak clipping and demand reduction measure which does not require shifting of cooking times [13]. Analogously, inefficient bulbs can be replaced with LEDs as part of an efficient devices DSM measure, with similar effects [181].

Furthermore, while cooking scheduling agreements may be hard to accept for cooks, they have the advantage over other technological DSM solutions of not requiring hardware or control software, although the Myanmar agreement did necessitate readable voltmeters [155]. Instead, similar agreements for other PEUs, such as industrial machines which draw high power, could reduce peak loads and demand generally, and make a significant difference to the availability of spare power for electric cooking, while general community agreements on limiting usage of electrical appliances and devices could have a similar effect [175].

2.6.2 Energy storage

Another potential solution for enabling increased adoption of electric cooking in constrained capacity grids is energy storage. Unused energy generated by the MHP in off-peak periods could be stored and used for electric cooking and/or additional PEUs [63]. As dump loads in MHPs are often resistive heaters in water tanks, thermal storage through water heating could be seen as a viable and economic form of energy storage. However, this would present the difficulty of integration into the electrical network infrastructure to provide power for electrical loads [173]. Innovative solutions also involving thermal storage are emerging, such as the use of phase change materials, which could become attractive due to low cost and local manufacturability, although they require behaviour change in terms of timings of food preparation and cooking, and ensuring sufficient insulation of the cooking vessel remains a key issue [182], [183].

Battery storage could be used to support electric cooking, enabling the demand to be distributed throughout the day by charging slowly at off-peak times, reducing peak loads [63], [184]. High-power electric cooking requires batteries which can discharge at a high C rate, which defines the rate at which a battery is charged or discharged, without a significant reduction in usable capacity [185]. If a 10 amp-hour (Ah) battery is discharged fully at a current of 10 amps (10 A) the discharge would theoretically take one hour, with the C rate 1C, while if the discharge current was 20 A, theoretically the battery would fully discharge in half an hour and the C rate would be 2C [185]. There are many different types of rechargeable batteries but the most common are lead acid, nickel cadmium (NiCd), nickel metal hydride (NiMH) and lithium ion. Table 2.2, a comparison of the common types of battery and important characteristics, was produced using data from [186].

Table 2.2: Comparison of key characteristics for battery types, reproduced from [186]**.**

Property	**Lead acid**	**NiCd**	**NiMh**	**Lithium ion**
Specific energy (Wh/kg)	30-50	45-80	60-120	90-250
Cycle life	200-300	1,000	300-500	500-2,000
Maximum discharge rate **Ideal discharge rate**	5C 0.2C	20C 1C	5C 0.5C	> 30C < 10C
Self-discharge/month (room temperature)	5%	20%	30%	< 5%
Overcharge tolerance	High	Moderate	Low	Low
Cost	Low	Moderate	Moderate	High

Lithium ion presents an attractive option for portable batteries where weight is crucial due to its high specific energy. It is also the most suited chemistry to supplying high-power devices due to its ability to deliver high currents with little capacity loss [187]. Prototyping of battery-supported cooking alongside MECS cooking diary studies showed that lithium ion batteries can provide sufficient power levels and energy for cooking staple dishes in Kenya and Tanzania [188], [189]. An ongoing trial associated with MECS is investigating the latest design of battery ‘Power Stations’ for electric cooking [190].

2.6.3 Control and sizing of battery energy storage systems

If the MHP community demand were increased above the constant generated power due to high penetration of electric cooking, the ELC would no longer be able to regulate the mini-grid frequency and the current would exceed the safe limit, causing the circuit protection to trip and the system to shut down [146]. Batteries could be used to store off-peak energy to be delivered during peak times for cooking, enabling increased uptake of electric cooking without unfeasibly increased peak loads [116], [191].

One study developed a control system for a centralised battery in an MHP which uses frequency and current control and to enable integration into the mini-grid [191]. Although the proposed scheme is thorough, it relies on complex control to integrate the ELC and inverter involving mode transitions based on large frequency deviations including reduction below 45 Hz, does not consider reactive power, and only considers a single, central battery energy storage system (BESS) [191]. A BESS could be incorporated into the existing ELC branch, sinking spare power and shunting excess to ballast loads. However, this integration is not as simple as it might appear, as it would require an upgraded inverter, additional control, and for the battery to be co-located with the ELC.

Generally, batteries could be introduced to MHP mini-grids in centralised, distributed or HH topologies. Centralised BESS would be easier integrate into a mini-grid control system, and easier to manage and maintain as it could be located in or near the MHP powerhouse where the operators could supervise its operation after receiving training, but would present a single point of failure [191]. Distributed BESS could be located at strategic points in the network, such as downstream of distribution transformers, possibly reducing load carrying requirements of cables and transformers [192].

Considering control systems for BESS in mini-grids, it is important to understand active and reactive power transfer within an electrical network [193]. A BESS would include an inverter interfacing the battery to the mini-grid, which has very low output impedance compared to the MHP generator and therefore no mechanical inertia, enabling it to respond to changes in electrical system parameters rapidly. The response of the inverter is therefore determined mostly by the control system [194].

HH BESS could support electric cooking within the homes of the cooks, as envisaged in MECS prototyping, although this would transfer the responsibility of operation and maintenance to HH members [188], [189]. Intelligent HH BESS control systems could integrate the batteries into the mini-grid so that any spare capacity is used for BESS charging, which are prioritised depending on their state of charge (SoC), as modelled for a solar mini-grid in [195]. Uninterruptible power supplies (UPS) provide continuous power to loads during grid faults, with a BESS either acting as a buffer between the grid and load, carrying the full load power, or power provision automatically switching from the grid to the BESS when required [196].

In terms of estimating HH BESS capacity requirements, research conducted under the MECS programme has included modelling and sizing of HH systems, based on cooking diary energy consumption data and accounting for additional factors such as capacity decay, which depends on C rate, depth of discharge (DoD), and temperature [121], [168]. The modelling tools can be used to estimate HH battery capacity and associated economic factors including BESS component costs and monthly repayments [121], [168].

Various studies have used simplified power flow modelling to estimate required capacities for centralised BESS in mini-grid contexts, based on energy dispatch strategies whereby the BESS charges and discharges according to the electricity demand and power generation [171], [172], [197]. Studies on electric cooking penetration in solar mini-grids included modelling of the network topology and electrical parameters throughout the grids, using OpenDSS software, enabling understanding of the voltage levels and load requirements of mini-grid infrastructure [49], [121].

2.7 Summary

This chapter has examined the most common cooking fuels and stoves, and presented electric cooking technologies which could provide convenience, health and cost benefits compared to existing cooking practices, depending on the context. Induction cookers are highly versatile in that they are easy to use for all important cooking processes. EPCs are automated, enabling multitasking, and highly efficient, demanding full power for relatively short periods. MHPs provide reasonably constant renewable power to communities, but much of the generated energy is wasted, and many plants have low load factors and therefore low financial sustainability. Electric cooking and other PEUs can increase the usage of MHP generation and thereby increase plant income and economic viability, improving power supply stability to better support electric cooking.

Clean cooking studies and rollouts have historically failed to take into account the deeply cultural nature of cooking. Recent cooking diary studies have captured detailed data on cultural cooking practices in a wide range of contexts, though not as yet in Nepali MHP communities. To examine the feasibility of electric cooking in a rural Nepali context, more detailed research is required into HH cooking practices, food energy requirements, acceptance of electric cooking technologies and practices, and mini-grid behaviour under cooking loads, through careful and detailed monitoring studies. This research aims to understand current rural Nepali cooking practices and the social aspect of the transition to electric cooking through data gathering (objectives 1 and 2).

Furthermore, very little data exists on the technical aspects of MHP mini-grids and load profiles of electric cooking in Nepal. This research also aims to explore the transition to electric cooking from a technical perspective, to understand the effects and scalability of electric cookers connected to MHP mini-grids (objective 3).

Electric cookers are high-power devices which, in large communities with high peak loads, are likely to be limited in scalability. Efficient cooking devices, DSM measures, and battery energy storage, represent solutions for increasing the potential adoption of electric cooking in constrained capacity grids. While these have been explored in other contexts, this thesis aims to determine their feasibility and suitability for MHP communities in rural Nepal, while also considering further applicability.

Alongside data collection and analysis through field studies, techno-economic modelling could enable assessment of these solutions and understanding of the potential for income generation from electric cooking to increase the economic viability of MHP communities (objective 4). A techno-economic model wouldprovide a breakdown of energy usage by consumer, enabling understanding of electric cooking costs and the income generated from different HHs. The model would be useful for assessing tariff systems and planning new connections for an MHP community.

Battery storage solutions for MHPs require consideration of topology, control system, and capacity requirements, which this thesis aims to explore through modelling techniques (objective 5). Finally, the identified solutions can be assessed and compared through techno-economic modelling to understand the degree to which they could increase the scalability of electric cooking, their income generation potential, and their economic viability (objective 6).

Chapter 3

Nepali cooking context and electric cooking trials

3.1 Introduction

The literature review determined that enabling widespread uptake of electric cooking in constrained MHP mini-grids and larger hydropower networks requires collection of high quality data on current Nepali cooking practices and the transition to electric cooking. The cooking diary study methodology was identified as suitable for this task, while there is also a requirement to assess the effects of introducing electric cooking on the electrical supply system and investigate community and cooking load profiles.

Therefore, two electric cooking trial studies were conducted, including cooking diaries and electrical system data collection, to address research objectives 1-3: understanding the current cooking context in Nepal and investigating the transition to electric cooking from social and technical perspectives. Each study had similar aims and methodologies, with the second designed to build on the first and gather more and better-quality data in a larger community in a different province, enabling comparison between the study communities.

3.2 Research context

The overarching objective of the studies was to gain understanding of the feasibility of electric cooking in off-grid MHP mini-grids in rural Nepal. This is an interdisciplinary problem, with issues able to be broken down into largely socio-cultural, economic and technical factors, which gave rise to relevant research questions for investigation.

3.2.1 Socio-cultural factors

A successful HH level transition to clean cooking involves changes in behaviour. HHs are required to adapt their cooking techniques and habits to suit the new appliance and cookware, potentially cooking different foods, while also adapting to any resulting changes in the size, texture and taste of the meals cooked with the new technology, which is all the while competing against deeply embedded cooking practices associated with traditional stoves. These socio-cultural factors lead to two research questions, based around the cook function within a HH:

1. What are the current Nepali cooking practices?
2. How compatible is Nepali cuisine with electric cooking and to what degree do rural Nepali cooks integrate it into their cooking fuel mix?

3.2.2 Economic factors

As previously discussed, HHs often believe electric cooking to be more expensive than other forms of cooking. To ascertain whether this is just a perception or reality, data on energy consumption, cost and affordability is needed, generating two further research questions:

3. How much electrical energy is required to cook with electricity?
4. How affordable is electric cooking for rural Nepali cooks?

Knowledge of the energy requirements of Nepali cooking is necessary to calculate running costs of electric cooking, and relevant when assessing the potential of energy storage to support electric cooking.

3.2.3 Technical factors

Introducing electric cooking in a mini-grid adds a high-power load to the power system – most cooking hotplates draw more than 1 kW. For highly constrained off-grid systems, this additional load will place a severe strain on the supply. Therefore, understanding how the electric cooking load effects the mini-grid will be critical, prompting the following:

5. What are the effects of electric cooking on an MHP mini-grid and what is its current scalability?
6. What are the load characteristics of HHs cooking with electricity and how does their electricity demand affect the community load profile?

These questions also lead to an understanding of the potential for widespread uptake of electric cooking in mini-grids.

3.3 Methodologies

Two methodologies were used to address these research questions: cooking diary studies were conducted with a total of 25 HHs and, in each community, the mini-grid system electrical data was recorded in the powerhouse. Overall, the combination of qualitative, quantitative, HH and MHP system data enabled analysis of the whole system effect of integrating electric cooking into off-grid supply networks, allowing assessment of its overall feasibility. The general methodologies are presented to provide an understanding of the nature of the studies, after which overviews of the studies are presented, including the rationale for the second study and improvements made to the methodologies. Subsequently, key results and lessons learnt from the studies are synthesised and outlined. Figure 3.1 presents a flow chart of the work conducted in each community..

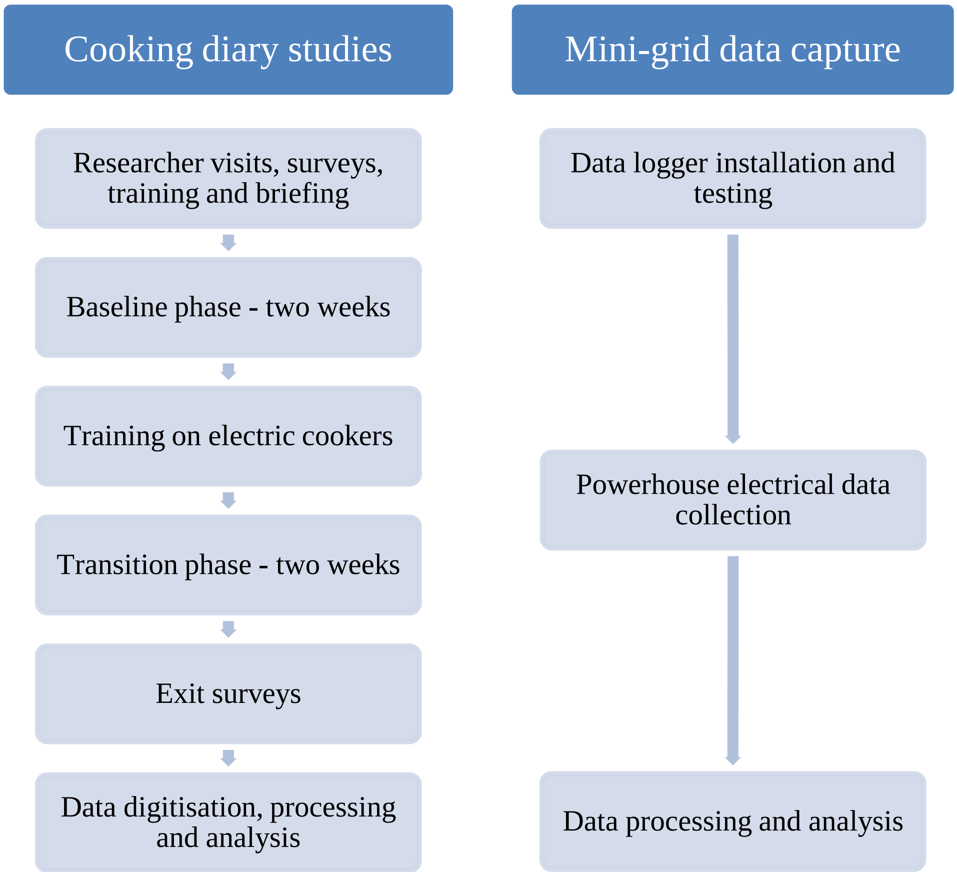

Figure 3.1: Flow chart of work conducted in each study.

3.3.1 Cooking diary studies

Cooking diaries

Cooking diaries were used to provide insight into exactly how cooking is performed: what do people cook; which fuels and appliances do they use; and how much energy/time is required to cook their meals. The cooking diaries methodology was adapted for the Nepali cooking context [122], [123], by including local meals and cookware in the cooking diary forms, which are presented in Appendix A1.1. Training was provided to study participants by the research team, including: how to cook staple Nepali dishes on the electric cookers; energy saving practices such as the use of lids; and technical information on the cookers, their operation and safety. For the two-week baseline phase, participants cooked as normal on their wood stoves, weighing the firewood they used before and after cooking to provide energy data. For the two-week transition phase, they were given induction cookers, which were chosen for their efficiency, versatility, and similarity to wood and gas stoves in basic concept. After a period of adaptation in which they practiced using the new cookers, participants were encouraged to use them for their cooking as much as possible during the transition phase, this time taking energy readings from electrical energy meters. The transition phases were shorter than specified in the Cooking Diaries Protocols [122] due to project constraints and to reduce the burden of continuous data collection for participating HHs.

Enumerators visited the HHs during mealtimes to record the data in paper versions of the cooking diaries. Energy saving practices such as the use of lids, and any saving of food for later meals, were recorded, as they can reduce the energy requirements of meals, which is particularly relevant for limited capacity grids. Quantitative data was recorded for the cooking diaries using hanging balances for measuring firewood, weighing scales and measuring cups/jugs for measuring food and water quantities, and plug-in energy meters for measuring electrical energy consumption. Figure 3.2 shows participants with the cooker and cookware and using the hanging balance.

(a) **(b)**

Figure 3.2: Participants with (a) the provided cooker and cookware and (b) using a hanging balance to obtain the weight of wood used for cooking. Credit: Kimon Silwal.

In both studies, the induction cookers were locally modified to draw a maximum of 1 kW due to limited spare power on the mini-grid, and HHs were provided with induction-compatible cookware suitable for Nepali cooking. Table 3.1 presents the equipment required for a cooking diary study in Nepal.

Table 3.1: HH-based equipment supplied and used in study.

Equipment	Function	Notes
Electric cooker	Induction stoves for cooking	Modified for max. 1 kW 230 V, 50 Hz
Pressure cooker	Cookware for rice, dal, etc	Induction hob-compatible cookware provided for transition phase
Kadhai	Cooking saucepan	
Tapke	Cooking saucepan	
Roti pan	Cooking flat plate	
Energy meter	Measure electric cooking energy consumption	SKN-Bentex, Botric (manufacturers)
Weighing balance	Measure weight of firewood	Hanging type
Weighing scales	Measure food quantities	
Measuring cups/jugs	Measuring food and water/tea quantities	

Participation and surveys

During initial site visits, discussions with the MHP secretary and other members of the MHP committee and community were conducted to understand community life, MHP status, current cooking practices, and existing knowledge and interest in electric cooking. Registration surveys, presented in Appendix A1.2 were conducted with HHs interested in project participation. HHs were selected for the studies from lists provided by the MHP secretary, according to the following criteria:

- HHs selected came from a diverse range of ethnic groups;
- HHs were grouped in clusters equally distributed across the three phases; and
- HHs were located close to the homes of the enumerators.

The aim of these selection criteria was to ensure that they were representative of rural communities in similar areas of rural Nepal, allowed integration with the mini-grid with minimal reconfiguration, and enabled enumerators to cover a number of HHs easily during the monitoring periods. During the baseline and transition phases, HHs were encouraged to record their opinions on their cooking experiences and, subsequently, exit surveys were conducted, as presented in Appendix A1.2A1.38.3A1.2. The surveys collected detailed feedback on their experiences and impressions of electric cooking in terms of benefits, drawbacks and the ease of cooking different dishes.

There were three main assumptions made in the studies: firstly, the selected participating HHs and the selected MHP system are assumed to be representative of cooking consumers and rural Nepali MHP mini-grids; secondly, that the cooking that takes place during both the baseline and transition phase is typical of standard cooking practices for Nepali HHs, with minimal changes due to the study; and finally that the cooking diary protocol captures the actual cooking practices.

3.3.2 Mini-grid powerhouse electrical data

In each study, the mini-grid powerhouse electrical data was recorded to understand how the power-constrained MHP system responded to the additional load placed on the system by the electric cookers. A CR1000 data logger [198] was installed in the powerhouse with voltage and current sensors. Figure 3.3 shows the technical setup of the powerhouse: turbine, generator, ELC, ballast (dump) loads, data logger and sensors. Current and voltage signals for each phase were used by the data logger to calculate frequency, power factor, real power and generation current.

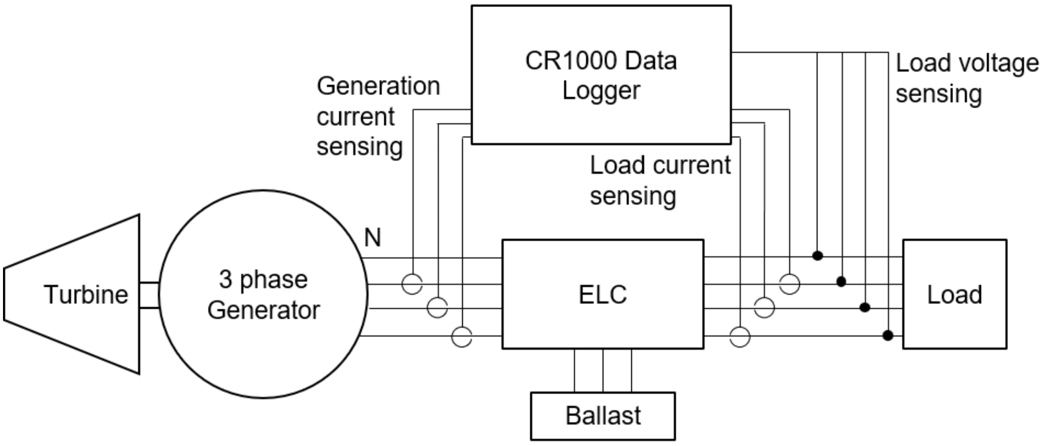

Figure 3.3: Technical setup of MHP powerhouse, including the turbine, generator, ELC, data logger with current and voltage sensors, and load.

The load at each distribution transformer in the communities was measured and evaluated against its load capacity to ensure there was sufficient spare power for the connection of electric cookers to the mini-grid. Tests were conducted on the electric cookers in the MHP powerhouse in preparation for installation in the HHs, as shown in Figure 3.4, to verify the system operation.

(a) (b)

Figure 3.4: (a) Testing induction hobs in the MHP powerhouse in Simli and (b) user training on cooking with the pressure cookers on the induction hobs. Credit: Kimon Silwal.

The data logger was configured with a two-second sampling time, recording five instantaneous values which were then averaged over ten-second periods and averaged again to a resolution of one minute. The sampling and logging intervals were chosen considering the transient spikes in electricity demand and the logger storage capacity.

3.4 Overview of electric cooking trial studies

The first study took place in the summer of 2018. Simli Village Development Committee (VDC), Rukum district, Western Nepal, was chosen by the AEPC as the site for implementation. The study, hereon referred to as the Simli study, received funding of £3,000 from The Cabot Institute at the University of Bristol. Figure 3.5 shows the community location and images of typical HHs. According to the most recent national census, there are 1044 HHs within the community, with an average of 5.1 people per HH, and all but ten HHs use firewood for cooking [199]. Within the community, there is a 29 kW community-owned MHP system which uses a Pelton turbine and provides electricity to around 450 HHs, and which is operated and managed by a committee of local people. Beneficiaries pay 12 NPR/kWh for electricity.

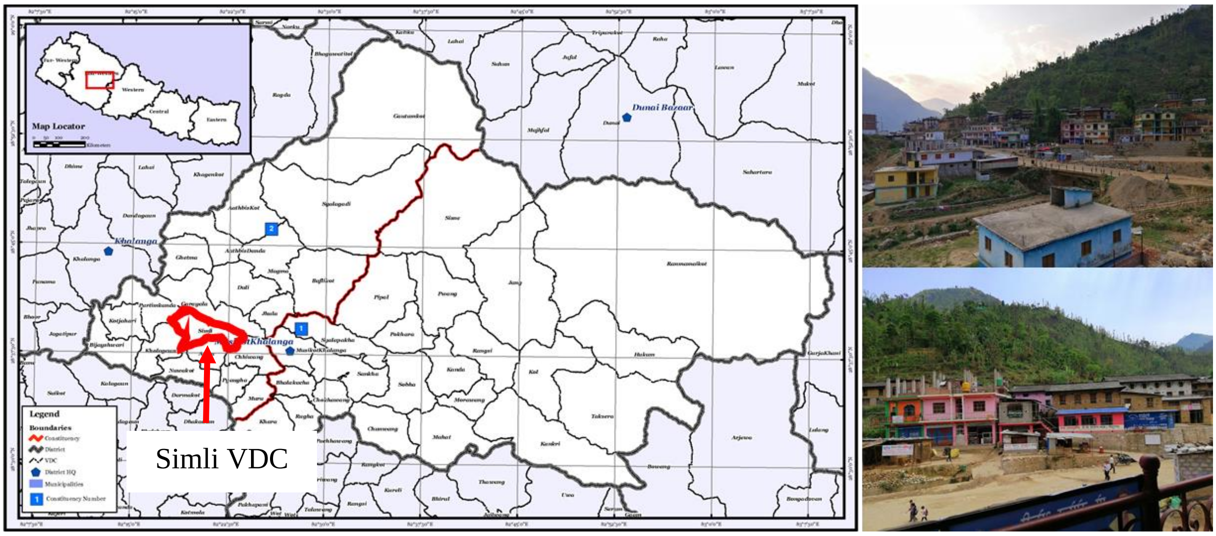

Figure 3.5: Map of intervention site in Rukum district in Western Nepal, with Simlihighlighted (Map [200]**), with images of typical HHs on the site.**

LPG is available in the commercial centre of Simli, with the main demand from hotels and restaurants, but it is not used as much outside of this locality. Where HHs do have LPG, it is normally only used for small, light meals due to the high expense and unreliable supply chain. Of the ten HHs selected for the study, only one used LPG intermittently. Three HHs changed between phases as the original three dropped out due to concerns over the perceived cost of electric cooking; these HHs were excluded from comparisons between phases during data analysis. The ten participating HHs were provided with IMEX single ring induction hobs.

A community called Salyan within the rural municipality Necha-Salyan in the Solukhumbu district, Eastern Nepal, was selected for the second study. The MECS Technology Research for International Development (TRIID) Challenge Fund supported this second study with funding of £30,000, hereon referred to as the TRIID study [201]. The study aimed to obtain high quality data on both Nepali cooking practices and MHP behaviour in a community with more spare capacity for electric cooking. Figure 3.6 depicts the community location and Figure 3.7 is a photograph of the MHP powerhouse.

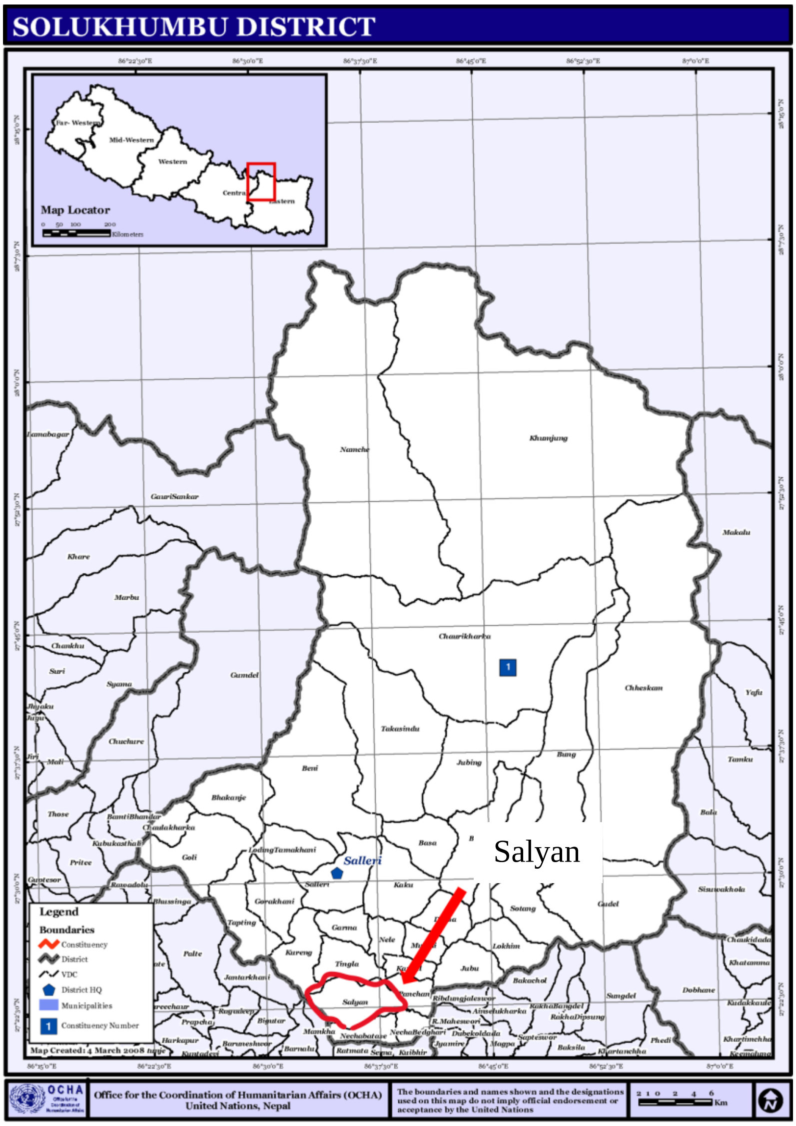

Figure 3.6: A map of Solukhumbu district, Eastern Nepal, showing the location of the case study community, Salyan [202]**.**

Figure 3.7: The MHP powerhouse in Salyan. Credit: Will Clements.

A much larger community than Simli, the MHP is rated at 100 kW and uses a Crossflow turbine, serving 1,093 HHs as well as business, community and industrial end uses including high-power agricultural machinery. The plant is community owned and currently most beneficiaries pay a flat rate of NPR 110 per month for electricity, while some industrial machine operators are charged according to their electricity consumption, at 8 NPR/kWh. Table 3.2 summarises the key information on the two communities. In this study, IMEX hobs were unavailable so eleven Bajaj Splendid and four Bajaj Cariboo induction hobs were sourced and provided to the fifteen participating HHs.

Table 3.2: Key information on the case study MHP communities.

Parameter	**Simli**	**Salyan**
Number of HHs	450	1093
Tariff system	NPR 12/kWh	NPR 110, flat rate
Generation capacity (kW)	29	100
Turbine type	Pelton	Crossflow

3.4.1 Simli, Rukum, 2018

The Simli study showed that electric cooking was feasible in MHP communities and generated valuable data on cooking practices before and after transitioning to induction stoves. Participants found dal and rice easy and fast to cook with the new technology while cooking roti was generally more difficult. However, the study revealed several limitations of the methodologies which affected the depth of the insights gained.

The energy meters used were low quality devices which led to poor energy data quality and coverage. Furthermore, energy data was collected at meal-level only, rather than for each dish cooked, and not for water heating events. Also, as HHs did not record data themselves, enumerators were required to be present for every cooking event, which may have led to tea and lunch data not being recorded, and which contributed to the lack of water heating data. The study led to the suggestion that, in future, HHs could be trained to record some or all diary data themselves so that enumerators could visit less often.

Furthermore, in the transition phase there was a significant level of fuel stacking, with participants using both electric and wood stoves but not recording the wood stove usage, which was confirmed in the exit survey. The cooking diaries were set up in such a way that it was not clear how to record wood stove usage as well as induction hob usage, and insufficient training led to the enumerators only recording data for electric cooking in the transition phase, preventing precise understanding of the penetration of electric cooking into HH cooking fuel choices. Although exit surveys were conducted, a limitation of the study was that daily checks were not carried out to verify whether any cooking had been missed. This information would have provided explanations for missed meals and data on fuel stacking. The exit surveys themselves were lacking in depth and conducted informally, leading to limited insights.

A further limitation of the study was that powerhouse electrical data was only collected for nine days, and included missing, erroneous and repeated values. It was recommended for future studies that weeks of data are collected before and after the introduction of electric cooking using a more robust data logging system, so that the behaviour of the mini-grid can be better understood.

Importantly, with just ten HHs of the 450 HHs in the community cooking with electricity, the MHP generation capacity was often reached by the community electricity demand, causing power supply instability which affected participant cooking experience. Only three HHs continued to use their electric stoves regularly after the project due to a lack of reliable electricity supply.

A follow-up study in the same village, which the researcher was only part of in the reporting phase, trialled different electric cookers including infrared hobs and EPCs, approximately a year after the first study was conducted. However, it was found that the village electricity demand had increased even more in the intervening period, leading to frequent power outages during the trials which reduced the perceived reliability of electric cooking and the quality and usefulness of the obtained data.

Load-shedding was performed in the community during the study and a number of DSM measures in place, such as an agreement to schedule industrial machine usage outside of peak demand windows, but the constrained power supply was unable to support additional electric cookers. Despite the difficulties, insights included that most participants ranked the induction hobs as the best electric cooker.

The studies in Simli had provided valuable data and encouragement but also highlighted cultural and technical barriers to electric cooking in rural Nepal, and limitations to study methodologies. The next step was to work towards overcoming these barriers by using improved methodologies in a community with sufficient spare capacity to allow electric cooking integration without additional power supply issues.

3.4.2 Salyan, Solukhumbu, 2019

The 100 kW MHP system in Salyan, the site of the TRIID study, powers over 1000 HHs, therefore providing each with an average of around only 100 W, but there was a lot more spare power at peak times than in the Simli studies, enabling better investigation into the potential of electric cooking. The baseline phase and transition phases took place for two weeks at the end of September and November 2019 respectively, towards the beginning of winter and dry season, a previously unexplored period of the year for electric cooking in rural Nepal.

Before the intervention, ten of the 15 HHs predominantly used traditional wood stoves for their cooking, whereas five used ICS. LPG was used by 8 HHs, mainly as a backup cooking fuel. Three HHs had bought rice cookers between the baseline and transition phases and two further HHs were provided with rice cookers, totalling five HHs, to enable assessment of how ownership of two electric cookers affected participant behaviour and the potential for an electric cooker combination to reduce fuel stacking.

Using modified cooking diaries to account for fuel stacking and extensive training for enumerators, with on-site researcher support, data coverage and quality were ensured to be high. Additional training on cooking roti with the induction hobs was provided to the participants. For the transition phase, columns were added to the diaries for dish energy data and number of people for water heating events so that water heating event energy per capita could be calculated. During the Simli study it had become clear that capturing dish-level electrical energy consumption data to generate a more detailed dataset was feasible. Furthermore, registration surveys and extended exit surveys were conducted to collect detailed feedback. MHP system data was collected for the entirety of the cooking diary study. Higher quality Botric energy meters were sourced for the study and, during HH wiring upgrades, cable ties were used to ensure that each induction cooker was the only device plugged in to the new socket that the energy meter was connected to.

During the study, after receiving feedback on the baseline phase which included that HHs found it difficult and tiresome to keep weighing and recording wood and food and water quantities, the operational set-up was adapted. It was clear from the baseline phase that HHs were able to record their own cooking diary data. Therefore, a supervisory enumerator was employed, who would visit each HH every day to ensure HHs were recording their own data correctly and provide any required support, removing the need for further enumerators. This meant that there was spare money which could be used to provide an incentive for the participant HHs to keep recording high quality data - HHs were paid 100 NPR/day for the duration of the transition phase. This appears to have worked as, for example, for electric cooking, dish energy data coverage was 100%.

The TRIID study built on the Simli study, generating high quality data on cooking practices and the transition to electric cooking, confirming its feasibility for rural Nepali communities while highlighting socio-cultural, economic and technical barriers to widespread uptake.

3.5 Results of studies

The results are presented according to the specified research questions, using data and insights gained from both studies to generate and present key conclusions.

3.5.1 What are the current Nepali cooking practices?

Although located in different areas, cooking practices and habits were similar across the studies. The studies generated datasets of hundreds of cooking events including cooking durations, energy consumption, the stove and cookware used, and the quantities of foods or water involved.

Menu

In both communities, the cooking diaries revealed that dal-rice-vegetables meals, known locally as dal bhat tarkari, and derivative meals, such as dal-rice and rice-vegetables, make up a large part of the local diet. Roti, a flatbread similar to chapati, meat, noodles and potatoes are also commonly cooked dishes in rural Nepal. Typical vegetables cooked included various forms of green leaves known as saag, local pumpkin known as pharsi, potatoes, cauliflower, beans and cabbage. Generally, HHs cooked 2-3 meals per day and heated water 2-3 times per day for tea, drinking water or animals. In both studies, meals were usually cooked fresh. Leftovers were rare in the Simli study but recorded for over 200 dishes in both phases in the TRIID study, where they are often given to animals. In each HH it was usually the mother, daughter or daughter-in-law who did the cooking.

Nepali cuisine is a mixture of boiling (rice, lentils) and light frying (vegetables, roti, meat). Table 3.3 outlines the cookware and processes used for the most cooked dishes in both studies, providing further insight into Nepali cooking practices. Rice and dal can generally be categorised as boiled staple dishes, mostly cooked in stove-top pressure cookers, with dal consisting of varieties of lentils or beans and various spices often including garlic, ginger, turmeric, cumin and chillies, and sometimes involving some initial frying. Vegetables, which are cooked in various combinations, are often shallow fried in oil and spices, or sometimes boiled in pressure cookers.

Table 3.3: Cookware and cooking processes used for common dishes in both studies.

Cookware	Processes	Dishes commonly used to cook
Karai – Traditional iron saucepan with spherical bottom, and induction version	Boiling, Frying	Rice, Vegetables, Spinach (Saag), Potatoes, Noodles, Tea, Fish, Meat, Dheedo
Kasaudi – Traditional metal cooking pot	Boiling, Frying	Rice, Vegetables, Mushrooms
Pressure Cooker, and induction version	Boiling	Rice, Dal, Curried Vegetables, Potatoes, Noodles
Deure/Tapke – Traditional iron pan with flat bottom, and induction version	Boiling	Water, Tea, Milk
Roti Pan – thin, flat iron cooking surface, and induction version	Frying	Roti

Many HHs in rural Nepal keep animals and cook large quantities of food for them in large pots on wood stoves. Using electric cookers for this purpose is impractical due to the large quantities required and would increase the cooking electricity demand even further. Usually, separate wood stoves located outside the home are used, reducing the negative health impact for the cook as the harmful emissions are less concentrated, though not eradicating it.

Schedule

The diaries revealed when people tend to cook. Figure 3.8 below provides an insight into the cooking schedule in each community, showing the average numbers of dishes being cooked in each ten-minute period of a typical day in each phase (the total number in each period is averaged across the two weeks). The curves, derived from the cooking diary data, visually represent the spread of cooking throughout the day, and show remarkable similarity between the communities, showing that the peak times for cooking were very similar in each phase at around 7 AM and 7 PM, with a small shift to cooking earlier in the transition phase. Higher peaks in Salyan are partly due to the TRIID study comprising fifteen HHs, as opposed to the ten in the Simli study. The two main meals of the day are had in the morning and evening and are often very similar: combinations of dal, rice, vegetables, roti or, less frequently, meat.

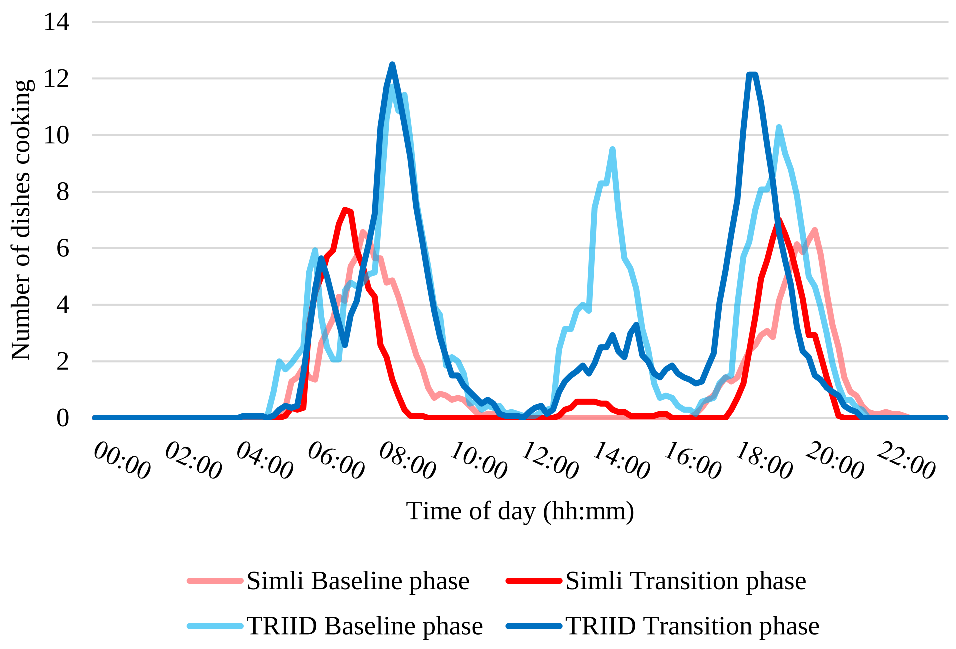

Figure 3.8: Mean number of dishes cooked throughout the day in each phase of each study.

Lunchtime meal practices vary between communities and across seasons, depending on work and school attendance. In Simli, only eleven cooked lunchtime meals were recorded in the entire transition phase, spread between five different HHs, and none in the baseline phase. In Salyan, noodles or potatoes are frequently cooked for this afternoon meal, usually by boiling in a pressure cooker or karai, although it was prepared far less often in the transition phase than the baseline due to school holidays.

The early morning peak in TRIID study data at around 6 am corresponds to water heating events for tea, milk, drinking water and water for animals. In Simli, it is possible that more morning tea or water heating events and lunches were prepared but enumerators and HHs did not record them, however experience in the field showed that lunchtime cooking is rare in Simli. Overall, the morning and evening peaks are similar in width in each community and cooking phase, showing that the two main meals are generally cooked between 5 and 10, AM and PM, and implying generally similar cooking times across cooking technology and location.

3.5.2 How compatible is Nepali cooking with electricity and to what degree do rural Nepali cooks integrate it into their cooking fuel mix?

In each study, the compatibility of Nepali cuisine with electric cooking was investigated by comparing the baseline and transition phases to determine how participants adapted to the electric stoves in terms of what they cooked, how long it took, and how often they used them, enabling assessment of the suitability of electric cooking for Nepali dishes.

Specific dishes and cooking durations

In both studies, dal, rice and vegetables were the most commonly cooked dishes, and participants reported finding dal and rice easy and fast to cook in pressure cookers on the electric cookers. Pressure cooker usage is commonplace in Nepal and so little adaptation was required for these dishes and the time saved by not having to light a fire was clear to participants. Changes in behaviour while adapting to the new stoves were expected. Generally, participants simplified their cooking in the transition phases of each study, cooking a narrower range of dishes and slightly fewer dishes per meal, on average reducing from 2.15 to 2 in Simli and 2.39 to 2.06 in Salyan. The simplification of cooking practices is likely due to HHs growing accustomed to the new stoves.

In Simli, roti was also found to be a key part of the diet in the baseline phase, often cooked with vegetables for one of the two main daily meals. However, due to difficulty experienced cooking roti with the induction hobs, participants increased their consumption of dal-rice meals, as presented in Figure 3.9, reducing their roti consumption or reverting to wood cooking for roti, this being unclear due to unrecorded fuel stacking. Extra dishes were likely cooked alongside these meals on wood stoves, such as vegetables as part of dal-rice-vegetables meals.

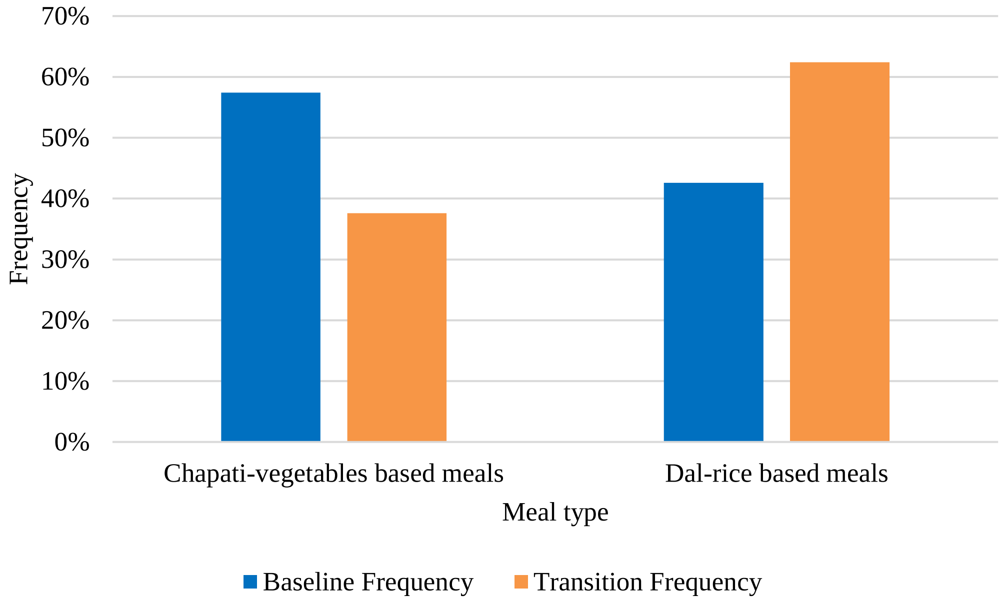

Figure 3.9: Frequency of most common meals in each phase in Simli during the first study.

All HHs in Simli reported having difficulty cooking roti on the induction hobs, due to inexperience cooking with the hobs and their dissimilarity to wood stoves, with the hobs less able to cook the roti evenly. Most participants cooked roti using maize rather than wheat flour, which is thicker and therefore takes longer to cook. Roti cooking requires low-medium heating and an even distribution of heat across the pan. Since induction hobs cycle on and off at full or half power, and heat a ring around the centre of the pan corresponding to the location of the induction coil, they are prone to burning the middle and/or undercooking the edges of the roti, depending on its thickness. Participants favoured the even, controllable heating provided by wood stoves. Therefore, the Simli study found that cooking roti on induction hobs could be made easier by provision of thicker pans with sufficient thermal mass to evenly distribute the heat.

Meat and fish consumption also reduced, with participants noting they normally require constant stirring which they did not feel comfortable doing on the electric cookers with the provided cookware. Meat, which is fried and cooked in pressure cookers as part of curries and stews, is cooked less frequently than the staple dishes, and so some participants had less practice and success adapting to the new cooker and cookware for it, finding it easier to stir the ingredients in traditional round-bottomed pans on wood stoves.

The improved methodology of the TRIID study enabled further and deeper insight into the compatibility of Nepali cuisine and electric cooking in another context. Learning from the Simli study, the TRIID study included increased training on cooking Nepali dishes on induction hobs, with a special focus on roti and meat, and the provision of a thicker induction frying pan for roti cooking. Roti cooking was actually found to be less common in Salyan, featuring in 39 meals across the fifteen HHs in the two-week baseline phase, as opposed to almost 100 across ten HHs in Simli. However, the learnings from the Simli study on facilitating electric cooking of roti are valuable for future interventions, programs and electric cooking rollouts.

In Salyan, HHs generally did not report difficulty cooking particular dishes with electricity, such as roti or meat, showing that experiences can vary between localities. Some HHs reported burning rice at first but that they quickly became accustomed to induction hob rice cooking. One HH reported missing the smoky taste instilled in food by wood cooking, but all remaining HHs strongly disagreed with this statement in the exit surveys. Two HHs did report that dheedo, a dense flour-based dish which resembles lumped together rice, similar to Ugali in Kenya, was best cooked using wood stoves, due to the vigorous stirring required which is easiest when tilting the cooking vessel. Dheedo is cooked to varying degrees across Nepal, often as a hearty winter dish and in lower income HHs, and was cooked only 30 times across ten of the HHs in thebaseline phase in Salyan, reducing to 8 times in the transition phase, and almost never in Simli.

Generally, in Salyan, the most commonly cooked meals in the morning and evening are rice-vegetables and dal-rice-vegetables, similarly to Simli, and noodles or potatoes are regularly had for the afternoon meal. Figure 3.10 below shows how the cooking menu changed across the HHs between the phases. The graph shows that dal was cooked less often in the transition phase. This was reported by some of the HHs as due to spinach (saag) being in season and providing the required moisture for the meal that dal usually provides. Moreso than in Simli, likely due to unrecorded fuel stacking, tea was frequently heated in both phases in Salyan, often on the induction hobs in the transition phase.

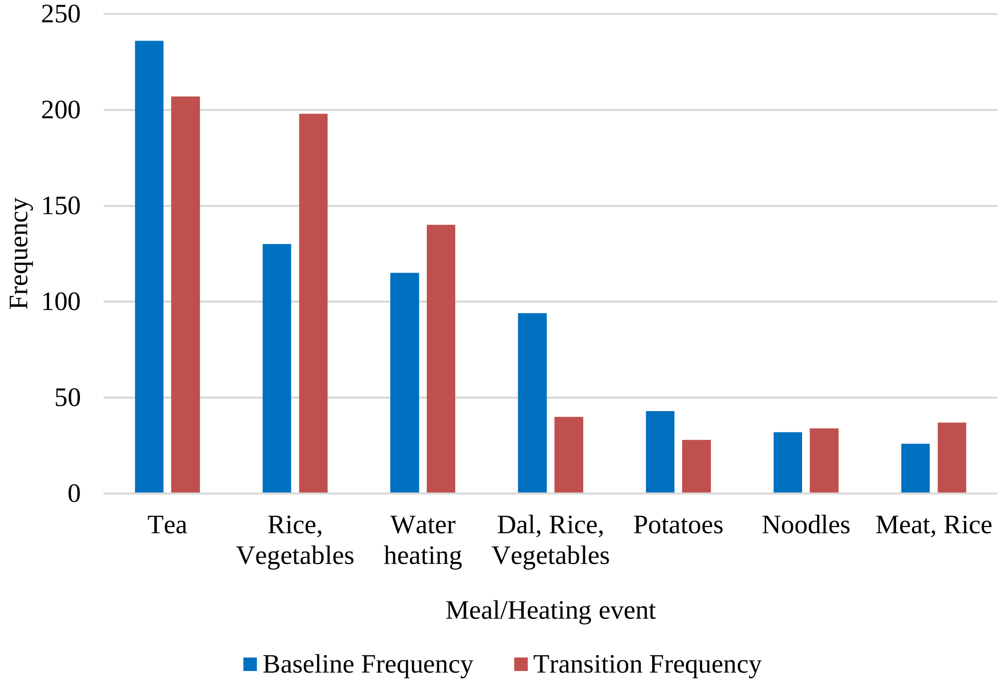

Figure 3.10: Frequency of common meals or events in each phase of the TRIID study.

Figure 3.11 below shows the variation in mean dish cooking time in the TRIID study for commonly cooked dishes. Similar results were identified in the Simli study and are presented in [137].

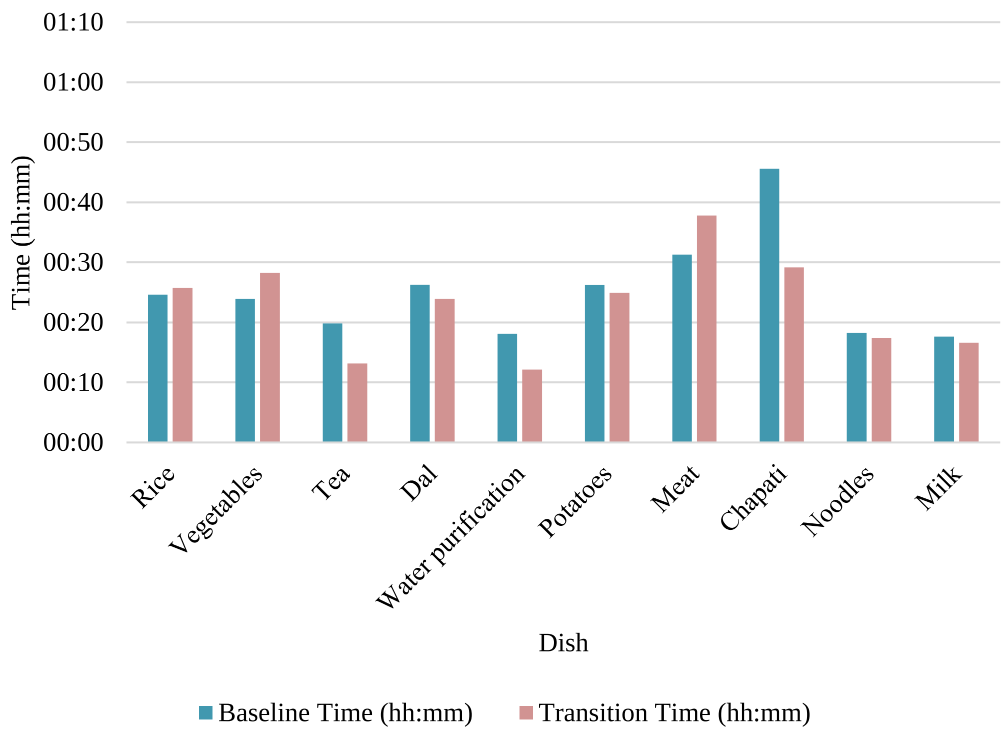

Figure 3.11: Average cooking times of common dishes in each phase in Salyan, with frequencies shown above, only considering electric cooking in the transition phase.

Generally, water heating events, including tea and milk, were faster on electric stoves, whereas other dishes such as meat and vegetables were slightly slower, while there was little change for rice, dal, noodles and potatoes. It might have been expected that induction cooking would generally be fast, as found in [203]. It is likely that a lack of experience cooking with electricity led to increased cooking times for some dishes. However, in Simli, vegetables were no slower across the phases and dal was actually slightly faster to cook with the induction hobs. In Salyan, rice was cooked in the rice cookers 92 times with a mean cooking time of 38 minutes. Rice cooked in pressure cookers on induction hobs took a mean of 25 minutes. This is unsurprising due to the higher power of the induction hobs compared to the rice cookers, and the pressurised environment, and, as the rice cooker is a separate device, the increased cooking time can be offset by cooking other dishes concurrently.

Despite some slightly increased cooking times, HHs generally reported feeling that the induction hobs and rice cookers saved time, partly due to not having to collect and chop firewood, and light a fire for cooking, the latter of which was found to require around five minutes in the Simli study. In both studies, the average daily cooking time across the HHs reduced across the phases, from 2:32 hours to 2:05 in Simli and 3:13 hours to 2:38 in Salyan. For the TRIID study, this is partly due to the baseline phase taking place during school holidays meaning that more afternoon family meals were had at home, increasing the daily cooking time. Furthermore, HHs reported that they were often working during the afternoon in the transition phase.

In addition to time savings, positive feedback included that the induction hobs were beneficial due to the lack of smoke produced while cooking as compared to wood cooking, that they were easy to use and easy to clean, and, importantly, that they enabled them to multitask: to do other things while cooking rather than needing to constantly tend to the fire of their wood stove. Some HHs also enjoyed the controllability of the induction hobs, cooking certain dishes such as milk on low power, and reducing the power level for simmering and gentle frying. Generally, the HHs were generally happy with the cookers and pleased to have been selected for the projects.

Overall, staple dishes including rice, dal, vegetables, tea, noodles and potatoes were easy to cook on induction hobs, but some participants had difficulty with roti, meat and dheedo. Even with extra training on roti cooking methods and a thicker pan to better distribute heat, it was clear that only those willing to experiment and get used to the new technology made the switch to electricity for roti cooking, and that some dishes will often be cooked on wood or LPG stoves. Generally, it was observed that younger cooks with more awareness of electric cooking benefits and more adept at using new technologies were more inclined to use the induction hob for a wider range of dishes. In both studies there was a slight simplification in menu, though this is likely partly due to the brevity of the transition phases.

Fuel stacking

A key finding of both studies was that electric cooking was not fully adopted for cooking by the participating HHs, far from it; fuel stacking was common, despite the participants being encouraged to use the electric cookers as much as possible in the transition phase. The nature and degree of fuel stacking, and variation thereof, are important determinants of the suitability and compatibility of electric cooking for Nepali MHP communities. The first study, in Simli, failed to capture fuel stacking data, although it was clear that HHs reverted to their wood stoves for much of their cooking, while the second study was more successful in this regard. There are many reasons for HHs to fuel stack, which became clearer as the research questions were answered.

In the baseline phase, in Salyan, 95% of dishes were cooked on wood stoves, and 2% with LPG. In the transition phase, electric cooker usage was high with 77% and 6% of dishes cooked on induction hobs and rice cookers respectively, but wood and LPG stoves were still used for around 20% of cooking overall. There was significant fuel stacking in this phase by nine HHs, with LPG and wood, for between 17% and 43% of their dishes. Table 3.4 details the stove breakdown across the phases.

Table 3.4: Stove usage data from the TRIID study showing fuel stacking across the phases.

	Baseline		Transition	
Stove	**Dishes**	**%**	**Dishes**	**%**
Induction cooker	0	0%	1129	**77%**
Rice cooker	0	0%	92	**6%**
Electric kettle	18	1%	0	0%
Wood stove	1172	66%	93	6%
ICS	517	29%	48	3%
LPG stove	32	2%	88	6%
None	41	2%	7	0%
Others	2	0%	0	0%
Total	1782	100%	1457	100%

However, six HHs cooked almost exclusively with electricity, four of which did not have rice cookers. These HHs therefore cooked dishes consecutively on their induction hobs and were still very positive about the study in their feedback. One of these participants, who has young children, was suffering from respiratory and eye problems during the study, and relayed her happiness at the smoke-free environment enabled by the electric cooker. After some time, when forced to revert to wood cooking during a brownout, a low-voltage event, the children were intolerant of the resulting smoke.

Nevertheless, practices and priorities vary between HHs, and this was for a two-week intensive monitoring period, in which HHs were asked to try to cook with electricity as much as possible. Therefore, natural levels of electric cooking usage may be significantly less than seen in the data, and are explored in Section 3.5.5. Generally, across the studies, it was found that even when asked to cook with electricity as much as possible, some degree of fuel stacking is inevitable.

As clear from changes in menu, limited compatibility of certain dishes with electric cooking led to fuel stacking. Another reason cited by participants for fuel stacking with wood stoves was the warmth provided by the fire, an important co-benefit of wood cooking. The culture of using wood stove cooking for space heating means that fuel stacking is inevitable during the colder, winter months in rural Nepali communities, especially in HHs with elderly family members [113]. This is also when dheedo is more regularly cooked, in some communities, which also requires fuel stacking, most commonly with a wood stove, adding to the inevitability in winter.

However, the transition phase took place at the end of November and first half of December 2019, the onset of winter. As some HHs chose to cook entirely with electricity, prioritising the associated benefits, it was found that wood cooking for warmth was not essential for all HHs, although it is likely that most HHs did it to varying degrees across the season. A further reason for fuel stacking found in the study is that it can reduce cooking times by enabling concurrent cooking across stoves.

Concurrent cooking

The studies found that electric cookers enable concurrent cooking, which led to fuel stacking and, for those HHs with rice cookers, electric stove stacking. HHs felt the benefit of being able to cook more than one dish at a time, speeding up their cooking processes, with an increase in concurrent cooking after the transition evident in both studies. Cooking concurrently also enables people to eat just when their food is ready and hot, whereas cooking everything using one electric cooker would leave one or two dishes cold unless kept warm on another stove or in an insulated container.

As with fuel stacking, the Simli study revealed little on concurrent cooking, as only electric cooker usage was recorded in the transition phase. However, the baseline phase in Simli provided the insight that concurrent cooking was very rare before the introduction of electric cookers. The TRIID study also found in its baseline phase that, even if concurrent wood cooking was possible, most HHs would cook dishes consecutively on their wood stoves to save firewood, rather than lighting a separate stove, and as a cultural norm. This is despite the fact that some HHs had both an ICS and traditional wood stove, some had two places on their wood stove, some had LPG stoves and, in the transition phase, all had induction hobs and rice cookers. Approximately 30-40 meals were prepared by each HH in each phase. In the baseline phase only two HHs seemed to cook concurrently on their wood stoves more than three times, and did so only 8 and 7 times.

In the transition phase, concurrent cooking was more common, though not ubiquitous. Only two HHs without rice cookers regularly cooked dishes concurrently between electricity and wood/LPG, for 8 and 12 of their meals. However, four of the five HHs with rice cookers used them concurrently with the induction hobs more than five times, with two HHs doing this frequently, for 15 and 24 of their meals, showing that the addition of a rice cooker generally encouraged concurrent electric cooking.

The remaining HH with a rice cooker used it only four times, reporting in the exit survey that they prefer the taste of rice cooked in the pressure cooker on the induction hob. For the remaining 8 HHs without rice cookers, concurrent cooking was rare, with cooks using the induction stove consecutively and sometimes fuel stacking. Rice cookers are already a feature of many HHs in rural Nepal and are becoming increasingly common. The TRIID study showed that the addition of one electric cooker, such as an induction stove, in such HHs could enable the adoption of electricity as primary cooking fuel.

Both studies showed that practices vary, with some HHs preferring to cook consecutively, and some concurrently. When there are no additional external influencing factors and for those without rice cookers, HHs choose between faster, concurrent cooking, enabled by fuel stacking, and reduced smoke from consecutive induction stove usage as encouraged by the research team, with the choice varying between HHs and across meals, dependent on their priorities.

Some participants without rice cookers commented that having an extra induction-friendly pressure cooker would improve their cooking situation, although they did not follow up on their interest when the MHP secretary offered to make an order. Manual pressure cookers are used widely in Nepal for cooking staple dishes such as dal and rice on wood stoves and most people have at least two, keeping the first dish warm in one pressure cooker while the next dish is cooked in another. As they only had one induction-friendly pressure cooker, participants were forced to empty and clean it after cooking the first dish, which requires effort and removes the first dish from the insulating environment, causing it to get cold while the second dish is cooked, and discouraging consecutive induction stove cooking. During the exit survey, one HH also asked if a vessel in which to keep food warm could be obtained. Therefore, future studies should consider providing extra cookware and insulating containers to make electric cooking easier and maximise its potential as part of rural Nepali life.

Overall, the studies showed that fuel stacking is common between firewood, LPG and electricity, due to preference for certain dishes, space heating from wood cooking, and to save time, and that electric cookers enable and encourage concurrent cooking between different fuels and cookers, including electric stove stacking.

3.5.3 How much electrical energy is required to cook with electricity?

The cooking diaries provided datasets of Nepali cooking habits and energy requirements, useful for comparing the costs of cooking fuels and for technical understanding of the cooking context. For the baseline phases, energy consumption was calculated by converting the weight of wood used for cooking into kilowatt-hours using a calorific value for wood of 4.42 kWh/kg [204]. As expected, due to the low efficiency of biomass cooking compared to electricity, average daily and meal energy consumption per capita in Simli were 20 times higher for the baseline phase (5.22 kWh/day and 2.61 kWh/meal) than for the transition phase (0.25 kWh/day and 0.14 kWh/meal). Corresponding consumption figures for the TRIID study were 6.84 kWh/day and 2.32 kWh/meal for the baseline phase, which reduced to 0.35 kWh/day and 0.15 kWh/meal for electric cooking in the transition phase. The mean meal electrical energy consumption for both studies was 0.67 kWh, while the mean number of people in each study was also the same at 4.8.

Importantly, the figures for transition phase electrical energy consumption would be higher if there were no fuel stacking and every dish was cooked with electricity. For the TRIID study an all-electric daily energy requirement was calculated as 0.43 kWh per capita, while this data was unavailable for the Simli study due to unrecorded fuel stacking. Figure 3.12 below shows the average daily and event energy per capita in each phase of the TRIID study, considering all-electric days and events in the transition phase.

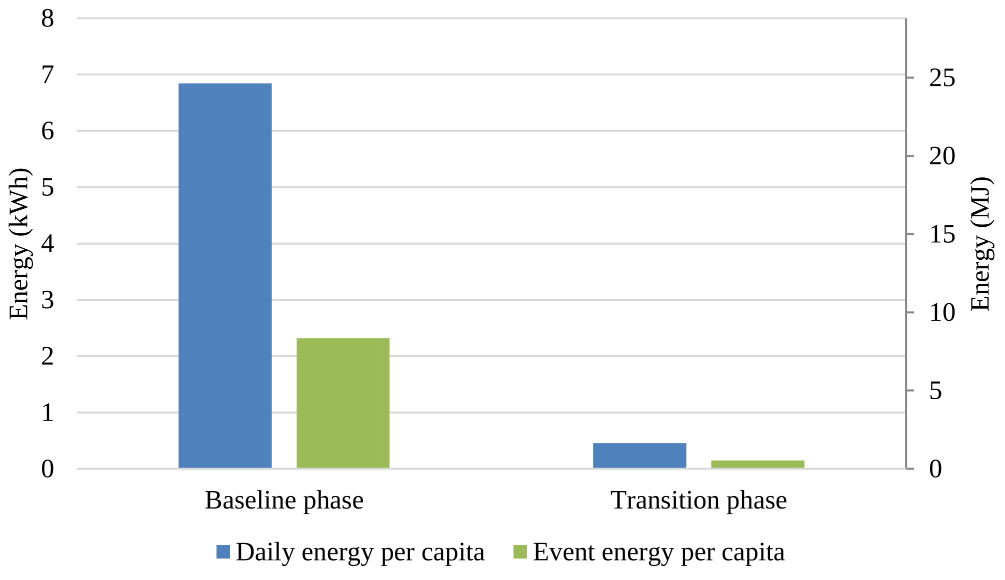

Figure 3.12: Average daily and event energy per capita in each phase.

In the TRIID study, for which firewood consumption data was obtained in both phases, the introduction of electric cooking led to a huge reduction in firewood used for cooking, from a total of 1700 kg in the baseline phase across the HHs, to 250 kg in the transition phase. On average HH wood consumption reduced from 111 kg across a two-week period to 17 kg, with average daily wood usage falling from 7.9 kg to 1.1 kg. As previously mentioned, natural levels of electric cooking usage may be significantly less than seen in the data for the transition phase, as explored in Section 3.5.5. Nevertheless, it is clear that introducing electric cooking can drastically reduce the amount of firewood HHs need to collect and use for cooking.

With firewood, there are significant efficiency savings for HHs cooking for bigger families, whereas with electric cooking the average meal energy per capita is almost independent of the number of people cooked for, as shown in Figure 3.13, using Simli data. For wood, the negative relationship shows that the energy required for cooking does not vary much with the number of people cooked for, as for any cooking the stove must be lit and once alight is difficult to turn down or turn off. Therefore, it is subject to significant losses for all cooking, whether heating water or tea for one or cooking dal and rice for ten. These losses represent a higher proportion of the total energy used for smaller and quicker heating events, such as making tea or cooking vegetables.

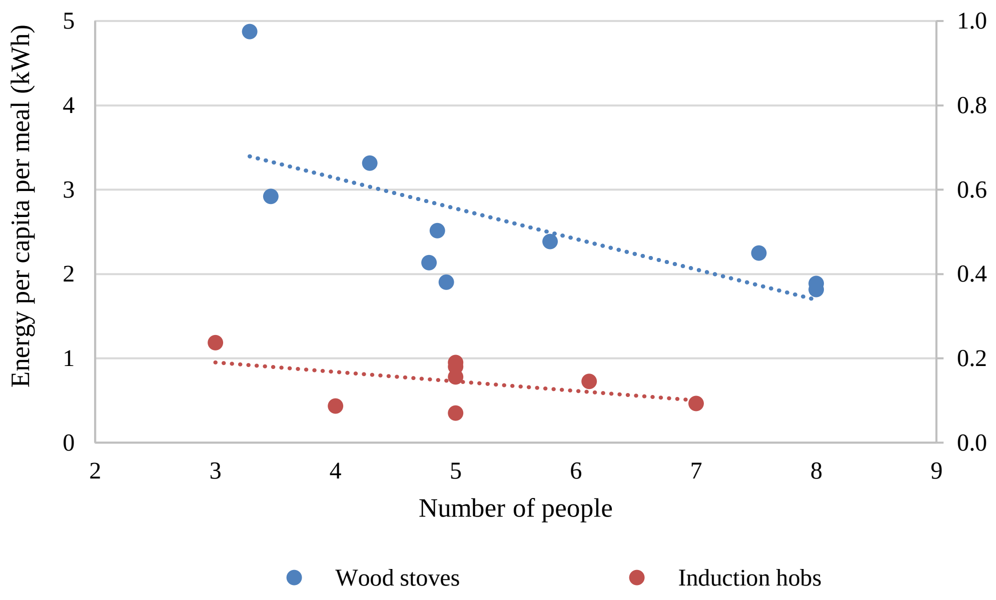

Figure 3.13: Relationship between energy per capita per meal and number of people for wood (primary vertical axis) and electric cooking (secondary vertical axis).

The Simli study provided useful indications of energy requirements of cooking different meals with the electric cookers, however, energy data coverage was limited, with only four HHs recording energy data for over 90% of all meals cooked, four other HHs recording between 9% and 50% of energy data, and two HHs recording no energy data at all. The average meal energy consumption per capita for meals with high data coverage is shown in Figure 3.14.

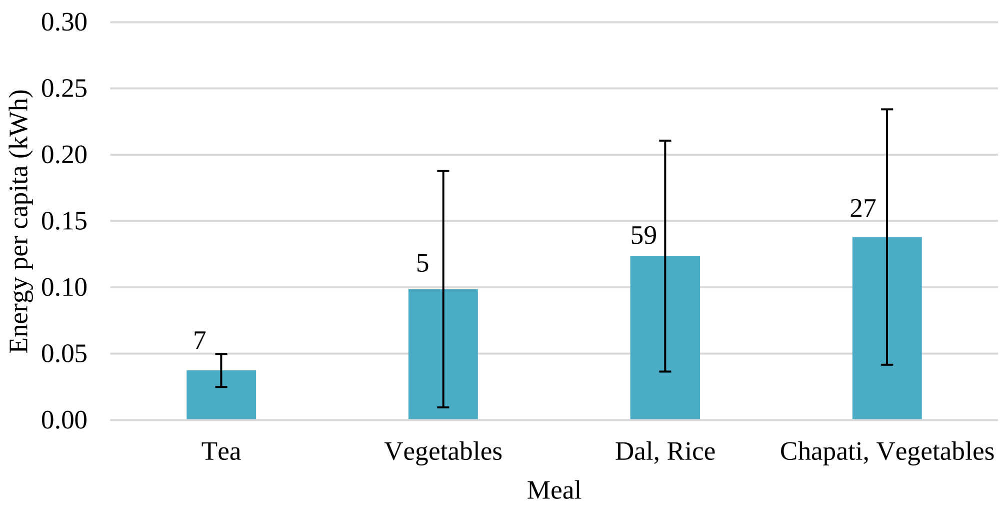

Figure 3.14: Average and standard deviation (error bars) of energy per capita for commonly cooked meals in the transition phase with corresponding numbers of data points.

Overall, electrical energy data was collected for electric cooking for 120 meals in Simli. Studies conducted under the MECS programme reported median daily electrical cooking energy consumptions per capita of 0.21 kWh, 0.49 kWh and 0.46 kWh for Zambia, Tanzania and Kenya respectively [95], compared to means of 0.25 kWh and 0.35 kWh for the Simli and TRIID studies respectively. The daily electrical cooking energy requirement from the Simli study is likely to underestimate actual HH needs due to limited data coverage and unrecorded heating events in the transition phase. Researchers observed that typical cooking practice in the village often included preparing one dal-rice based meal, one roti-vegetables based meal, and tea once or twice in the day. For this set of events, a typical daily energy consumption per capita can be calculated as 0.34 kWh, which is in closer agreement with the referenced studies and the TRIID study.

Scaling up by the average number of people in a HH, a realistic daily energy consumption is therefore 1.61 kWh, similar to the all-electric figure of 2.06 kWh found in the TRIID study. Lunchtime meals are consumed more often in Salyan, possibly accounting for the 0.45 kWh difference, alongside general differences in cooking practices between communities and HHs. If inevitable fuel stacking were considered, the daily requirement in Simli would be less than this value of 1.61 kWh. Overall, the studies show agreement in energy consumption data, providing confidence in the datasets.

The Simli study only provided meal-level energy data, whereas the TRIID study improved the methodology and resulting data by using higher quality meters and capturing dish-level electrical energy consumption data, generating a more reliable and insightful dataset. Table 3.5 shows the key energy outputs from the transition phase of the TRIID study, all of which are calculated from meals, events and days with 100% electric cooking, with the exception of 'Daily energy (all days)', which includes all days, summarising electrical energy requirements including realistic fuel stacking. 'Event energy' includes all heating events i.e. dish cooking and water heating events.

Table 3.5: Key energy outputs from the transition phase of the TRIID study.

Key output	Median (kWh)	Median (MJ)	Mean (kWh)	Range (kWh)	Standard deviation (kWh)
Daily energy (all days)	1.50	5.40	1.63	5.20	1.01
Daily energy	1.90	6.84	2.06	4.60	1.01
Daily energy per capita	0.42	1.51	0.43	0.74	0.15
Meal energy	0.70	2.52	0.72	2.20	0.40
Dish energy	0.30	1.08	0.35	1.30	0.20
Event energy	0.30	1.08	0.45	2.20	0.41

Figure 3.15 shows electric cooking energy requirements of dishes in the transition phase, with the error bars depicting one standard deviation either side of the mean, and the number of times each dish was cooked with electricity shown to the left of each data point. Rice was cooked in pressure cookers on the induction cookers (IC) 261 times with a mean energy per capita of 0.07 kWh, whereas it was cooked in rice cookers (RC) 92 times with a similar mean of 0.08 kWh.

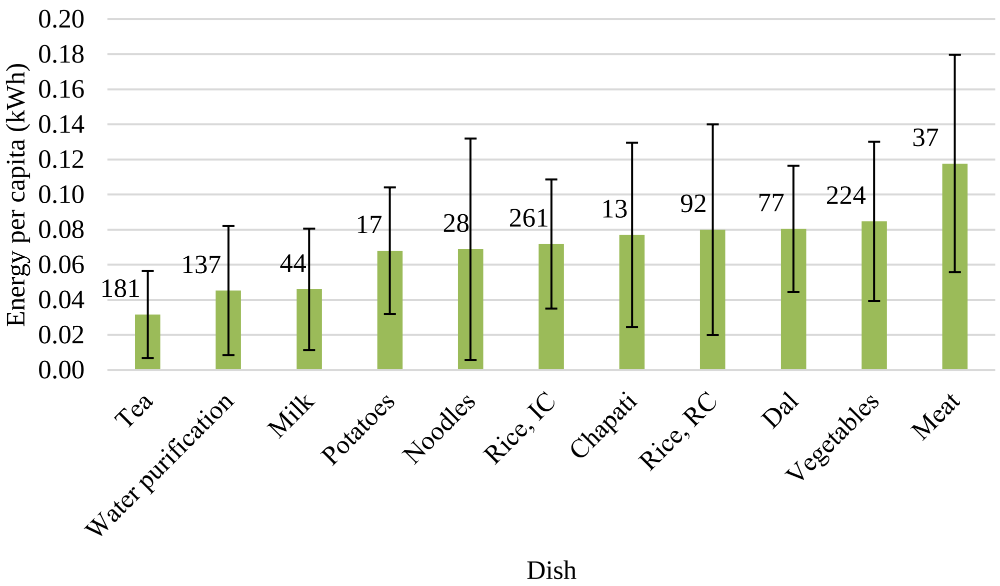

Figure 3.15: Mean and standard deviation (error bars) of energy per capita of most common dishes in the transition phase of the TRIID study, with corresponding frequencies.

The graph shows that water heating events and milk require little energy. Cooking meat consumes more energy than other dishes, which generally require a similar amount of around 0.06-0.08 kWh per person.

Table 3.6 and Figure 3.16 below break down the transition phase fuel stacking and energy data, presenting HH electric cooking usage fractions, providing further insight into HH energy requirements and fuel stacking. They show that energy requirements, which are all in kWh, vary between HHs but that, generally, higher electric cooker usage leads to higher daily electrical energy consumption, as expected.

Table 3.6: HH fuel stacking and energy data (in kWh) from the TRIID study.

HH	Electric cooking %	Daily energy per capita (all events)	Meal energy per capita (no Milk)	Dish energy per capita (meals)
1	100%	0.54	0.18	0.08
2	73%	0.29	0.10	0.08
3	100%	0.58	0.18	0.08
4	99%	0.48	0.18	0.08
5	99%	0.38	0.20	0.08
6	59%	0.27	0.13	0.07
7	78%	0.32	0.17	0.08
8	83%	0.25	0.13	0.07
9	100%	0.36	0.17	0.07
10	70%	0.21	0.07	0.05
11	54%	0.38	0.15	0.11
12	99%	0.35	0.10	0.07
13	74%	0.07	0.03	0.02
14	74%	0.28	0.13	0.07
15	80%	0.43	0.18	0.10

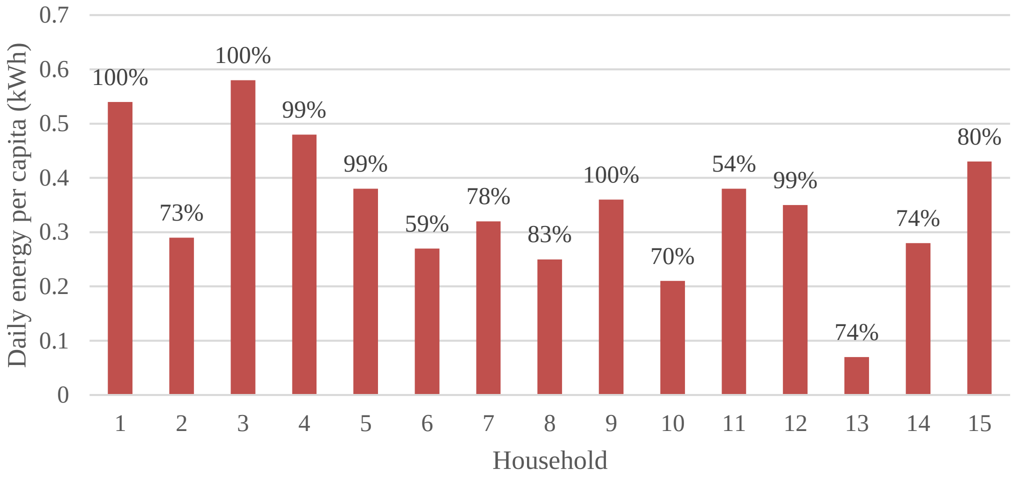

Figure 3.16: Average daily energy per capita for each HH, with their electric cooking fraction above.

The data also shows that the energy data of HH13 was very low compared to that of the other HHs. 27 of its 73 electric cooking events were reheatings of dishes, which could explain some of the low values, while 20 dishes had zero energy readings, likely due to the precision of the energy meters being limited to one decimal place. In case the data for this HH was erroneous due to faults with meters or their lack of precision, average daily and meal electrical energy consumptions were recalculated excluding it, obtaining 1.71 kWh/day and 0.7 kWh/meal, slightly increased from 1.63 kWh/day and 0.67 kWh/meal.

Saving food and reheating it later are cooking practices which have the potential to provide significant energy savings – food can be eaten cold for the next meal, requiring no energy, or reheated, which requires less energy than cooking a meal fresh as the food is already cooked. However, these practices were generally rare across the studies and it is likely that lack of safe food storage such as refrigerators and inertia in cultural cooking habits affect the adoption of such practices.

Overall, the studies provided valuable datasets of Nepali dish and meal energy requirements, and insight into daily electrical energy requirements for cooking at different levels of fuel stacking. The studies showed that practices are similar in two different communities in different areas of Nepal, although further studies are required to understand variability across the country and in other contexts. The energy consumption datasets were used to understand the running costs of electric cooking and compare it to other fuels.

3.5.4 How affordable is electric cooking for rural Nepali cooks?

The electrical energy data were used to assess the affordability of electric cooking. In Simli, HHs paid for the electricity they used for cooking. However, in Salyan, community members are not currently charged based on their electricity consumption, instead paying a monthly flat rate of NPR 110. In fact, HHs were incentivised with payments of NPR 100/day to continue recording high quality cooking diary data. Therefore, the TRIID study did not assess affordability directly, instead insight was gained from surveys.

Three of the ten HHs in the Simli study changed between phases as the original three dropped out due to concerns over the perceived cost of electric cooking, providing further evidence for the perception of unaffordability identified in the literature. All the participating HHs in Simli collected their own firewood and so had no direct cost associated with it. The Simli community is located next to a large river by which firewood is collected, close to the community, but several hours are still required for cutting and transportation. Some HHs collect wood in large quantities over several days, storing it for months, whereas many do so on a weekly basis.

In Salyan, firewood collection practices also vary between HHs, both in regularity, with some collecting weekly or monthly and others biannually or annually, and source: their own land or the community forest. A common practice in Salyan and many other rural Nepali communities is a cultural phenomenon called ‘Perma’, where HHs help each other to collect wood in bulk once or twice a year with the expectation that the favour would be returned. Participants placed an equivalent cost on this at NPR 500 per person per day. A typical reported case was collection twice a year, including travel to the community forest, wood cutting, transportation and provision of meals, requiring around five people over five days each time. It is common for wood to be collected firstly before monsoon season, which includes June and July and during which a lot of agricultural work is done, and secondly in winter. An annual equivalent cost was calculated as NPR 25,000, which is NPR 962 over two weeks. Four of the 15 HHs in the TRIID study collect wood themselves from their own land, and therefore have no equivalent cost except that of their own time.

In Simli, the cost for electric cooking across the transition phase for the HHs was NPR 150-323, based on the energy data of HHs with high data coverage and the tariff of NPR 120 for the first 5 kWh consumed per month, followed by 12 NPR/kWh after. Energy consumption data coverage and quality were limited so electric cooking costs may have been underestimated. However, even when the synthetic daily energy requirement for a family of five cooking entirely with electricity is considered, the cost would be NPR 343 for the two-week period, still markedly less than the equivalent time cost of wood collection of NPR 962, assuming a similar equivalent cost for Simli as in Salyan.

In Salyan, energy meters have not yet been installed in every HH connected to the mini-grid. However, there is an intention to introduce a tariff system when more HHs have energy meters, which will mean HHs paying 7 NPR/kWh. The proposed tariff is relatively low in Salyan when compared to, for instance, the 12 NPR/kWh paid in Simli. This is because many of the villagers helped with the construction of the MHP. The total energy consumption of each HH was used to calculate what the cost of electric cooking would be if the tariff system was implemented. The mean cost across the HHs was NPR 193 for the two-week period, with a range of NPR 90-477. For the six HHs that used electricity for almost all of their cooking, the mean was NPR 249 and range NPR 114-477, similar to Simli and markedly less than the NPR 962 equivalent wood cost.

An LPG cylinder costs NPR 2000 in Salyan, increased from NPR 1380 in Kathmandu due to the remoteness of the community [140]. Participants from the 8 HHs that used LPG as a back-up cooking fuel estimated the number of months a cylinder usually lasts, allowing calculation of an annual LPG cost, which was scaled down to two weeks, giving a mean of NPR 281 and range of NPR 82-614. Therefore, even though it is only used as a back-up fuel, LPG costs are similar to the costs of electric cooking when the latter is a primary cooking method.

Excluding the investment cost of cooker and cookware, there is a significant cost saving that HHs can make by adopting electric cooking, contrary to the perceived higher cost discussed in the literature. Rural Nepalis do not necessarily attach the same monetary value to wood collection time as has been done in this analysis. However, for communities like Simli and Salyan with income-generation opportunities in commercial centres and nearby markets, time can be of high value.

To assess affordability further, in the exit surveys participants were asked how much they would be willing to pay for electricity for cooking per month, and what an affordable price for the electric cooking system would be. In Simli, all HHs reported that they would be willing to pay NPR 300-600 in additional monthly electricity costs. Most HHs referred to NPR 3,000-6,000 as a reasonable price range for the electric stove and cookware, with some HHs who were more aware of the health benefits of a smoke-free HH selecting NPR 6,000-10,000. In the TRIID study, the options for participant responses on monthly electric cooking running costs were expanded to include more precise ranges, with HHs generally split between willingness to pay NPR 200-400 and NPR 400-600, similar to Simli. In terms of upfront cost, participants were generally willing to pay more than in the Simli study for the electric cooking system, with ten selecting NPR 6,000-10,000 and four choosing NPR 10,000-15,000 as reasonable price ranges.

Comparing participant responses to the data, in Simli, the synthetic daily energy requirement scaled to a 30-day month of 100% electric cooking would cost NPR 707, which is slightly more than the higher end of the range HHs would be willing to pay in additional monthly electricity costs, although some inevitable fuel stacking would reduce this cost. Therefore, a further driver for fuel stacking in Simli, in addition to difficulty cooking certain dishes, may have been to keep costs down. One HH did report that 'electrical expenses were remarkably high' and, as mentioned, three HHs did not participate in the transition phase due to economic concerns. For the TRIID study, the average electric cooking cost scaled to a 30-day month would be NPR 414, with a range of NPR 194-1022 while that of the HHs which cooked mostly with electricity would be NPR 533. The HH with the highest energy consumption would pay NPR 1022 per month, but the next highest NPR 602. Therefore, apart from one HH with much higher electrical energy consumption than the others, monthly electric cooking bills would be seen as affordable for some of the participating HHs.

The cooking systems for each study, comprising induction hob and cookware, were purchased for NPR 12,000-14,000 each, which is considerably more than what most HHs in deemed an affordable initial cost. The rice cookers purchased for the TRIID study cost around NPR 3,000. The cookware makes up a large proportion of the expense for induction cooking, costing around NPR 7,000-8,000. However, all HHs paid a discounted price of NPR 4,000 and NPR 3,500 in Simli and Salyan respectively at the end of the transition phase to keep their electric cookers, showing that, although the upfront costs were beyond reported affordability, participants saw value in electric cooking.

For HHs that do not use LPG and collect wood themselves from their own land, electric cooking is an extra expense. However, for those who use LPG as a back-up fuel and/or collect wood according to Perma, electric cooking running costs are similar to their previous costs and in some cases, lower. With a change in thinking on the value of time spent collecting firewood, and if LPG costs can be transferred, electric cooking could be seen as approaching affordability. Overall, in both communities, electric cooking is approaching affordability for certain HHs according to their current cooking fuel usage and perceptions, but initial capital expenses of the electric cooking system are a considerable barrier to adoption in rural Nepal.

3.5.5 What are the effects of electric cooking on an MHP mini-grid and what is its current scalability?

The studies aimed to investigate how electric cookers affect the electrical system. Within this research question, the studies also enabled assessment of how capable MHP mini-grids are of meeting their existing electricity demand.

The data logger provided one-minute resolution data for each signal, with each value the average of six ten-second averages of a further five two-second instantaneous samples. Therefore, the profiles cannot reflect changes in demand, generation or voltage that happen between samples, and averaging may lead to a slight under- or overestimation of the reality. In terms of cooking, the induction cookers used in the studies cycle on and off at full power to output effective intermediate power levels, generally over short cycles of around ten seconds. For example, on its 700 W setting, a 1 kW hob will pulse ON for seven seconds and OFF for three seconds, while on its lowest setting, 200 W, the ON period is two seconds. It is likely that the logger captured reasonably accurate averages for electric cooking, outputting the effective intermediate power levels, rather than capturing the pulses of full and zero power. The data may therefore under- and overestimate peaks and troughs which occur when electric cookers pulse in sync. However, it is still useful for assessing power supply stability and electric cooking scalability, as the analysis showed that there were voltage drops when the demand neared the generated power. Furthermore, the diversity in the timing of the peaks between electric cookers may lead to the averages providing accurate representations of the total electric cooking and community loads.

In Simli, mini-grid powerhouse electrical data was only collected for a period of nine days in August 2018, with the data of limited quality compared to that collected during the TRIIID study. Therefore, this section focusses on the TRIID data after briefly summarising the understanding gained from the Simli data. In the Simli study, as reported in exit surveys, there were many blackouts across the transition phase. One cause was the wooden distribution poles falling down or requiring maintenance due to poor material condition. Another cause was high electricity demand, which also led to brownouts frequently reported by participants, which in turn led to increased cooking times and uncooked food in periods where the system was running. The voltage often dropped as low as 50 V for short periods of time. The research team have found that cooking is slower at 200 V and virtually impossible below 150 V, a finding also obtained in the Myanmar cooking diary study [156]. Blackouts and brownouts caused participants to fuel stack, reverting to their wood stoves for dishes or entire meals.

The load power reached the generation capacity on every day for which data was available, and demand was always high during the morning and evening cooking times. The main community and cooking peaks occurred at similar times, showing that people cook when demand is already high, compounding the problem of increased demand posed by electric cooking in limited capacity grids. Although HHs continued to cook most of their meals and dishes with the electric cookers despite the brownouts and blackouts for the following month, during the follow-up study it was found that only three HHs were still using the electric cooker regularly.

The study took place during monsoon season when the water flow was at its strongest. In the following, drier, winter months the water flow can be significantly weaker and therefore the MHP generating capacity can be lowered [205]. Also, since the study, members of the community have at times diverted water from the MHP canal for irrigation, reducing the flow further and contributing to grid instability. Reduced generation capacity and high load demand prevented participants from being able to use their electric cookers, rendering electric cooking feasibility limited and scalability effectively zero, despite only ten of 450 HHs having induction stoves.

The TRIID study took place towards the start of the dry season, from September to December 2019, enabling investigation of its effect on generation capacity in Salyan. There was more spare power for cooking, a higher power (100 kW nominal) MHP system, and no routine daily outages, enabling better data capture and analysis. As with HH energy meter data, the TRIID study improved on the Simli study by collecting data for the entirety of the diary study, enabling comparison between the Baseline and Transition phases and more detailed analysis.

Figure 3.17 presents average profiles of total generated power and total load power in each phase of the TRIID study, with the background clouds one standard deviation either side of the mean. It confirms the successful operation of the ELC, which dumps excess generated power that does not serve the loads, mostly during off-peak periods. However, the operators regulated the voltage and frequency manually by adjustment of the turbine butterfly valve, due to the ballast loads being of unknown capacity, reducing the stability of the plant. Thirteen and twelve days of data were included in the Baseline and Transition load profiles respectively, while the generation profiles included seven and three days, due to blackouts on certain days between 11 AM and 3 PM reducing their clarity, although the peak generated power was very similar with or without these days.

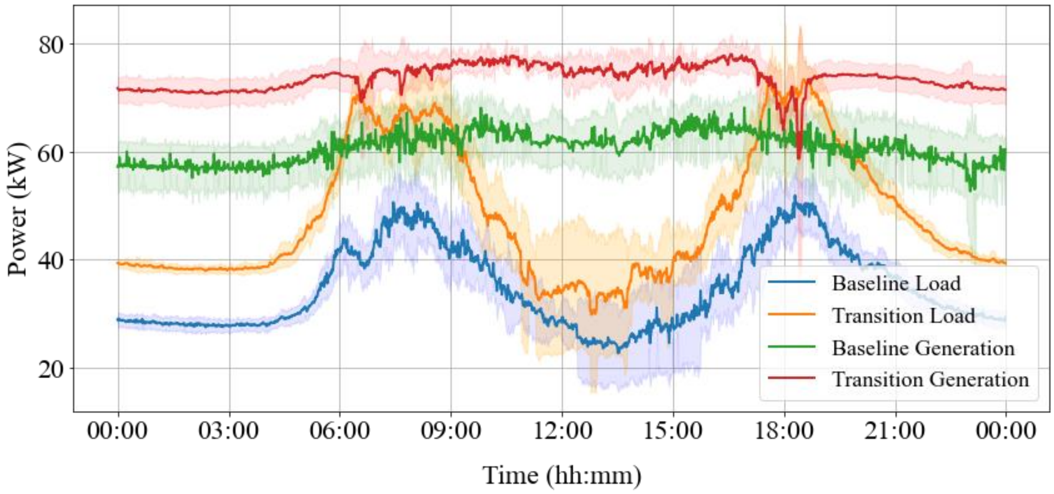

Figure 3.17: Average generation and load profiles from MHP powerhouse electrical data collected in Salyan in 2019, with background clouds plus and minus one standard deviation.

The profiles show that there are two peaks, morning and evening, in the daily community electricity demand. These are due to highs in HH activity including electric cooking, lighting, phone charging, television and radio usage, etc, as well as business, community and industrial activity including shops, schools, poultry farms, rice mill operation, etc. There was a significant increase in load after the introduction of the cookers of around 10-20 kW across the day, from around 30 kW to 40 kW in off-peak times and 50 kW to 70 kW in peak times. As the increase was present during off-peak times as well as cooking times, additional end use connections other than electric cookers must have contributed, such as, potentially, electric heaters, due to the onset of winter, and high power devices like electric kettles and rice cookers purchased from markets by HHs in the community. In the ECO study, presented in Chapter 4 and conducted a year after the TRIID study, ten of thirty HHs in the same community reported having bought one or more high power devices in recent months, suggesting this is commonplace.

In the Baseline phase, there was clearly much more spare power, with the total load power never reaching the generated power, while in the Transition phase, the load frequently reached the generated power, causing instability. Figure 3.18 shows the average voltage profiles plus and minus one standard deviation, from the same data as used to calculate the average load profiles in Figure 3.17. Focussing on peak times in the morning and evening of 6-9 AM and 5-7 PM respectively, due to outages and shutdowns skewing off-peak averages, brownouts were much more severe in the Transition phase than the Baseline phase, especially in the evening, with the voltage sometimes dropping down to around 200 V and 180 V in the morning and evening respectively, and occasionally well below these levels, due to the load often reaching the generation capacity in the electric cooking phase. As in Simli, cooking times coincided with peak community electricity demand.

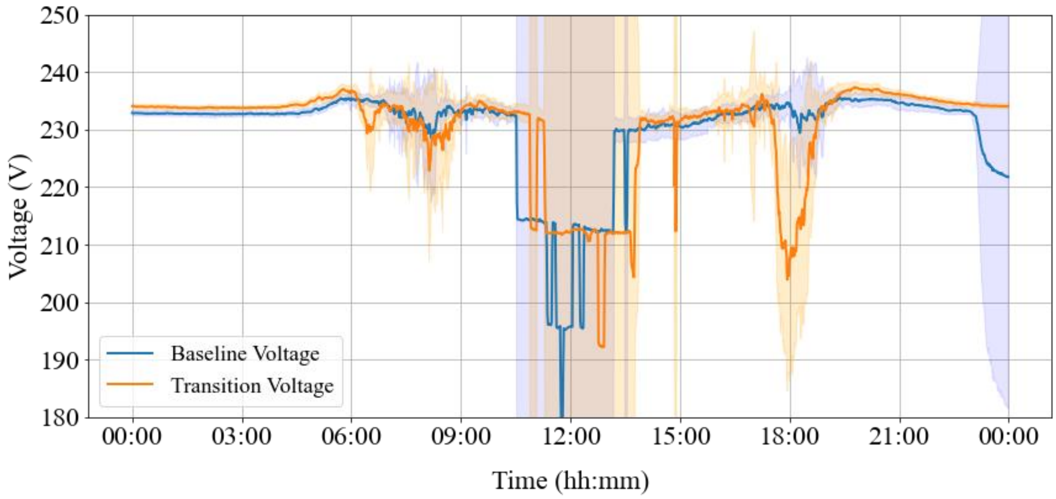

Figure 3.18: Average voltage profiles plus and minus one standard deviation in each phase of the TRIID study.

The maximum total electricity demand of a community varies each day, both in magnitude and time, according to diversity in the timings and levels of electricity usage of HHs and other end uses. The daily load peak can be referred to as the after diversity maximum demand (ADMD), while the presence of two, separate morning and evening demand peaks enabled specification of morning ADMD and evening ADMD. Figure 3.19 illustrates the concept, displaying two consecutive days of community load data, 30th November 2019 and 1st December 2019. The ADMD on each day is the highest of the two peaks within the day, which is the evening peak for the 30th November, while the second day peaks are very similar in magnitude. Morning and evening ADMD within each day can also be discussed, referring to each peak in the figure.

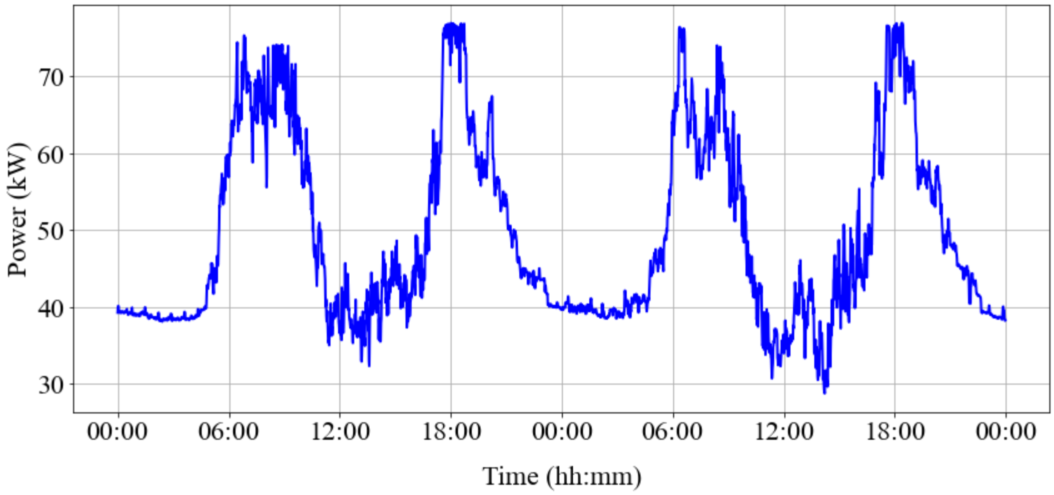

Figure 3.19: Illustrating the concept of ADMD, depicting two consecutive days of total load data in the TRIID study.

The diversity in the time-coincidence of electrical loads leads to slight underestimation of true peak loads by the phase averages depicted in Figure 3.17. The mean morning and evening ADMD across the Transition phase was 77.4 kW and 78.8 kW respectively, reaching maxima of 80.2 kW and 83.0 kW respectively on certain days. As it was the dry season, the generated power in the mini-grid dropped to around 80 kW, due to reduced water flow in the river. The generation power could theoretically be increased close to its rated capacity of 100 kW, although this is less feasible in the dry season. Also, during the colder months the MHP secretary and operators are disinclined to restore the generated power to a higher level by diverting more water to the MHP canal at the intake due to the coldness of the water and climate, preferring to wait for warmer weather [140].

Therefore, as in Simli, the mini-grid struggled to support electric cooking, in this case with just fifteen of almost 1,100 HHs cooking with electricity. Once again, power supply issues led to fuel stacking. In the exit surveys, the main problem cited was low voltage or power outages, sometimes just after starting to cook. Six HHs reported this occurring, with the most affected HH without power for three to four days, forcing them to revert to wood or LPG stoves for cooking. During the exit survey site visit, HH cooking energy meter readings were taken to understand how much the HHs had been using the electric stoves in the two months following the transition phase, from December 2019 to February 2020, the peak of the dry season. These readings were used to estimate the fraction of cooking done using the electric stoves during this intervening period by calculating how much energy HHs would have consumed had they used them for the entirety of their cooking. Table 3.7 presents the results for each HH.

Table 3.7: Estimating electric cooker usage fractions in the two months following the transition phase of the TRIID study.

HH	Energy consumption post Transition phase (kWh)	Mean daily electricity consumption (kWh)	100% electric cooking projection (kWh)	Actual cooking fraction
1	12.3	2.27	127.31	10%
2	46.3	1.56	88.76	52%
3	166.8	4.01	220.39	76%
4	107.2	2.04	114.24	94%
5	68.3	1.81	101.20	67%
6	8.8	2.06	115.51	8%
7	27.8	2.00	110.00	25%
8	34.3	1.98	108.90	31%
9	43.2	1.97	108.43	40%
10	84	2.06	113.45	74%
11	30.3	2.06	113.45	27%
12	21.5	1.11	60.92	35%
13	24.3	2.06	115.51	21%
14	62.5	1.41	78.68	79%
15	130.7	1.59	88.80	147%

The ‘100% electric cooking projection (kWh)’ column was calculated by multiplying the number of days between the end of the transition phase and 3rd February (when energy meter readings were taken again) by the mean daily electric cooking energy consumption of each HH during the transition phase. For HHs with low data coverage of all-electric cooking days, the overall mean was used. The ‘Actual cooking fraction’ is the ratio of actual electrical energy consumption in that intervening period to the projected consumption if the HHs had been cooking entirely with electricity.

The electric cooking fraction had a very wide range of 8% to 147%. HH15’s data produced the 147% (the only percentage over 100%) because they used the electric stove for only around 50% of their cooking during the transition phase, giving rise to a low mean daily electrical energy consumption, but subsequently adopted the electric stove as their primary stove. HH13 used the electric stove 21% of the time but this percentage is reduced due to their stove breaking down in January. Despite the same problem, HH14 used theirs 79% of the time. Six of the HHs used their electric cookers for over two thirds (67%) of their cooking, while six other HHs cooked with electricity less than 40% of the time. The mean percentage of electric cooking was 52%, and the median 40%.

Therefore, the TRIID study showed that the high load demand of electric cooking, alongside reduced MHP generation power in the dry season, caused power supply instability which reduced the feasibility of electric cooking, and provided a further driver for fuel stacking. Despite this, most HHs continued to use the electric cookers regularly, where possible. However, as in Simli, the scalability of electric cooking, at least in the dry season, was found to be very low.

3.5.6 What are the load characteristics of HHs cooking with electricity and how does their electricity demand affect the community load profile?

In the absence of measured electric cooking load profiles, synthetic load profiles were created from the TRIID study data by calculating an average power for each dish cooked in the day from its energy and cooking duration, to investigate the time-coincidence and spare power requirements of fifteen HHs cooking with electricity across the two-week period. The profiles consist of one average power value for each dish, failing to capture changes in electric cooker power level applied by participants, for example reducing the heat to a simmering level, and therefore lack precision, but should provide an indication of the shape of the total electric cooking profile and the cooking ADMD. Figure 3.20 shows the average total daily electric cooking profile for the fifteen HHs, across the transition phase, with morning and evening peaks of 6.18 kW and 5.89 kW respectively.

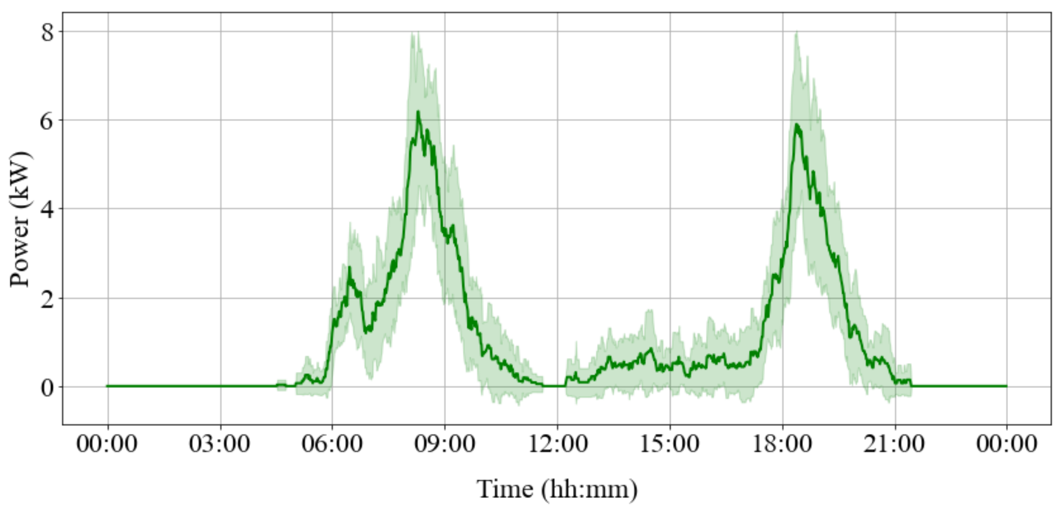

Figure 3.20: Average total daily electric cooking load profile for TRIID study HHs, with the background cloud plus and mins one standard deviation.

Therefore, although HHs tend to cook around the same time, fifteen HHs cooking with electricity does not tend to require 15 kW. However, the total cooking electricity demand can and did approach this value on some days. The mean morning and evening ADMD for cooking across the two-week period was 7.89 kW and 7.02 kW respectively, with corresponding maxima of 10.75 kW and 11.16 kW on certain days. The profiles provide a useful insight into the effect of diversity in timing and duration of cooking on the resulting total electric cooking demand of fifteen rural Nepali HHs, and include the fuel stacking practiced within the transition phase. They may in fact overestimate the total cooking demand of HHs during settled, unmonitored periods.

The cooking profiles were compared to the community-wide load profiles from the transition phase which, of course, contain the electric cooking approximated by the average cooking profiles. Figure 3.21 presents the average total Baseline, Transition and electric cooking load profiles, reiterating the point that the TRIID study electric cookers were not the only additional loads present in the Transition phase, and confirming that people in rural Nepali MHP communities cook at the same time as peak community electricity demand. This coincidence contributed to the reduced mini-grid stability experienced by the participants, which led to fuel stacking.

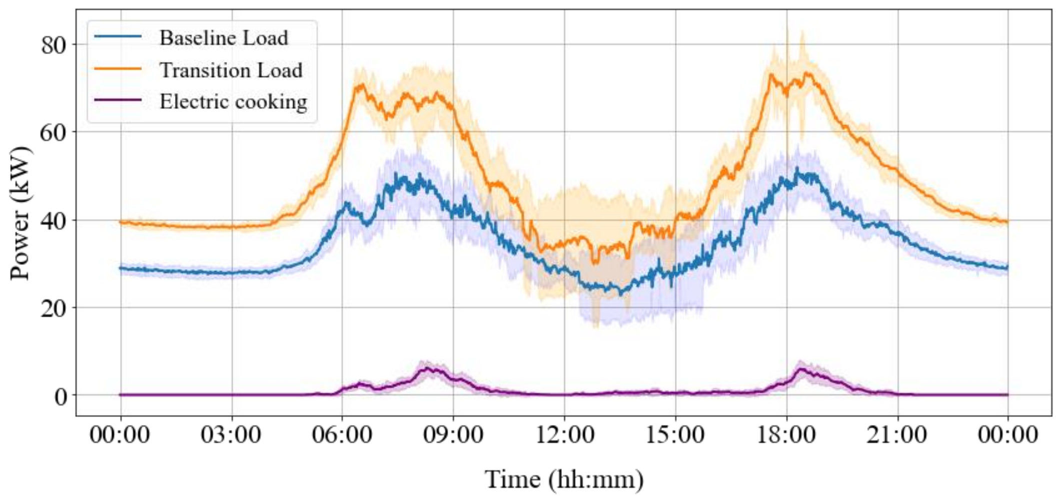

Figure 3.21: Average total Baseline, Transition and electric cooking load profiles, with background clouds plus and minus one standard deviation.

To investigate the extent to which electric cooking increased the total community electricity demand further, the data was inspected on a day-by-day basis, by comparing the total community load with that minus the corresponding electric cooking profile, for each day of the transition phase. The timing, shape and duration of the load peaks of both the community profiles and the electric cooking profiles varied across days, leading to variability in the coincidence of cooking with community loads. It was found that, on around half of the transition phase days, electric cooking increased peak demand significantly, by up to around 8 kW, whereas on other days diversity led to smaller contributions. Figure 3.22 shows a day in November 2019 where electric cooking added around 7 kW to both the morning and evening peaks. Importantly, maximum contributions of around 8 kW were only slightly less than the maximum ADMD of around 11 kW, showing that, in worst case scenarios on certain days, electric cooking peaks can coincide almost totally with community load peaks, increasing the community load significantly.

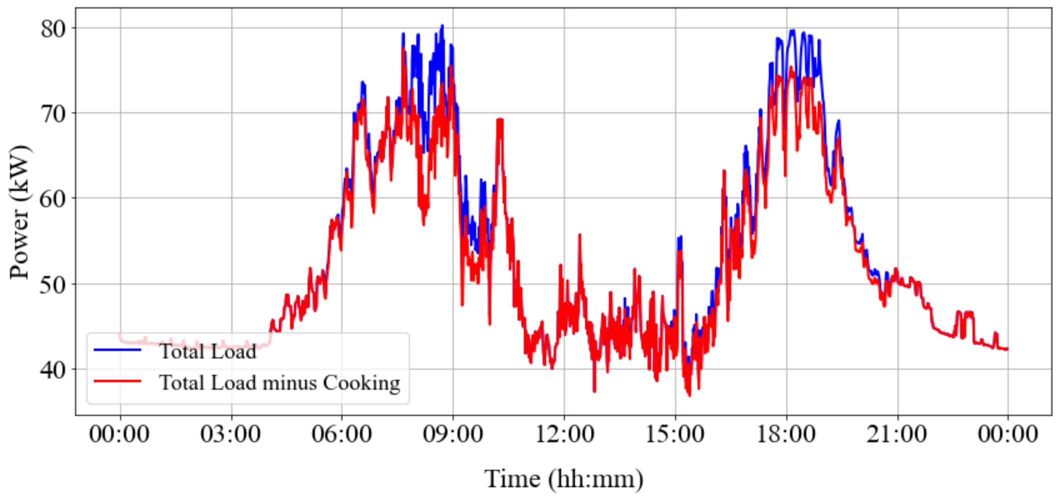

Figure 3.22: Total load and total load minus cooking load on 26th November 2019 in the TRIID study.

The relationship between the cooking and community profiles is limited by their precision, with the community profiles more likely to contain power level changes, e.g. from 1 kW to 700 W, and the cooking profiles limited to average dish power values. The community minus cooking profiles, in Figure 3.22, are therefore imprecise, with their true values likely to oscillate around the calculated values, but still provide an indication of the degree of coincidence of cooking and community loads.

Overall, the approximate total cooking load of rural Nepali HHs was understood, as was its relationship to the community load profile, finding that electric cooking can cause significantly increased total community electricity demand and, with limited generation capacity, mini-grid instability.

3.6 Discussion

This chapter summarised two cooking diaries studies which addressed research objectives 1-3 of this thesis, on understanding the current cooking context in Nepal and investigating the transition to electric cooking from social and technical perspectives. These research objectives were addressed by obtaining data and insights in two MHP communities. However, there was a focus on induction cookers. Further studies would enable the objectives to be addressed to a greater extent. The conducted studies attempted to answer six research questions in order to assess the primary question of the feasibility of electric cooking in rural off-grid Nepali communities. The studies were able to answer research questions 1-5 effectively, while research question 6, on the electricity demand of electric cookers, was not fully addressed due to the imprecision of the average power profiles, and requires further investigation.

Overall, the feasibility and acceptability of electric cooking was confirmed, but there was insufficient spare power in the mini-grids for participants to use their electric cookers comfortably, without power supply instability, let alone for widespread adoption of electric cooking. DSM measures and energy storage could help to enable increased uptake of electric cooking in MHP communities. Of the DSM measures outlined in Section 2.6.1, efficient devices, load scheduling agreements and demand reduction present suitable options for exploration.

Most Nepali cooks are already familiar with manual pressure cookers and rice cookers, suggesting that EPCs could be well received and play a primary role in Nepali cooking. EPCs only demand continuous high power during relatively short preheat phases of around 10-20 minutes, whereas induction cookers generally took around 20-30 minutes to cook, often at high or medium power levels. Staple boiling dishes such as rice and dal are well suited to cooking in EPCs as they are generally cooked in manual pressure cookers, while lunches such as noodles and potatoes are also mostly boiled, and EPCs can be used for frying, although the convenience and performance of EPC frying requires investigation. Unlike induction cookers, EPCs are fully integrated and do not require specialist cookware, reducing the cost of the cooking system.

Furthermore, it was decided to investigate load scheduling agreements for high power community loads and electric cooking, which do not require any additional technology, unlike load limiters or intelligent DSM devices such as Gridshare. Such agreements are simple but can be effective if adhered to, as identified in Section 2.6.1, while understanding the willingness of community members to adapt their electricity usage was also deemed important as a DSM measure.

Even with more efficient cooking devices and load scheduling agreements for industrial machines or electric cooking, in communities of hundreds or thousands of HHs, electric cooking scalability is limited. The energy generated by MHPs during off-peak times could be stored and reused. Therefore, the potential of energy storage to make use of off-peak MHP energy, effectively reducing peak loads and enabling increased connections, was selected for investigation, as the Simli and TRIID studies determined that electric cooking scalability is low in each community with only ten and fifteen HHs respectively, of several hundreds, using electric cookers.

The villages of Simli and Salyan present contrasting images of Nepali MHP mini-grids. In Salyan, without energy meters, people were wasteful with energy, leavings their lights on all day with no fear of higher electricity bills. With better load management, it was likely that more HHs could cook with electricity without destabilising the mini-grid. However, even with monitored electricity consumption in Rukum, the electricity demand was so high relative to the MHP capacity that electric cooking was unfeasible. Therefore, the solutions of efficient cooking devices and further DSM would be unlikely to create enough spare power for increased uptake of electric cooking in a community like Simli, with energy storage the most suitable solution**,** instead. Whereas, in communities like Salyan, where the supply was more stable, the generated power possible to increase, and DSM measures not yet in practice, DSM *and* energy storage could form part of the picture for enabling electric cooking. The first solution explored, in Chapter 4, was efficient devices. First, limitations of the Simli and TRIID studies, which led to improved methodologies for investigating efficient devices, are outlined.

The studies provided a number of areas for improvement. Firstly, the use of paper cooking diary forms led to human error in data recording and onerous data processing. Digital data collection methods should be explored. Furthermore, the contrasting approaches used across the studies of, firstly, only enumerators recording the diary data and, secondly, only participants doing so, may have led to unrecorded events and errors, and could be improved by a blended approach to reduce the burden on both parties. Participants could record simplified data which is then collected by enumerators at convenient times. The Simli and TRIID studies provided detailed cooking practices data, including quantities of ingredients and water in cooking events, which increased the effort required from HHs. Having obtained detailed datasets, future studies can omit arduous tasks such as weighing ingredients and measuring water quantities, with typical recipes now well understood.

Furthermore, the studies were limited by their length and approach, partly due to available resource. A longer period of transition phase data collection would have allowed participants more time to adapt to the electric stoves and therefore provided greater insight into the transition. Encouraging HHs to use their electric cookers as much as possible during the transition phase may have encouraged and enabled high levels of usage and confidence in the cookers, but may have obscured natural, settled usage patterns. The brevity of the studies meant that comparing data between phases was problematic due to external factors such changes of season and school holidays. The feedback from the exit surveys in the TRIID study and estimated electric cooking usage fractions gave indications of settled usage levels. However, an extended study could collect more data and capture usage patterns after a period of months, when cooks are likely to have settled into adapted cooking habits and their preferred usage fractions of electric cooking and other cooking fuels, as well as during the transition.

Neither study was able to determine how much electricity cost affects usage and causes fuel stacking, as there is no tariff system in Salyan, and as both studies were too short for monthly bills to affect usage, with perceptions of costs gained instead from surveys, and perhaps affecting levels of electric cooking in Simli before participants could make informed decisions. Increased data collection periods could enable deeper insights.

An extended study could also generate longer electrical system datasets, alongside extended cooking diary data, to enable the effects of each on the other to be analysed, and generate further insight into MHP electrical system behaviour across seasons. Rather than energy meters, HH data loggers could be used to record electric cooking power consumption data and HH voltage data, as well as energy requirements, to enable comparison of powerhouse and HH load and voltage profiles, generating improved understanding of the aggregate demand of electric cookers and their scalability. It was not possible to source such data loggers at the time of the study.

The usability of the electric cooking systems in the Simli and TRIID studies was affected by the lack of extra cookware and difficulty keeping cooked dishes warm. Future studies could trial EPCs with two interchangeable interior pots and/or insulating containers to maximise the comfortability of participant cooking experience, revealing the full extent of EPC penetration potential for Nepali cooks.

A notable barrier to reducing wood stove usage in MHP communities identified in the studies was animal food cooking. Some people use the same wood stove for meals and animal food, located inside the house. The research team advised one family in Salyan to create a new wood stove outside for cooking animal food, and during the exit survey they remarked that having a smokeless kitchen was a key advantage of electric cooking. Raising awareness of the dangers of indoor air pollution from biomass cooking will be important to encourage HHs to move their animal food stoves outside. The reduction in wood consumption in Salyan after the introduction of electric cookers did not take wood used for animal food cooking into account, as this data was not captured in either phase.

HHs who keep animals, which is a large proportion of rural HHs, must continue to collect large quantities of wood, and it is culturally essential that animal food is cooked rather than served cold. Nevertheless, wood collected for meal cooking clearly reduced significantly, and participants reported HH smoke level reductions. Future studies should obtain data on health of participating HHs and smoke levels, at the start and end of the project, to better understand impacts of the transition.

The studies provided knowledge and understanding that can be applied to any mini-grid context in Nepal and other similar countries. All contexts with similar menus and similar electricity demand patterns, i.e. concentrated activity in peak times, would benefit from the data and insights obtained on cooking practices and the limited scalability of electric cooking due to coincident cooking windows. Key indicators of mini-grid suitability for electric cooking have been generated, including the available spare power and energy for cooking; MHP mini-grid stability under high peak loads; coincidence of cooking windows with peak community loads; variation in generation and load data over the year; planned future loads; cooking fuels and costs/supply; electricity tariff; and MHP team competency. A tool to enable a macro assessment of MHP mini-grids could be developed and used by Nepali government actors such as AEPC or NGOs such as PEEDA, which uses these indicators, to identify MHP sites that are currently capable of supporting electric cooking, and pathways for MHP sites to be suitable to integrate electric cooking.

Further cooking diary and electrical data collection studies should be performed, in other areas and in different seasons, to generate more data on Nepali cooking practices, the behaviour changes required to transition to electric cooking, and MHP mini-grid behaviour. In the TRIID study, two induction hobs broke down in mid-January and were repaired in the PEEDA office in Kathmandu, a day’s travel from Salyan. Investigations into institutional support needs, such as electric cooking service centres for repair and maintenance, and supply chain management, will be necessary to provide a firm base for electric cooking to grow within both urban and rural Nepal, and prevent reversion to wood cooking.

3.7 Summary

In this chapter, two cooking diaries studies investigating the feasibility and acceptability of electric cooking in rural Nepali MHP communities were outlined and their findings summarised. Overall, it was found that electric cooking is feasible but that there are cultural, economic and technical barriers to its widespread adoption. Generally, it was found that electric cooking was accepted into the daily cooking practices of the participants, who generally adapted to the electric cookers and enjoyed using them, appreciating the benefits of easy, smoke-free cooking and the ability to multitask. Participants who were more willing to experiment cooking different dishes on the induction hobs and spend time trying to adapt to the new technology were able to make a more complete transition to electric cooking.

However, the significant level of fuel stacking during and, especially, since the studies is evidence that a transition to a new cooking fuel is far from straightforward, and that a total switch is unrealistic, at least at first. Fuel stacking was common due to a variety of factors, including: cultural inertia in existing cooking practices; certain dishes being easier to cook with other stoves; to save time by cooking concurrently, which was encouraged and enabled by the electric cooker; due to a perception or the reality of unaffordability; for warmth provided by wood stoves in colder months; and due to power supply instability. Two electric cookers could enable electric stove stacking and the use of electricity for the majority of cooking. With one electric cooker people choose between faster cooking and smokeless kitchens, whereas two could enable both.

Limited power generation capacity and high peak loads led to brownouts, which also caused fuel stacking. People cook at similar times as each other and as the community electrical load peaks, and reduced flow in the dry season lowers generation capacity, exacerbating the problem. The ADMD of the total electric cooking profiles was always significantly less than maximum coincident demand but, generally, there was not enough spare power in the mini-grids during peak times for any further electric cooking, even with only 1-2% of HHs in the communities provided with electric cookers, showing that the scalability of electric cooking in MHP communities is low. Running costs of electric cooking are approaching affordability according to study participants and generally provide savings compared to equivalent time costs of firewood collection and, in some cases, LPG costs. However, upfront cooking system costs are prohibitive.

Overall, a combination of technical solutions, such as energy storage and DSM measures, and financial mechanisms would be required before electric cooking can be adopted on a larger scale. This conclusion is applicable to all micro- or mini-grid systems with limited capacity. Efficient cooking devices such as EPCs could reduce electric cooking loads. Limitations of the cooking diary methodology were identified and improvements taken forward to assess the potential of EPC cooking in MHP communities. The datasets and knowledge generated in this chapter are taken forward to the techno-economic modelling outlined in Chapter 5, where they are used to model electric cooking loads, essential for understanding the impact of electric cooking on the financial sustainability of MHPs and the estimated load profile of increased adoption of electric cooking.

Chapter 4

Efficient electric cooking devices (ECO study)

4.1 Introduction

The Simli and TRIID cooking diary studies described in Chapter 3 showed that, while electric cooking is feasible in rural Nepal, solutions such as DSM measures and energy storage would be required to increase the feasibility of widespread uptake of electric cooking in MHP mini-grids. The studies also revealed limitations of the employed methodologies. This chapter presents a further cooking study, supported by the MECS Electric Cooking Outreach (ECO) Challenge Fund with funding of £60,000, hereon referred to as the ECO study, which aimed to understand the suitability of EPCs for Nepali cooks, thereby assessing the potential of the DSM solution of efficient devices, through peak clipping and demand reduction, to enable increased uptake of electric cooking. Figure 4.1 shows a study participant using an EPC.

Figure 4.1: An ECO study participant using their EPC.

The previous studies showed that Nepali cuisine heavily relies on boiling for rice, dal and water heating, which is often done in manual pressure cookers, and light frying for vegetables and meat, making EPCs a suitable option for investigation. The ECO study partly addressed research objective 4 on exploring solutions which could enable increased uptake of electric cooking, while also contributing to research objectives 1-3, gathering more data from new HHs on the current cooking context in Nepal, and investigating the transition to electric cooking from social and technical perspectives, this time for EPCs, using refined study methodologies. The study was conducted in Salyan, Solukhumbu, the same community as the TRIID study.

While primarily addressing efficient devices and their potential to reduce demand, the ECO study was also able to explore other DSM strategies by analysing the effect of load shifting of industrial end uses, which was implemented by the community following advice from the project team, and that of peak clipping and demand reduction by encouragement of HH electrical energy saving practices.

4.2 Research context

The ECO study considered new aspects of the transition, including the long-term acceptability of electric cooking, acceptability with only basic training and limited support, and measured HH load profiles. The long-term acceptability of EPCs in rural Nepal was assessed using an improved cooking diary study methodology which collected data over an eight-month period and included a third intensive two-week monitoring phase, the Endline phase, at the end of the study. HH data loggers which measured power consumption and voltage were installed in each HH and provided EPC cooking load profiles for the duration of the study, while MHP electrical system data was also collected for the extended study period. Therefore, the study was able to investigate the level of assimilation of the EPCs into the daily life of the participants after a period of adaptation, capturing settled cooking habits in the endline phase including EPC usage fractions and accompanying fuel stacking levels. The first research question explored in this chapter was, therefore:

1. How suitable and acceptable are EPCs for Nepali cooks on a long-term basis?

Within this research question, the study addressed the most important areas identified in the previous cooking diary studies, for EPCs this time, generating understanding of how acceptable EPCs are in terms of: compatibility with Nepali cuisine, including menu and cooking durations; initial and settled EPC usage fractions and accompanying fuel stacking; concurrent cooking capability; and energy requirements and cooking fuel costs;

while obtaining participant opinions through surveys. The ECO study also included the provision of insulating pots (hot cases) and extra EPC inner pots to HHs in the endline phase, to assess their usefulness for keeping food warm and enabling easier consecutive EPC dish cooking.

The study also investigated the acceptability of electric cooking in a ‘rollout’ style intervention, where the device is provided to HHs along with basic training and demonstrations, but no further support extended to them, and cooker usage monitored remotely through HH data loggers. The cooking diary study methodology is resource- and time-intensive and therefore unrealistic for large groups of HHs and, with billions of people without access to clean cooking globally, most transitions will lack external, in-person support. Therefore, the second research question explored in this chapter is:

2. How much will EPCs be assimilated into rural Nepali cooking practices with basic training and limited support?

The ECO study further improved on the previous studies by using HH data loggers, provided by A2EI and described in [158], [206], to capture real, high resolution cooking load data, enabling quantification of the ADMD of HHs cooking with EPCs in rural Nepal and its variation across days and months. HH logger data and powerhouse logger data were analysed to: understand the effects of the EPCs on the electrical system in terms of voltage stability and on the community load profile; investigate community load profiles and EPC load profiles and their variation, including the effects of additional DSM measures of load shifting of industrial machines and demand reduction by HH electricity saving practices; and assess the current scalability of EPCs in MHP communities. The third research question was:

3. How do EPCs affect the MHP system and contribute to the community load?

As EPCs are efficient cooking devices, which do not draw constant power from the mini-grid for the duration of cooking due to their insulation, it was important to understand the load profiles of groups of EPCs to assess their potential for enabling increased adoption of electric cooking. The HH logger and electrical system data analysis also provided further insight into the results of the cooking diary study.

4.3 Project overview and improved methodologies

The ECO study discussed in this chapter took place within a wider project which included a second, concurrent cooking diary study, which was conducted in an on-grid community in South Lalitpur, near Kathmandu, as well as a Nepali EPC market assessment to determine the availability and suitability of EPCs in Nepal, and the development of an eCookbook to support cooks with simple Nepali cooking recipes for EPCs [70]. The MECS-ECO report contains the full details of every aspect of the project [207].

This thesis concentrates on the cooking diary study conducted with 30 HHs in Salyan, Solukhumbu, from January to August 2021, the subsequent rollout study conducted with 20 different HHs, also in Salyan, from November to December 2021, and the electrical system and cooking load profile data collection over the study period. Cooking diary data, MHP electrical system data and HH logger data were analysed and combined to address the research questions specified in Section 4.2. The methodologies used were essentially the same as those detailed in Chapter 3, with some notable extensions and improvements, which are outlined in this section, after the other useful aspects of the overarching project are briefly explained.

4.3.1 Market assessment, laboratory tests, eCookbook

In the market assessment, six EPCs available in the Nepali market were evaluated by visual inspection and laboratory water boiling tests to assess usability and efficiency. Electron, Philips, Geepas, Baltra, Urban, and Kenwood were the six brands found in the Nepalese market at a price of below NPR 12,000, with power ratings between 0.85 kW and 1 kW range [207]. The Urban EPC, rated at 0.96 kW, was selected as the most suitable for the project, with high efficiency, fast cooking time, and a robust design [207].

Controlled cooking tests (CCTs) were conducted across different cooking technologies for three traditional Nepali dishes: rice, dal, and chicken curry, finding that cooking with an EPC required less than half the cost of LPG and firewood cooking [207]. Generally, laboratory tests on EPC cooking revealed how to cook the staple dishes in EPCs: boiling dishes include a preheat period followed by little or no extra power input due to the insulation, and frying dishes demand nominal power more frequently to maintain the temperature above a setpoint while the EPC lid is off [207]. Tests were also conducted at lower voltage to assess the load profile of EPC cooking. Figure 4.2 depicts the results for rice cooking in an Urban EPC at nominal voltage and 180 V, showing that the preheat phase increases from around 12 minutes to 18 minutes at reduced voltage, and that in each case power is pulsed once during the cooking phase to maintain the required temperature [207].

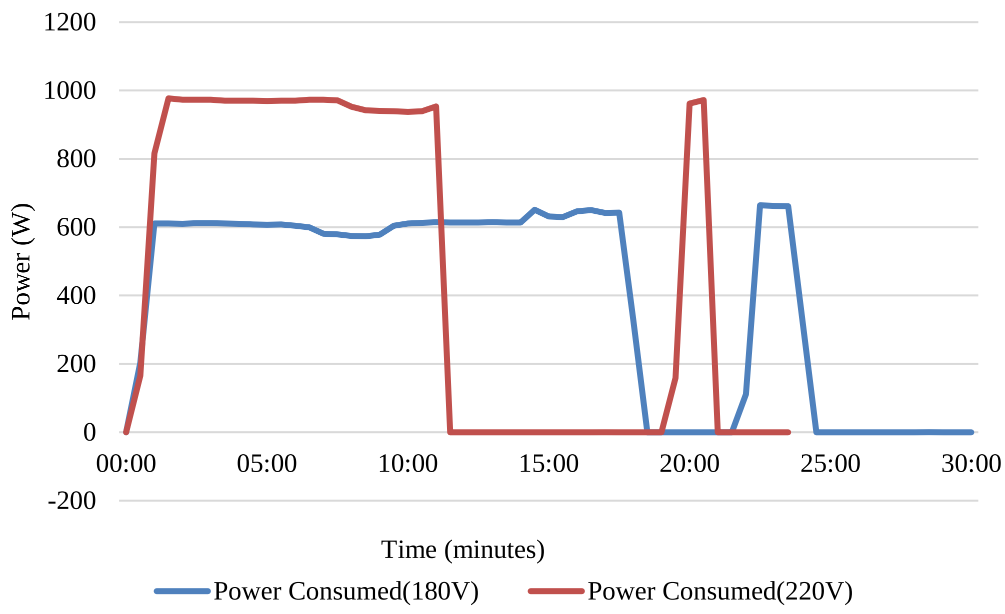

Figure 4.2: Measured load profile of an Urban EPC at nominal and reduced voltage during rice cooking, reproduced from [207]**.**

Through the experiences cooking with EPCs, the project team developed an eCookbook. The book included comparisons between the different cooking technologies available in Nepal and a series of recipes to cook with an EPC [70].

4.3.2 Cooking diary study

Salyan was chosen for the ECO study due to the good relationships developed by the research team with the MHP committee during the TRIID study, and the assurance from committee members of sufficient spare capacity in the mini-grid for additional electric cooking. The spare capacity was increased by the MHP committee by the introduction of DSM measures around the beginning of the transition phase, when the electric cookers were introduced, which included shifting mill usage to the afternoon and encouraging HHs to use less electricity.

Cooking diaries and monitoring

The study featured the following phases:

- Baseline – intensive data collection capturing existing cooking practices
- Transition – intensive data collection of initial EPC usage patterns
- Remote monitoring – remote monitoring and support over a five-month period
- Endline – intensive data collection after 6 months of EPC ownership

During the remote monitoring phase, the research team conducted regular phone calls with participants to understand how they were using the EPCs and provide support where necessary. The three intensive data collection phases were each two weeks in duration and aimed to capture cooking practices at specific points in time. The baseline phase took place, as in the TRIID study, before the EPC intervention, enabling comparison across phases. The transition phase began soon after the HHs had been provided with the EPCs and training on how to use them, once they had become comfortable cooking staple dishes in the EPC, to capture initial EPC usage habits and any changes in menu compared to the baseline phase. Finally, the endline phase aimed to understand how HHs used the EPCs once enough time had elapsed that they had assessed the usefulness of the device and incorporated it into their cooking stove mix to their desired degree.

In a slight, but important departure from the TRIID study, HHs were only encouraged to use the electric cookers as much as they wanted to, rather than asked to use them as much as possible. In the TRIID study, participants were asked to use their electric cookers as much as possible, because the brevity of the two-week transition phase of data collection meant that the priority was to understand how compatible the induction stoves were with Nepali cuisine and encourage usage. In this ECO study the participants were encouraged to use their electric cookers as much as they wanted to, not as much as possible, because the extended study period and its extra, endline phase, enabled determination of settled usage habits as well as dish compatibility.

Participants were asked to pay a discounted price to receive the EPC at the start of the transition phase and continue to participate in the study. All HHs paid the NPR 3,000, 40% of the market price of NPR 7,500, in a measure which aimed to test participant interest in the cookers and develop a sense of ownership which could increase their usage and care of the EPC.

The cooking diary methodology was refined based on lessons from the previous projects, the MECS cooking diary study protocols and advice from MECS researchers [208], [209]. The KoBoToolbox platform was used to create digital cooking diaries, assimilated from the TRIID cooking diaries and a new MECS template and localised for Nepali culture, as presented in Appendix A2.1 [210]. Participants were provided with paper ‘notepad’ forms, see Appendix A2.2, on which they recorded simple information about their cooking activities, including time, dish, stove, energy and number of people. Enumerators visited each HH once per day, entering cooking diary data from the previous day into the cooking diaries on a tablet, by discussing the participants’ cooking activities and eliciting greater detail from them where possible, on leftovers, reheating, usage of lids and cookware, and any extra comments on their cooking experiences.

This strategy aimed to reduce the data recording burden for participants and enable enumerators to visit the HHs at convenient times, rather than needing to be present at mealtimes. The diaries were simplified compared to the TRIID study by removing the imperative to weigh food and water quantities, and by asking for quantities of wood for cooking at the beginning and end of each day only, generating datasets of daily wood requirements which are sufficient for understanding reductions enabled by the addition of electric cookers.

As in the TRIID study, participants were selected based on advice from the MHP secretary, fulfilling the criteria of sufficient literacy level for recording data on the notepad form and a high level of interest in trialling electric cooking. Members of the local community who were enthusiastic about the study, had good communication skills, and were computer literate and therefore able to use Kobo effectively, were selected to be enumerators and received intensive training for high-quality data collection. The main cook in each HH was trained on using the EPC and on recording data on the notepad form. Additionally, short videos on how to cook the staple dishes in an EPC were shared with participants, and an EPC usage brochure was distributed to familiarise them with the various functions of the EPC, including which settings to use for each dish.

A live cooking demonstration event was organised in each of the three clusters where the participants were located. The main cooks and enumerators were encouraged to use the EPC during the event to understand its operation, in the presence of members of the research team, who provided guidance and support. The researchers supported the participating HHs and enumerators both onsite, during the intensive data collection phases, and remotely. The data collected by the enumerators was stored on the KoBoToolbox platform and was regularly checked and verified for quality.

At the start of the endline phase, to gain greater insight into participant cooking experience with EPCs and investigate potential improvements, hot cases were distributed to all HHs, and five HHs were provided with an additional EPC inner pot, with the aim of evaluating their effectiveness in keeping food warm during meal cooking and assessing their potential to enable easier consecutive EPC dish cooking. Digital registration and exit surveys, as presented in Appendices A2.3 and A2.4 were also created in Kobo and conducted to gain deeper insight into participant experiences, including on health issues and smoke levels before and after the introduction of electric cooking, in a further improvement on the TRIID study.

Community and HH electrical data collection

Alongside the cooking diary phases, mini-grid powerhouse electrical system data was collected for the duration of the study, generating a much longer dataset than that obtained in the TRIID study, using the same methodology outlined in Section 3.3.2. Importantly, HH data loggers, provided by the Access to Energy Institute (A2EI), were installed in the homes of the participants and recorded data including current and voltage readings, whenever there was a change in the current drawn by the EPC. The loggers measured data for the duration of the study, except when the mini-grid was down, which was uploaded to an online platform and processed by A2EI, enabling remote monitoring of EPC usage by the research team. The current and voltage records were used to calculate power consumption of the EPC, and the datasets processed and resampled to 1-minute resolution, generating HH and total cooking load profiles, which were analysed using Python. Capturing HH voltage data was another improvement on the TRIID study and enabled comparison between powerhouse and HH voltage profiles, providing understanding of typical voltage drops across the transmission lines.

The processing of the raw HH logger data, which was conducted by A2EI, included the following steps:

- Changing zero voltage records to missing values, recalculating the power from the voltage and current, and marking the records when the connected appliance seems to be active (in use) based on changes in energy consumption
- Extending the dataframe within cooking events to one-minute resolution using the values from previous records
- For missing power and current values, within cooking events, assigning the average cooking event power and current values
- For the very rare events with no valid values (approximately 1%), assigning an average power value of 0.51 kW

The loggers identified cooking events based on measured changes in energy consumption and calculated event and daily energy consumption. Appendix A2.5 outlines the cooking event definition along with further detail on the data cleaning and processing conducted by A2EI. The cooking diaries also included fields for entering daily electrical energy consumption readings, which were obtainable from the HH loggers by changing the display setting. It was hoped that participants would be able to record their daily electrical energy consumption of the EPCs on their notepad forms, but it was found that the coverage of the resulting data was variable due in part to the loggers not automatically displaying the energy reading, requiring a change of display settings to obtain it.

4.3.3 Rollout study

The rollout study was conducted with 20 different HHs, also in Salyan, from November to December 2021. HHs purchased the EPCs at a reduced cost of NPR 4,000, and A2EI loggers were installed in their homes to record their EPC usage including event frequency and duration, energy consumption load profiles and voltage. The EPCs used in the rollout phase were Electron EPCs, rather than Urban EPCs, due to the research team being unable to source more of the Urban model due to supply issues of the brand. The Electron EPC, rated at a slightly lower 0.9 kW, also scored highly on the market assessment.

Participants were self-selecting, with the research team receiving guidance from the enumerators on identifying community members who were interested in transitioning to electric cooking. EPC cooking demonstrations were conducted with groups of HHs on how to use the EPC, after which the participants were left to their own devices, with remote monitoring conducted by the research team through the A2EI data. Powerhouse MHP electrical system data continued to be collected during the rollout study period, enabling understanding of the effect of increasing the number of HHs with electric cookers on the MHP system and community load profile.

4.4 Results of ECO study

The results of the ECO study are presented according to the research questions, after which the key points, limitations, and implications for further work and discussed.

4.4.1 How suitable and acceptable are EPCs for Nepali cooks on a long-term basis?

Cooking diary data overview

Table 4.1 summarises the key averaged quantitative data from the cooking diary study. The data shows that the EPC was used significantly and consistently across the study period, nearly twice per day on average, and that, once EPCs were introduced to the community, the participants were able to save on average over half an hour in cooking time, and were using less than half as much firewood for cooking by the end of the study, reducing from 138 kg to 62 kg per fortnight on average. Participants generally reported that EPC cooking is easy, cited the ability to multitask and save on wood as important benefits, and said that they would continue to use the device every day. They appreciated the time savings enabled by the EPC and being able to leave it safely to cook by itself.

For example, one HH reported being able to *"cook daily food items in a smart way and use the time to do other HH stuffs"*, while another appreciated being *"able to go anywhere without worrying about food being burnt."*

Table 4.1: Summary of data from cooking diaries in ECO study.

Parameter	Baseline	Transition	Endline
EPC events per day	-	1.8	1.78
Daily cooking time (hours)	3.90	3.28	3.20
Heating events per day	3.74	3.51	3.30
Dishes per meal	2.14	1.95	1.77
People per HH	4.64	4.63	4.53
Wood used (kg) (total/HH)	3,713/138	1,986/74	1,483/62
EPC energy consumption per HH (kWh/day)	-	0.5	0.45

The cook mostly remained the same member of the HH, with most meals being cooked by the female head of the HH, showing that having the EPC did not encourage any shift in gender norms. However, the new technology, which is more dissimilar to traditional cooking methods than induction stoves, was comprehensible for some older family members as well as younger, more technologically literate members, with one participant reporting that their *"old mother has learned to cook rice in the EPC by herself now. She is empowered in a way. Cooking is faster now."*

Sixteen HHs reported health improvements in the exit surveys compared to before the intervention, for example, one HH said: *"Eyes get burn less. Headaches were often before with smoke now it's very less".* The surveys also revealed reductions in smoke levels in the kitchens of some HHs, with the majority of HHs reporting mild smoke in the endline phase as opposed to very dense smoke before the introduction of the EPCs, likely due to reductions in the amount of wood being collected and burnt for cooking, as depicted in Figure 4.3. Therefore, this study was able to provide evidence for a link between reduced smoke due to reduced wood stove usage and improved health.

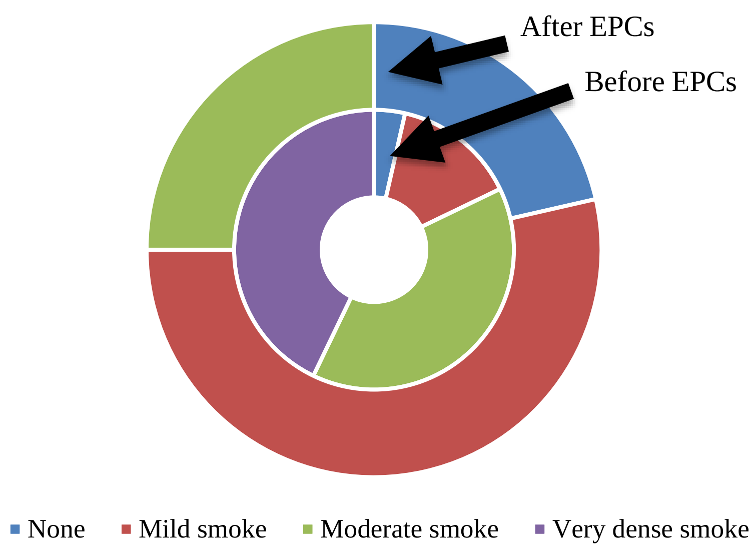

Figure 4.3: Doughnut chart showing how smoke levels changed across the duration of the study, before (inner) and after (outer) the introduction of EPCs to the community.

Figure 4.4, provided by A2EI, shows the variation in cooking events and total cooking energy consumption across the EPC usage study period, from the transition phase in late February and March to the endline phase in August [207]. It was found there was an overall mean of 1.44 events per HH per day, with an average daily HH energy consumption of 0.48 kWh, which would cost NPR 3.4 per day under the proposed tariff system of 7 NPR/kWh. The chart shows that there was reasonably consistent usage of the EPCs over the intervention period. The drop in events and HHs using their EPCs in early June was likely due to data loss during a period of MHP downtime, in which some HH loggers were unable to record data.

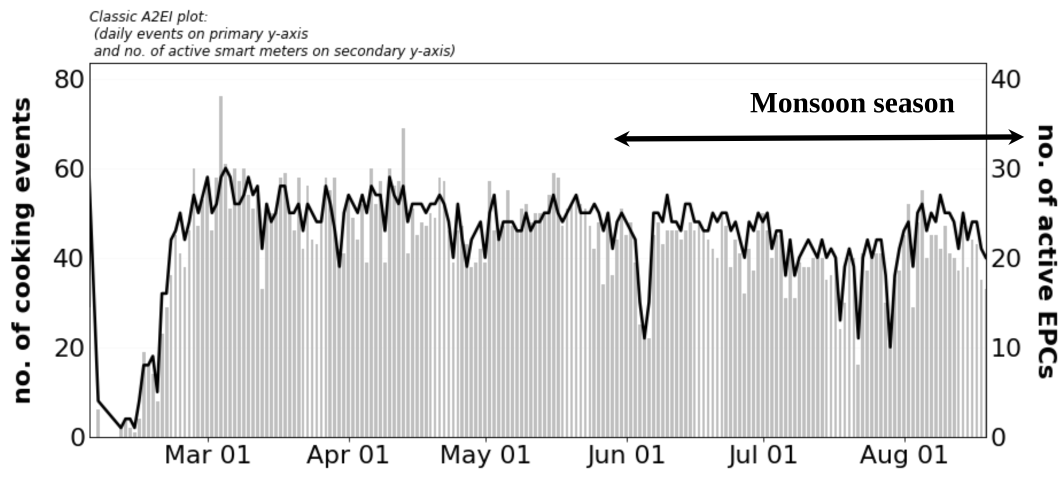

Figure 4.4: Number of cooking events (grey) and HHs actively using their EPCs (black line) across the study period, with the monsoon period highlighted. Figure provided by A2EI.

There was a slight drop in usage during the monsoon season, from June to August, which explains the reduction in the overall mean EPC events per day compared to during the transition and endline phases, from around 1.8 to 1.44. The fixed capacity of the EPCs restricts the amount of people it can cater for, so when feeding large groups, such as during the rice planting and harvesting time, some HHs reverted back to their firewood or LPG stoves. Furthermore, some HHs reverted to biomass in order to cook simple and quick meals due to being busier with work, simplifying their menu and using cooking methods they were completely comfortable with, as reflected in the slight reduction in dishes per meal in the endline phase included in Table 4.1. However, compared to July, Figure 4.4 suggests an increase in EPC usage at the start of the endline phase in August, likely due to the intensive data collection encouraging the participants again, and researchers being present to provide support.

Overall, the data shows that EPCs were assimilated into daily life for the participants, revealing that their settled cooking habits included a similar level of EPC usage at the end of the study as at the beginning, of just under two usages per day on average.

Menu and dish compatibility

Figure 4.5 shows the most common dishes cooked across the phases, with small increases in the relative frequency of rice and vegetables, and slight reductions in dal over the intervention, due to the simplification in menu.

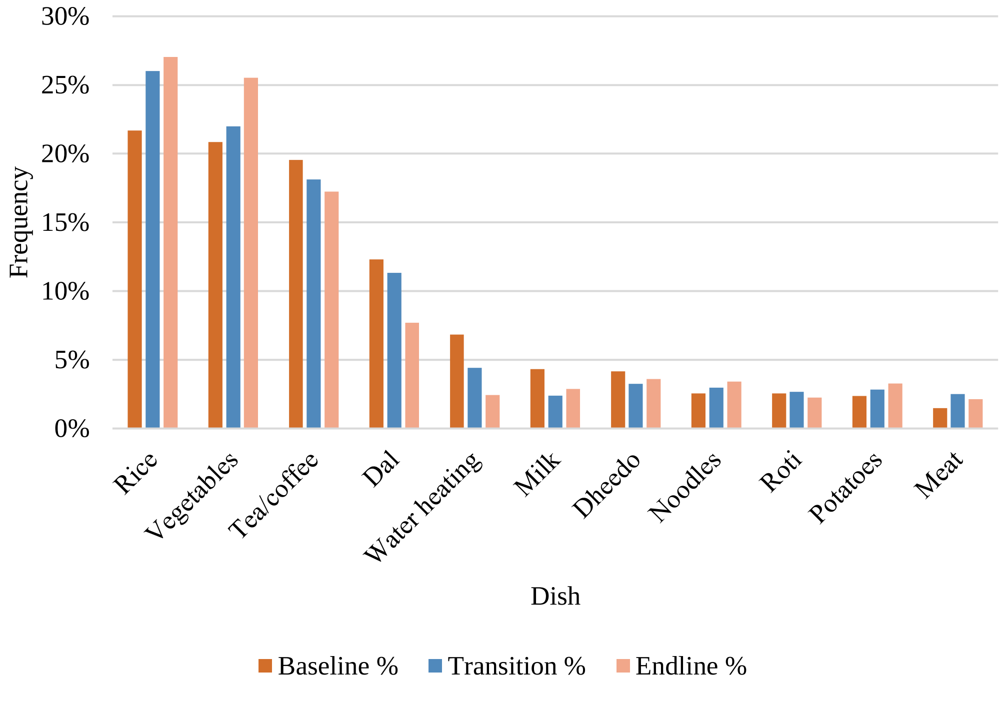

Figure 4.5: Relative frequencies of dishes commonly cooked across the study phases.

Generally, the menu was very similar in the ECO and TRIID studies, increasing confidence in the research outcomes for objective 1 on understanding the rural Nepali cooking context. The meals cooked were generally similar across the phases in the ECO study, with rice-vegetables and dal-rice-vegetables the most popular.

The EPC was mostly used to cook rice, with participants finding EPC rice cooking easiest and most comfortable, comprising almost 80% of dishes cooked with the EPC in the electric cooking phases. Dal was also cooked regularly in the EPC by some HHs, making up around 10% of EPC dishes, while vegetables, noodles, potatoes and water heating together represented the remaining 10% of EPC usage. In the exit survey one participant outlined their settled usage of their EPC, reporting that they were *"so used to cooking Rice in EPC that I don't like cooking it in other stoves at all."* Figure 4.6 shows the relative usage of the EPC and fuel stacking (FS) using other stoves for each dish across the phases.

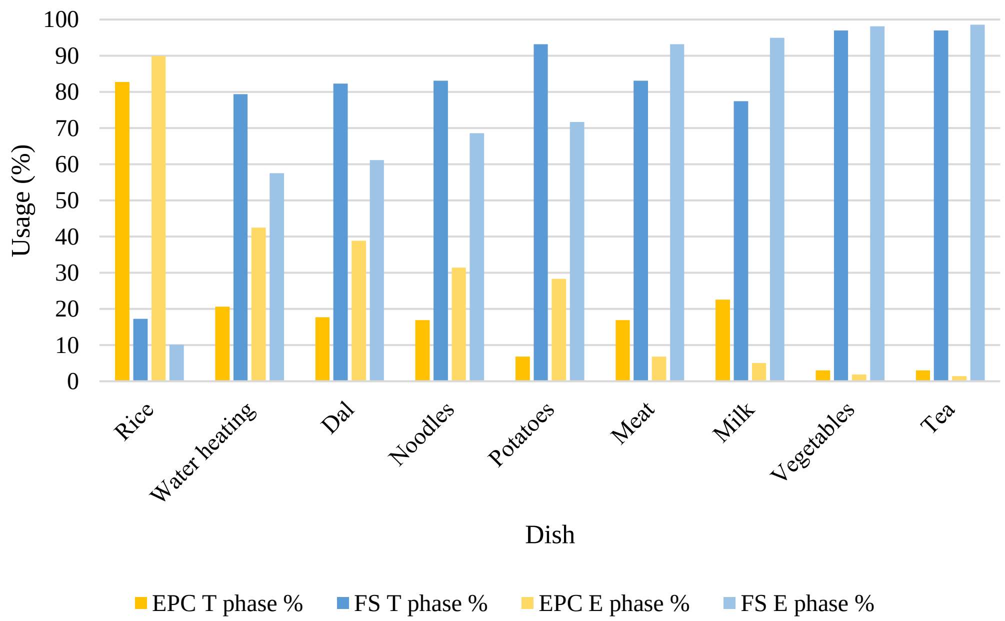

Figure 4.6: Percentage of each dish cooked in the EPC or a fuel stacked (FS) stove during the Transition (T) or Endline (E) phases.

Almost all participants reported that rice is easy to cook, most thought the same of dal and water heating, while there were a mix of opinions for vegetables, meat, potatoes, and noodles. Roti was reported to be hard to cook with the EPC, due to difficulty accessing the roti as it cooks, which was already known. Several HHs reported that frying vegetables in the EPC was difficult as the oil did not reach a high enough temperature, which is due to temperature feedback mechanisms limiting the maximum temperature achievable in the EPC. Some participants were reluctant to cook frying dishes which require stirring, such as vegetables, due to lacking a suitable utensil such as a wooden spatula which would enable them to stir hot food without damaging the EPC inner pot.

Although rice was nearly always cooked in the EPC, some HHs also experimented with cooking other dishes, evident in the increases in the proportions of water heating, dal, noodles and potatoes in the EPC in Figure 4.6, showing that some HHs became more adventurous in their EPC usage across the study period. HHs self-assessed the usefulness of the device throughout the study and used it accordingly, as found in the TRIID study, with those more willing to experiment more likely to use the EPC more often and for more dishes**.**

However, generally HHs found the EPC to be useful for a narrow range of dishes, chiefly rice and dal, perceiving that it lacked the versatility to be used for a higher proportion of their menu. As found in both of the previous cooking diary studies, fuel stacking was common, for several reasons, including: being accustomed to existing cookstoves and practices, unsuitability of EPCs for some dishes; preference for other stoves for some dishes; to enable concurrent and therefore faster cooking; and due to power supply issues such as brownouts and blackouts.

Fuel stacking

Figure 4.7 shows that the EPC was used for around 30% of cooking events, significantly reducing firewood consumption for the participants, who appreciated the benefits of reduced smoke, and leading to a slight increase in LPG usage as well as electricity. Although the EPC usage was only 30%, it displaced 55% of wood usage, shown by the reduction of firewood consumption, showing that the displaced cooking events are energy intensive. There was significant variation between HHs in their usage fractions of the EPCs, suggesting that some felt more comfortable using the EPC than others and were able to integrate it into their daily routine. One participant reported that usually they *"cook with EPC and gas only, completely abandoning the use of wood. Only when family members increase we burn wood. Rice in EPC and dal in LPG"*.

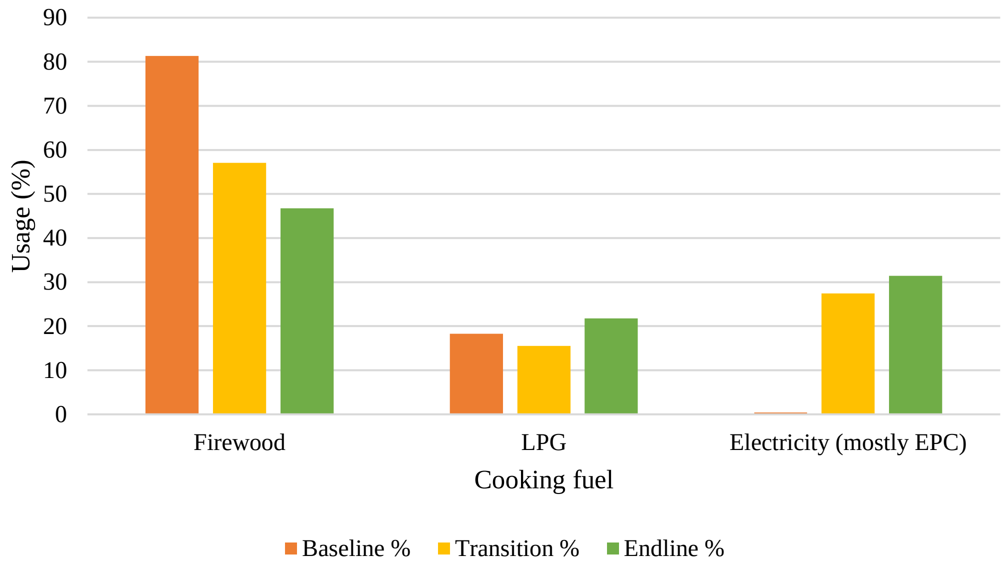

Figure 4.7: Cooking fuel choice for cooking events across the study phases.

Two HHs transferred all of their wood usage to LPG from the transition to endline phase, cooking with a clean cookstove stack of EPC and LPG stove, while six other HHs reduced their wood stove usage while increasing their usage of LPG, suggesting that many HHs prioritised having a less smoky kitchen and reducing firewood collection requirements over saving on LPG costs. This was backed up by survey responses: of the eleven HHs which either transferred some or all of their wood stove usage to LPG, or only ever used LPG for cooking, even in the baseline phase, seven reported that having a smokeless kitchen was their top priority, ahead of optimising the cost, speed, ease and taste of cooking. The speed and ease of cooking were priorities for the other four HHs, two commonly reported attributes of LPG cooking.

Overall, between the transition and endline phases, over 50% of HHs increased their usage of the EPC, 16% had similar usage, and the remaining 30% reduced their usage. One HH increased its usage fraction to 73% of dishes, while no other HHs were using their EPC for more than 50% of their dishes in the Endline phase. Two HHs approximately halved their EPC usage between the phases, one citing increased work in the monsoon season as the reason, and the other blaming a fear of damaging the EPC.

An additional reason for fuel stacking not identified in the previous cooking diary studies was a fear of the device breaking if used too often or for more than simple EPC dishes, and being unable to repair it due to a lack of local repair and maintenance capability. Some participants, once comfortable cooking rice in the EPC and, in some cases, dal, preferred not to experiment with other dishes, perceiving a risk of damaging the device if they tried using other functions, such as frying mode, for other dishes. This reluctance to explore using the EPC for a higher proportion of their menu was unfortunate, as the research team tested cooking a wide range of dishes with the EPCs without issue, although 17 EPCs in the study did require maintenance or replacement during the study due to insect infestation, malfunction, or accidental damage. Some faults, such as malfunctioning buttons, required the EPC to be replaced, a difficult process due to the remoteness of the community, whereas others could be fixed by ensuring the weight valve was cleaned, the lid correctly aligned, and the device and cooking environment kept clean. Low voltage events, brownouts, sometimes caused error messages on the EPC displays. Cockroaches can be deterred by covering the EPC with a cloth when not in use.

Therefore, the study revealed the importance of local repair and maintenance capability for enabling the potential of electric cooking in rural areas to be realised. The lack of local after sales services meant that some HHs did not use the EPC as much as they would have liked to. For HHs to be able to rely upon electric cooking, they need a reliable product that can be repaired locally with limited downtime. A network of electric cooking service centres would increase confidence in the devices, and, in turn, create economic opportunities. Improving supply chains would also help consumer confidence by enabling increased availability of good quality, durable electric cookers.

Cooking durations

As in the previous cooking diary studies, dish cooking durations contributed to fuel stacking, with participants often finding the EPC too slow to use for multiple dishes per meal, and brownouts sometimes exacerbating the issue, increasing cooking times further. The cooking times for rice and dal increased from the baseline, as the EPC takes more time to cook these dishes than other stoves due to the period after the cooking is complete during which the pressure is released. Also, HHs sometime left the EPC to cook and so recorded longer cooking times than usual if they were not present at the point when cooking was complete. Figure 4.8 compares the cooking times across the phases for commonly cooked dishes.

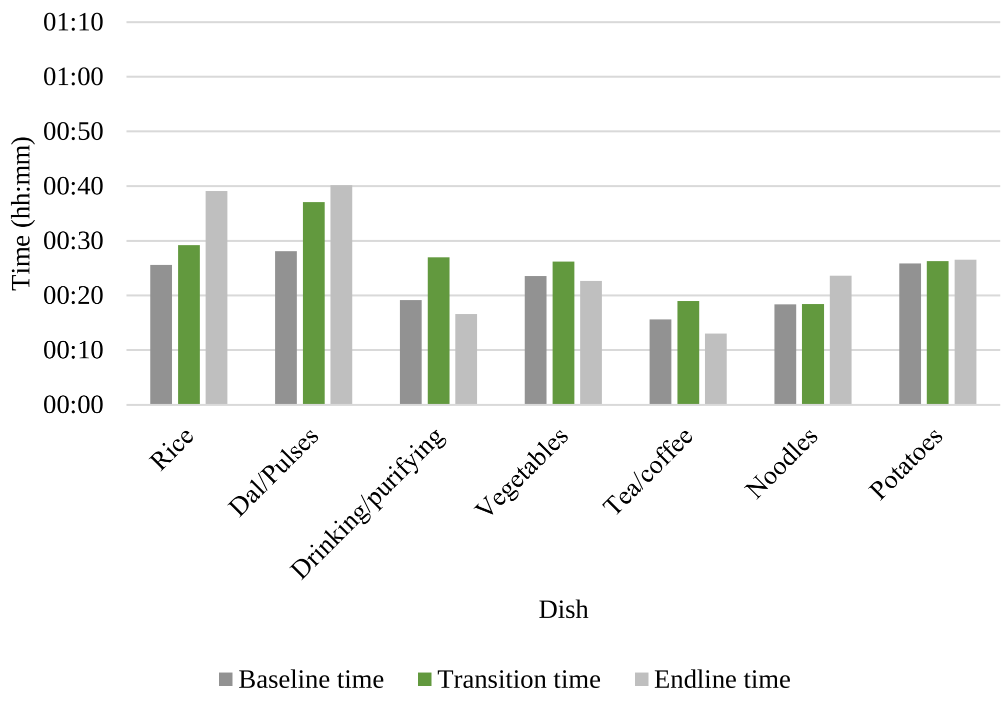

Figure 4.8: Mean cooking durations for commonly cooked dishes across the phases.

As detailed in the eCookbook, produced as part of the wider ECO project [70], the cooking processes for rice and dal are similar, featuring a preheat period of around 10-15 minutes depending on water and food volumes in which the EPC reaches the target pressure, followed by a period of boiling at increased pressure for a further 10-20 minutes, and a final period of pressure release once the cooking is complete for 10-15 minutes. The quick pressure release option was available to the participants, but they mostly used the natural pressure release on the advice of the researchers due to better resulting texture and taste as the cooking continues during this period due to the temperature remaining high thanks to the insulation. EPC cooking times for rice and dal, depicted in Figure 4.8, therefore amounted to around 30-40 minutes, compared to closer to 25-30 minutes for wood or LPG cooking, and around 25 minutes for induction stove cooking in the TRIID study.

A small number of HHs noted that EPC cooking was “time-consuming” or “takes more time”. Clearly, EPCs save time on firewood collection and lighting a fire for cooking. However, there is also a perception that wood and gas cooking are significantly faster, due to the visibility and controllability of the cooking flame, not needing to wait for the EPC pressure to be released, and, for frying dishes, EPCs not reaching high temperatures. Therefore, even though very few participants reported that the EPCs were slow, the slightly increased EPC cooking times are likely to have limited their EPC usage fractions.

Furthermore, brownouts increased EPC cooking times further, compounding the issue and discouraging more frequent EPC usage, with one participant commenting that with *"low voltage... it takes lots of time to cook"*, and several reporting that the electricity supply needs to be "more stable", implying that brownouts caused EPC cooking to take too long and that blackouts rendered it impossible at times. In the exit surveys, 21 of 28 HHs reported that the electricity supply sometimes failed, with one HH explaining that *"sometimes the electricity is cut off while we cook."* When there was a supply failure, only three respondents said that they would usually wait until power returned and resume EPC cooking, with every other HH reverting to wood or LPG stoves. Therefore, as in the TRIID study, electrical system instability and outages caused increased cooking times and fuel stacking, reducing the potential penetration of the EPC into the participants' cooking fuel mix. One HH called for improvements to the *"reliability of the electricity"*, underlining power supply issues as a key barrier to electric cooking in MHP mini-grids. Section 4.4.3 investigates the mini-grid reliability using the electrical system data.

Concurrent cooking

A crucial way in which the EPCs did save time for participants was by enabling them to do other things while the EPC was cooking, which was cited by eight HHs as a key benefit. This included saving people time on HH activities, which they could now complete during EPC cooking, and enabling concurrent cooking on other stoves to reduce overall meal cooking times, as observed in the TRIID study. The increased EPC cooking times discouraged consecutive EPC cooking, which was less common than consecutive induction stove cooking in the TRIID study. Instead, the ability to cook concurrently between the EPC and another stove was another important driver for fuel stacking, with one HH reporting: *"Dal with LPG, Vegetables with wood and Rice in EPC. I cook all the 3 dishes simultaneously and it has saved me so much time"*. Figure 4.9 shows that concurrent dish cooking within meals increased from around 10% before the introduction of the EPCs to around 30% at the end of the study. This likely contributed to the fall in total daily cooking times seen in Table 4.1.

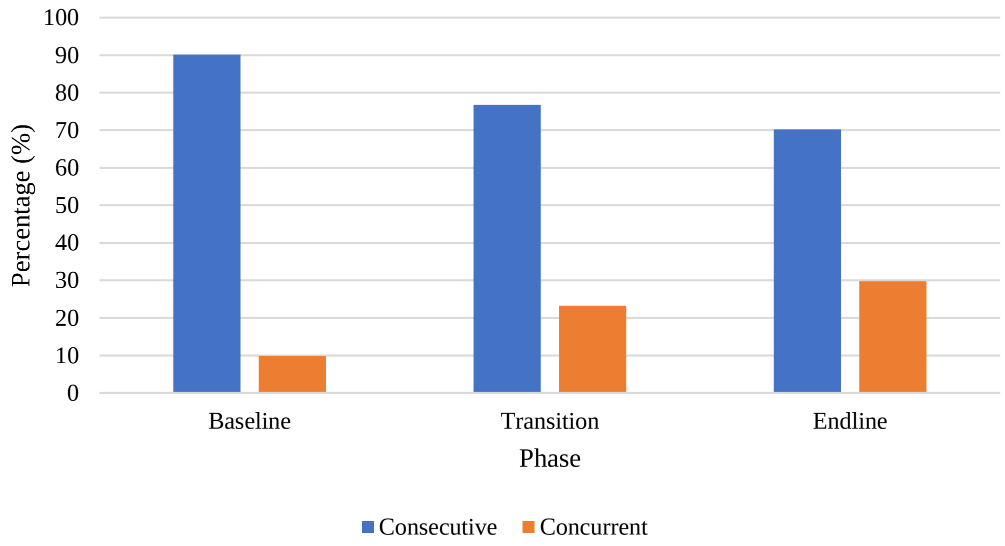

Figure 4.9: Percentages of meals with all dishes cooked consecutively versus meals with at least one dish cooked concurrently, across the phases.

Although concurrent cooking increased after the introduction of the EPCs, consecutive cooking was still common. As found in the TRIID study, consecutive cooking with firewood is common in rural Nepal for HHs with wood stoves who want to save firewood by lighting only one fire and cooking dishes sequentially on it. Some HHs prefer to cook dishes consecutively using their LPG stoves. Nevertheless, the provision of another cooker increased the range of cooking method possibilities for the participants.

The EPCs were often used alongside wood or LPG during meal cooking, usually for one or sometimes two dishes, with variation in practices between HHs. Consecutive cooking with the EPC was relatively rare, with some HHs doing so increasingly from the transition to endline phase and others reducing this behaviour. Five and seven HHs cooked more than one dish in their EPC within a meal a total of five or more times across the two-week transition and endline phases respectively, showing that the most common practice was to cook only one dish in the EPC per meal. Table 4.2 breaks down the way the EPCs were used in the two electric cooking phases, considering meals comprising at least two dishes.

Table 4.2: Breakdown of the number of dishes per meal cooked in EPCs.

Dishes in EPC per meal	Transition phase % of meals	Endline phase % of meals
0	42%	32%
1	51%	58%
2	6%	9%
3	1%	0%

There was a slight increase in the proportion of meals in which one and two dishes were cooked in the EPC between phases, with 10% fewer meals containing including no EPC usage at all. In the transition phase there were ten meals across five HHs where three dishes were cooked in the EPC, requiring high total meal cooking times, which likely discouraged this practice. Responding to a question in which they could select more than one option, half of the HHs said EPC consecutive cooking is worth it because of the benefits, while 29% said it is fine because they cook consecutively normally. However, 68% said it is inconvenient as it takes a long time and requires the inner pot to be cleaned between dishes. One HH reported that *"if we cook double then more time is required"*, showing that HHs often want to save time by fuel stacking so that they can cook dishes concurrently, with another saying: *"Easy cooking with EPC. I have lot of family members. I fuel stacked it with wood and doing this saves a lot of time."*

Hot cases and extra inner pots

Generally, to keep food warm, most HHs reported leaving the EPC switched on until they were ready to eat the dish that had been prepared. The 'keep warm' mode on the EPC uses a very small amount of energy, pulsing power at infrequent intervals, as confirmed in laboratory experiments by the research team. Then, after the introduction of insulating pots called hot cases, depicted in Figure 4.10, in the endline phase, HHs mostly used the hot cases every day to keep their food warm, transferring a dish that had been cooked in the EPC into the hot case while they reused it for another dish or used their other stoves to cook the remaining dishes.

Figure 4.10: Hot case provided to participants in the endline phase. Credit: Mahesh Shrestha

The provision of hot cases did not increase the usage of the EPC, based on the cooking diary data, but participants were very pleased to have them and reported that they were very useful and used frequently, storing dishes, such as dal or roti, whilst others were cooking. Hot cases may be even more useful in the winter, when the cold climate makes keeping food warm even more important. However, it is also possible that people will prefer not to transfer food from the EPC to the hot case in case heat is lost in the process, and will mostly cook one dish in the EPC per meal, keeping it warm by leaving it in the device until it is time to eat.

Five HHs were given additional inner pots at the start of the endline phase. It was thought that this might encourage consecutive cooking in the EPC, as the second inner pot could be used for the second dish, rather than the single inner pot requiring emptying and cleaning before being used again. However, this did not occur, with no change in the level of consecutive EPC cooking, and HHs generally preferring to cook concurrently by fuel stacking. Participants generally reported that hot cases are more useful than extra inner pots, although they were happy to receive both. Many HHs thought that extra inner pots would improve their cooking experience, but although they appreciated having them and being able to alternate their usage of their inner pots, the cold climate in Salyan meant that hot cases were preferred.

Participants could keep all dishes of a typical meal warm by cooking the first dish, putting it in the hot case, and then cooking the second and third dishes at the same time, so all dishes were warm when the meal was ready to be served. HHs did this using a variety of combinations of stoves. Generally, they did not find emptying and cleaning out the EPC inner pot inconvenient as the pots are easy to clean, although having a second dinner pot removes the need to do this immediately if cooking a second dish in the EPC. Crucially, consecutive EPC cooking was uncommon anyway, most likely due to the time saving opportunity of concurrent cooking across stoves and unsuitability of the EPC for many dishes. A second hot case could enable three dishes to be cooked consecutively in the EPC and kept warm, for HHs interested in a complete transition to electric cooking.

Generally, as found in the TRIID study, HHs choose between reducing cooking times, by fuel stacking and cooking currently, and reducing wood/LPG usage and therefore smoke levels and/or expenditure on these fuels, by cooking two or more dishes per meal in the EPC. Having two electric cookers, such as EPC plus induction, EPC plus rice cooker, induction plus rice cooker, two EPCs, etc, would encourage HHs to cook mostly with electricity, enabling concurrent electric cooking, as found in the TRIID study with induction cookers and rice cookers, although this would increase the load on the grid.

Energy requirements and costs

The mean daily EPC electrical energy consumption was 0.5 kWh and 0.45 kWh in the transition and endline phases respectively, see Table 4.1, while the overall mean across the study period was 0.48 kWh, with a range of 0.25 kWh to 0.95 kWh across the HHs. The transition phase figure was corroborated by the cooking diary electrical energy consumption data, which gave a corresponding figure of 0.49 kWh, providing confidence in the data. However, there was insufficient cooking diary energy data obtained in the endline phase to provide a reliable summary, likely due to enumerators and participants struggling to maintain their motivation to record high quality energy data, as this required careful inspection of the HH logger. Figure 4.11, provided by A2EI, illustrates the variation in average HH EPC daily energy consumption across the study period, showing consistent usage.

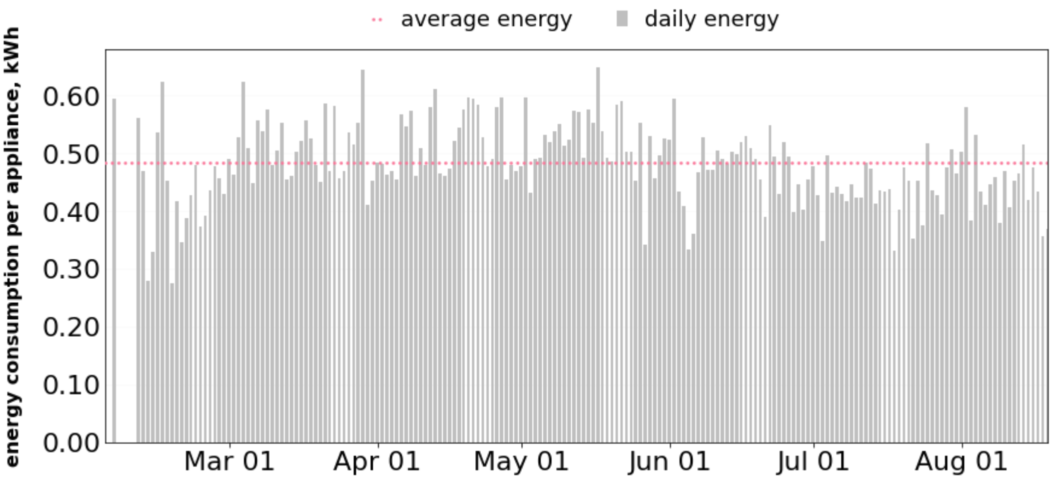

Figure 4.11: Average daily EPC electrical energy consumption and overall average, across the study period. Figure provided by A2EI.

The average annual cost of LPG cooking for the ECO study participants was NPR 6,000, based on the average cylinder replacement frequency of four months reported in the exit surveys and a reported cylinder cost of NPR 2,000, encompassing a range of NPR 2,000 to NPR 24,000 for HHs that reported replacing their LPG cylinders once per year and once per month respectively. For EPC cooking, based on the HH logger data, the average monthly cooking cost was NPR 102, an annual cost of NPR 1,220, which of course includes significant fuel stacking. The annual costs varied across the HHs with a range of NPR 633-2,402, depending on usage, much less than the equivalent wood cost according to ‘Perma’ of around NPR 25,000 as outlined in Section 3.5.4, and generally less than LPG costs.

The ECO study was able to capture changes in wood usage and EPC usage across the eight-month study period, improving on the TRIID study, in which settled cooking habits and the resulting reduction in wood used for cooking were not captured. In the ECO study, wood usage reduced by half after the introduction of the EPCs, on average, as shown in Table 4.1, with LPG usage remaining similar, as presented in Figure 4.7. However, data was not obtained on the quantities of wood used for cooking animal food. All ECO study participants kept and cooked for animals. Although corresponding firewood usage data was not collected, local knowledge of members of the research team enabled the estimation that, generally, a similar amount of wood is used for animal food cooking as for HH members. Therefore, assuming that HHs reduce their wood consumption for HH member cooking by around 50% on average, as seen in the ECO data, while their wood usage for animal food cooking remains the same, the equivalent wood cost can be approximated as reducing by 25%. The resulting savings on firewood per year would be approximately NPR 6,250, which would more than cover the cost of the EPC electricity to cover around 30% of heating events and provide additional savings of around NPR 5,000 to fund the EPC itself. This data is summarised in Table 4.3.

Table 4.3: Summary of costs on the transition to electric cooking with EPCs.

	Annual Costs (NPR)	
Energy Source	**Before**	**After**
Wood	25,000	18,750
LPG	6,000	6,000
Electricity	0	1,220
Total	**31,000**	**25,970**
Savings with Electricity	5,030	

In reality, equivalent savings on wood varied between HHs due to varying fuel stacking behaviour, but the data shows that HHs who did reduce their wood usage significantly would save time and associated equivalent costs that could be transferred to EPC purchase and/or running costs.

The calculated average EPC monthly electricity costs, based on the proposed tariff system of NPR 7/kWh, were quite low, with a range of NPR 53-200, as compared to NPR 194-1022 and an average of NPR 414 for induction stove cooking in the TRIID study. Generally, the participants reported that they think electric cooking is affordable.

However, as in the TRIID study, the HHs are yet to pay for their cooking electricity as they still pay a flat rate for the MHP electricity. The calculated cost data is nevertheless relevant for if/when a tariff system based on electricity consumption is implemented, and for other MHP communities which commonly use similar tariff systems.

The HHs had a range of views on what they would be willing to pay per month for electricity for cooking, with a majority of twelve participants choosing NPR 400-600, eight selecting NPR 200-400, and four HHs stretching up to NPR 1,000-1,200. With hindsight, there should have been an option for lower than NPR 200. However, the willingness of most HHs to pay more than the average calculated monthly cost of NPR 104 was evident.

The perception of EPC cooking as expensive was mostly down to the upfront cost. The EPC was purchased for NPR 7,500, with participants paying NPR 3,000 to keep the device. The majority of HHs, 16 of 28 respondents, selected NPR 3,000-6,000 as the cost they would be willing to pay to purchase an EPC, were they not part of the project. Five HHs commented in surveys that the market price of the device was high. Most HHs were positive about the idea of being able to pay for an EPC in a co-finance system i.e. monthly instalments over a long period, to reduce the upfront cost, suggesting it was beyond immediate affordability. However, four HHs were positive about the price of the EPC, with one reporting that they *"will buy anyway. I need it"*, despite it being expensive, and another that it is *"important for a smokeless kitchen and [good] health"*.

Overall, calculated EPC running costs were relatively low, partly due to the efficiency of the device, and partly due to low usage fractions. Even for a relatively high usage fraction of 73%, however, the calculated monthly EPC electricity cost was NPR 216, which was well within reported affordability for the majority of HHs, and much less than the equivalent wood cost and what most HHs pay for their LPG. The upfront cost presented a greater barrier. Therefore, support to enable poorer HHs to afford the initial outlay is important, through subsidy, co-financing, micro-finance arrangements or others.

The cooking diaries showed that EPCs were used consistently in the ECO study, but for a limited portion of the menu, with low usage fractions of around 30%, due to being difficult to use for frying dishes, taking longer to cook than other stoves, concurrent cooking across stoves enabling participants to save time, a fear of damaging the device, and power supply instability. However, they are suitable for some staple Nepali dishes, namely rice, dal, and water heating events such as tea, and lunch dishes such as noodles and potatoes, and their running costs would be relatively low compared to other fuels and other electric cookers. EPCs are not a complete solution for transitioning to electric cooking in rural Nepal, but they can be integrated and accepted into cooking practices on a long-term basis, and alongside another electric cooker they could be very useful and enable a mostly clean fuel stack, albeit at an even higher expense.

4.4.2 How much will EPCs be assimilated into rural Nepali cooking practices without cooking diary study support?

The twenty HHs which comprised the rollout phase of the ECO study were monitored using the same HH data loggers as the thirty cooking diary study participants, for just over a month from 3rd November to 4th December 2021. Figure 4.12, provided by A2EI, shows how the number of active HHs and cooking events varied over that period. No data was obtained for one HH due to an issue with their data logger, reducing the group size to nineteen. The data shows that the devices were used regularly by the HHs, confirming that there is demand for EPCs. The rollout HHs paid NPR 1,000 more for their EPCs than the thirty cooking diary study HHs, showing that NPR 4,000 is generally regarded as an affordable and reasonable price for an EPC for people in rural Nepal.

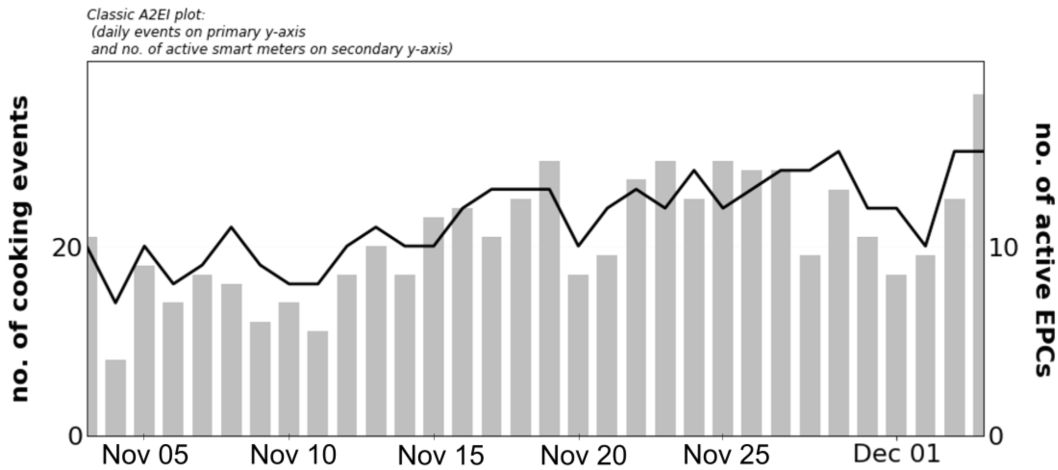

Figure 4.12: Number of cooking events (grey) and active EPCs (black line) across the rollout study period. Figure provided by A2EI.

However, as evident in the figure, it was common for only around ten HHs to be active each day, implying that not all HHs used their EPCs every day. In fact, the mean usages per day across the nineteen HHs was 1.11, significantly less than the 1.44 of the thirty diary study participants. The trend in the number of cooking events per day in the figure suggests a slight increase over time, perhaps as participants adapted to their new cookers. Figure 4.13, provided by A2EI, depicts the daily and average daily energy consumption across the rollout phase. The overall average daily EPC energy consumption was 0.47

kWh, similar to that of the thirty HHs, likely due to days with zero EPC usage, which were more common among the rollout HHs, being discounted from the average.

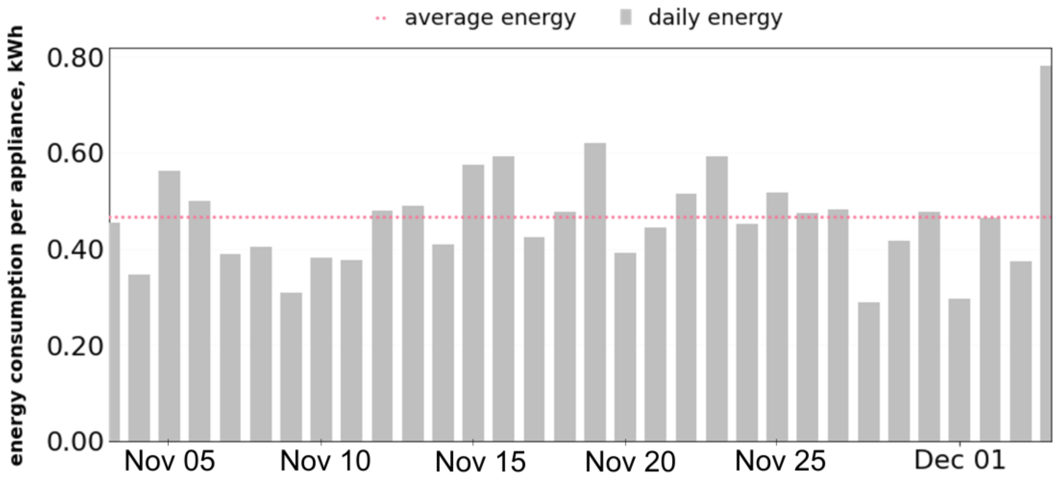

Figure 4.13: Average daily EPC electrical energy consumption and overall average, across the rollout study period. Figure provided by A2EI.

It is possible that, as the rollout phase took place as winter was approaching and settling in, HHs used their EPCs less than they would have done in warmer months due to prioritising wood stove usage for space heating. Furthermore, as presented in the following section, Section 4.4.3, it is also possible that brownouts during cooking times discouraged EPC usage. A limitation of the employed methodology for the rollout phase was that exit surveys were not conducted to capture the reasons for the EPC usage levels seen in the data, due to lack of resource. However, overall, it appears likely that the cooking diary study setup, including training and regular monitoring, encourages higher levels of EPC usage than rollout-style provision of devices. For larger rollouts, the level of support of a cooking diary study is likely not possible, so other support mechanisms need to be developed to enable HHs to use the devices more frequently.

4.4.3 How do EPCs affect the MHP system and contribute to the community load?

Data overview

MHP electrical system data was collected and analysed to understand the status of the mini-grid and the effects of the connection of a total of 50 EPCs during the study. Useful data was collected for the transition phase in February and March, during the summer period including the endline phase, and during the rollout phase in November and December, while an issue with the data logger meant that data collected during the baseline phase was erroneous and unusable. The HH data loggers collected useful data throughout these periods, from the start of the transition phase to the end of the endline phase for the 30 HHs, and for the duration of the rollout phase for the 20 HHs.

As found in laboratory tests as part of the wider ECO project [207], and in the literature, EPCs do not pulse power for short intervals in the same way that induction cookers do. Instead, they consume full power for the entirety of the preheat phase, while the EPC heats up to temperature and reaches the desired pressure, and then, during the cooking phase, only consume power for short periods when the temperature drops below a setpoint, in a temperature control loop. Generally, these periods are short, around one minute, and may not happen at all if the temperature remains high. The A2EI loggers aim to capture the power profiles of the EPC, including any power pulses after the preheat phase. The preheat phase power consumption is subject to the HH voltage and varies accordingly. As the EPCs used in the study do not appear to pulse power for shorter intervals than one minute, it is likely that the CR1000 MHP electrical system data profiles, which are one minute resolution, mostly contain and represent the power consumption of the EPCs reasonably accurately.

MHP status and stability

The MHP operators were still manually regulating the voltage and frequency in the powerhouse during the ECO study, as initially discovered in the TRIID study. Inspection of the MHP plant and powerhouse data during the ECO study revealed that further problems had developed. An issue with the ELC motherboard meant that the load was not balanced correctly across the phases. Furthermore, a problem with the AVR meant that the phase voltages were not controlled properly, with the voltage higher than nominal in one phase. The system frequency was slightly lower than the nominal 50 Hz at around 48 Hz and it was not possible to increase it without further increasing the voltage. The project team and MHP committee members discussed solutions to these issues [140]. Similar technical faults with MHP components are common in Nepal [55] and are often responsible for mini-grid weakness.

The mini-grid in Salyan can be considered as a weak grid, with high variations in voltage and frequency, beyond 5% deviations from nominal. Figure 4.14 presents the average powerhouse voltage across the study period, and HH logger voltage, along with their variation shown as one standard deviation either side of the mean, with the HH logger profile an average across all HHs. Days with data issues and blackouts were excluded from the powerhouse data so that the voltage profile only includes brownouts, reflecting the mini-grid stability during normal operation, while the HH profile includes all days, as all zero voltage records were excluded from that dataset. It can be seen that the powerhouse voltage was often stable but regularly dropped down to around 210 V, and beyond, during peak times. The average voltage drop between the powerhouse and HHs is evident, at around 10 V during off-peak periods and 20 V during peak times, as is the high variation in voltage across the HHs, with the average low at around 210 V during peak times and sometimes reducing well beyond that, to 180 V and even lower. Therefore, the feedback provided by the participants is reflected in the data, with the voltage dropping during peak times, which led to difficulty cooking with electricity and increased cooking times. There were also occasional blackouts, where the system was shut down or collapsed, during which electric cooking was impossible.

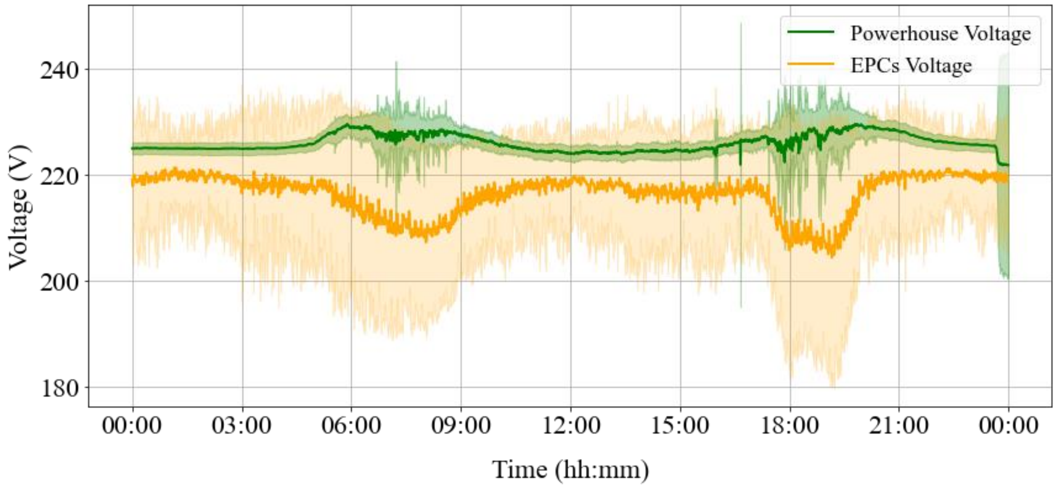

Figure 4.14: Powerhouse and HH average voltage profiles across the study period, with background clouds plus and minus one standard deviation.

DSM measures

DSM measures were implemented by the community following advice from the project team: load shifting of industrial end uses, specifically mills, through a community agreement, so that they operated in between the morning and evening peaks only, from around 10 AM to 4 PM; and peak clipping and demand reduction by encouragement of HH electricity saving practices, such as turning off lights when not in use. The measures were realised at around the same time the EPCs were introduced to the community, to ensure that there would be sufficient spare power in the mini-grid for the addition of thirty EPCs. As no useful MHP electrical system data was obtained during the baseline phase of the study, it was not possible to quantify the community electricity demand just before the addition of the EPCs. Instead, Figure 4.15 presents the nearest approximation, which is the load profile from 12th December 2020, one of the only days with useful data, and compares it to the average transition phase load from February and March 2021, which includes the EPCs, with the background cloud depicting variation.

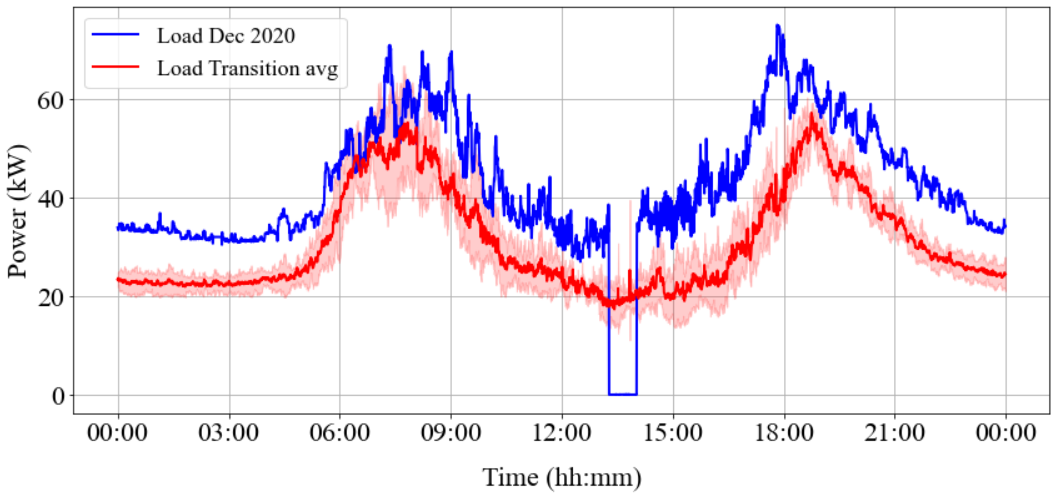

Figure 4.15: Comparison of load profiles before and after implementation of DSM measures.

The load actually decreased between December 2020 and February 2021, even though the transition phase profile includes 30 EPCs. Therefore, the DSM measures had a high impact in reducing the existing electricity demand in the community, creating spare capacity for EPC cooking during peak times. The graph shows that the load reduced throughout the day, even though mill usage in the afternoon is likely to have increased, suggesting that many HHs in the community reduced their electricity consumption.

Community and cooking load profiles

Figure 4.16 below shows that the transition and endline phase community loads were both relatively low, on average around 50 kW in peak times, with mean morning and evening ADMD of around 57 kW and 58 kW respectively in the transition phase and 54 kW and 56 kW respectively in the endline phase. The ADMD is higher than the average peaks due to the diversity in timing of activity across days, and reached maxima of 73.6 kW and 64 kW in the transition and endline phases respectively. The generated power was highest in the transition phase, at almost 80 kW on average, and therefore able to cope with the highest peak loads. It dropped to around 65 kW in the endline phase, due to testing of a new hydropower plant requiring additional water flow to be redirected to it, thereby reducing the flow to the MHP at the intake. This explains why the voltage was less stable in the endline phase than in the transition phase, seen in Figure 4.16 dropping to around 210 V on average in the evening peak, measured in the powerhouse, and to 200 V on average across the HHs. The total load rose close to the generated power in the evenings during the endline phase, causing this instability.

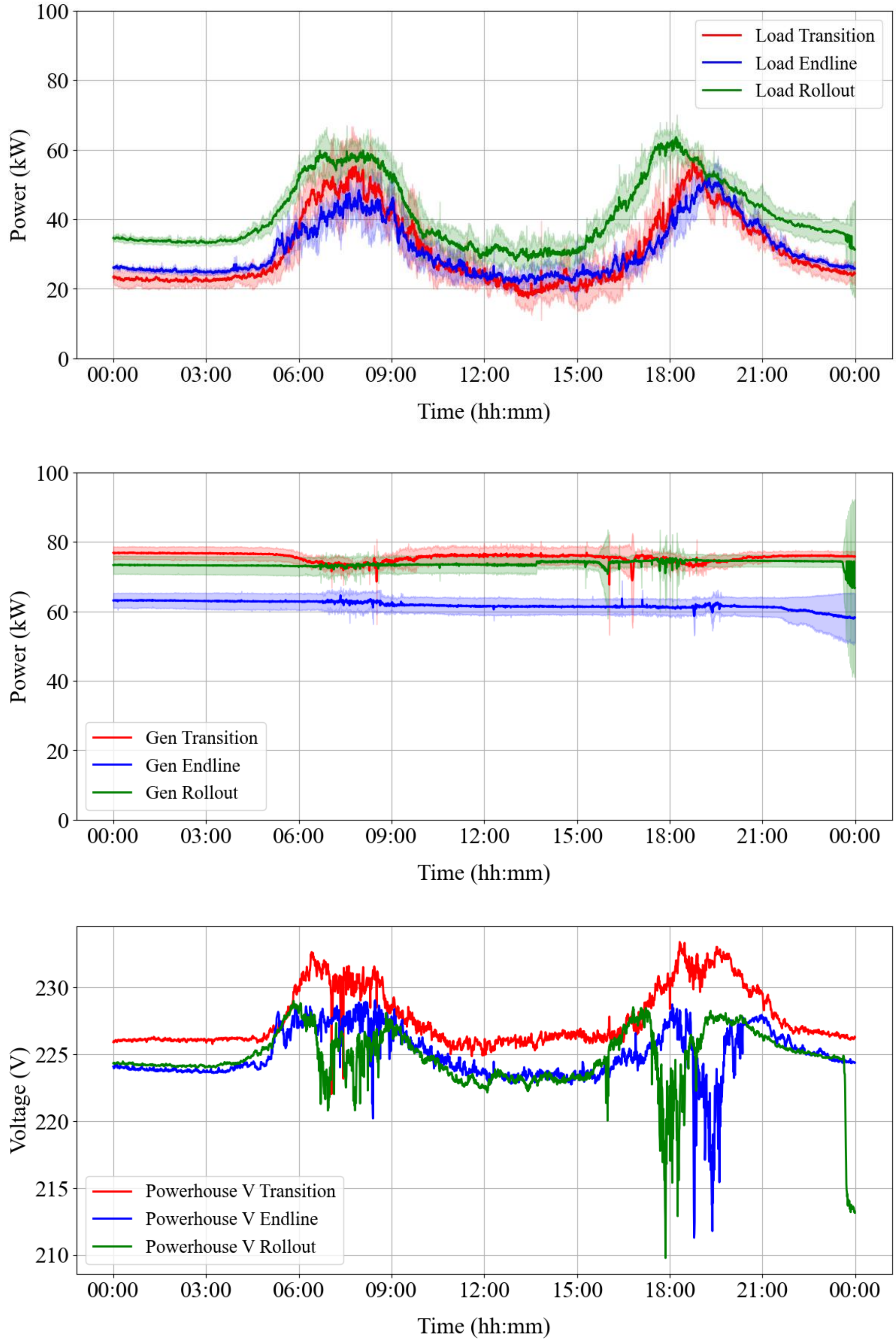

Figure 4.16: Average total load (top) and generation (middle) profiles for each electric cooking phase, with variation i.e. plus and minus one standard deviation and average powerhouse voltage profiles for each phase (bottom).

However, as clear from the voltage stability in the transition phase, and the low load compared to generated power, the system was able to comfortably support the addition of 30 EPCs to the community, partly due to the community DSM measures considerably reducing peak loads. Then, in the rollout phase, in November 2021, the load increased significantly, throughout the day, reaching average peaks of around 60 kW and mean morning and evening ADMD of 68 kW and 67 kW respectively, while the operators also increased the generated power to around 75 kW to cope with the increased load.

The 20 HHs provided with EPCs in the rollout phase increased peak loads, but the graph shows that other connections must have contributed, as the total load increased by around 10 kW across the day. Community members purchasing devices such as rice cookers and electric kettles from local markets, and other potential reasons such as the use of electric heaters as the winter approached, a relaxation of HH electricity saving practices such as switching off lights in off-peak times, and the addition of further domestic, commercial and industrial loads, may also have contributed to the discrepancy between the endline and rollout phases**.** As mentioned in Chapter 3, the registration surveys conducted in the ECO study revealed that ten of the thirty HHs reported having bought one or more high power devices in recent months, suggesting this is commonplace.

As shown in Figure 4.16, the increased load during the rollout phase led to further voltage instability, with the powerhouse and HH average voltages dropping to minima of around 210 V and 170 V respectively. The maximum ADMD across the rollout period reached 75.6 kW and 74.2 kW in the morning and evening respectively on certain days, explaining why there were severe brownouts despite the generated power being higher than in the endline phase. The low voltage seen in the HHs is likely to have prevented higher EPC usage among the rollout HHs by slowing down cooking.

Figure 4.17 shows the average total EPC load profiles for the three project phases, along with their variation of one standard deviation either side of the mean. The noise in off-peak times is likely due to data loss causing loggers to continuously record previous values. The graph shows that the 30 EPCs led to average peaks of around 3-5 kW in the transition and endline phases, and the 20 EPCs, which were used significantly less, for only around 1.1 events per day, led to much lower average peaks of 1-2 kW. The slightly lower rated power of the rollout EPCs, which were Electron brand and 0.9 kW rather than Urban and 0.96 kW, also contributed to the lower total demand, albeit minimally. Nevertheless, the reduction in peak power in the rollout phase is not commensurate with the reduction in total power draw, indicating that lower usage was a key factor.

The standard deviations indicate that the peaks varied day to day, as found by analysis of the mean ADMD in the morning and evening, which were calculated as 6.9 kW and 6.5 kW respectively in the transition phase, with maxima of 8.2 kW and 10.2 kW on certain days. The mean ADMD dropped slightly to 5.8 kW in the morning and 5.6 kW in the evening in the endline phase, with maxima of 7.1 kW and 8.5 kW respectively, while the corresponding figures for the rollout phase were significantly lower, with mean morning and evening ADMD of 2.8 kW and 2.9 kW respectively and maxima of only 4.5 kW and 5.4 kW respectively. Interestingly, the maxima occurred in the evening even though the morning ADMD was similar or larger than that of the evening in each phase, suggesting slightly higher variation in evening practices. Overall, the data reveals that, generally, the daily ADMD of 30 EPCs in the morning and evening can be expected to vary between around 3 kW and 8 kW, but that it can reach 10 kW when coincidence of cooking is high.

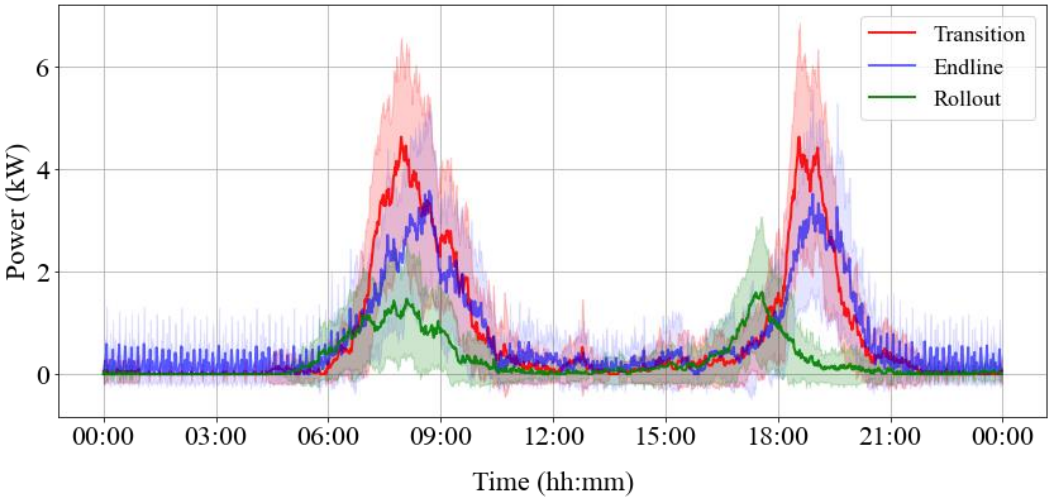

Figure 4.17: Average total EPC load profiles and variation (plus and minus one standard deviation) for each of the electric cooking phases.

However, although it is useful to understand the average EPC profiles and ADMD and their variation, their relationship to the community load profiles on a daily basis in terms of coincidence is the most important indicator of their relative contribution and EPC scalability. Generally, the profiles illustrate that the coincidence of community and cooking load peaks in each phase was high, with the morning peaks in Figure 4.16 and Figure 4.17 occurring at around 7-9 AM across the phases, although there was more variation in the timing of the evening peaks. The average transition phase evening peaks occurred at around 7 PM for both community and cooking loads, while the endline peaks occurred slightly later at around 7:30 PM, and the rollout peaks occurred significantly earlier, at around 6 PM for the community profile and 5:30 PM for the cooking profile. The coincidences observed suggest that electric cooking contributed significantly to the community load, with an evident correlation between timings of peaks in each phase. The reasons for the differences between phases are unclear and show diversity in cooking practices within the community, as well as suggesting significant changes in electricity usage in the community between the endline and rollout phases. Changes in sunset times may affect the timing of the evening meal.

On a more granular level, as found in the TRIID study, coincidence of peak community loads and cooking loads varies day to day, with the EPCs sometimes increasing the total load by around 7 kW, as shown in Figure 4.18, and on other days the peaks occurring at different times, leading to very small peak load contributions by the EPCs. The ADMD of the total load and of that minus the cooking load were compared and the latter subtracted from the former, generating a dataset of the approximate contribution of cooking to the peak load in the morning and evening of each day. Across the study period, the average contribution was around 2 kW in the morning and evening, although the maximum was much higher at around 7 kW. The average value is somewhat misleading as zeroes or missing data due to blackouts reduce it, and as often there are two or three community load peaks as part of the overall peak, of which one or two may not contain electric cooking, sometimes reducing the average identified contribution. Inspection of daily profiles revealed that contributions of 5 kW at some point during peak times are common. The maximum contribution of 7 kW is a more reliable and important result.

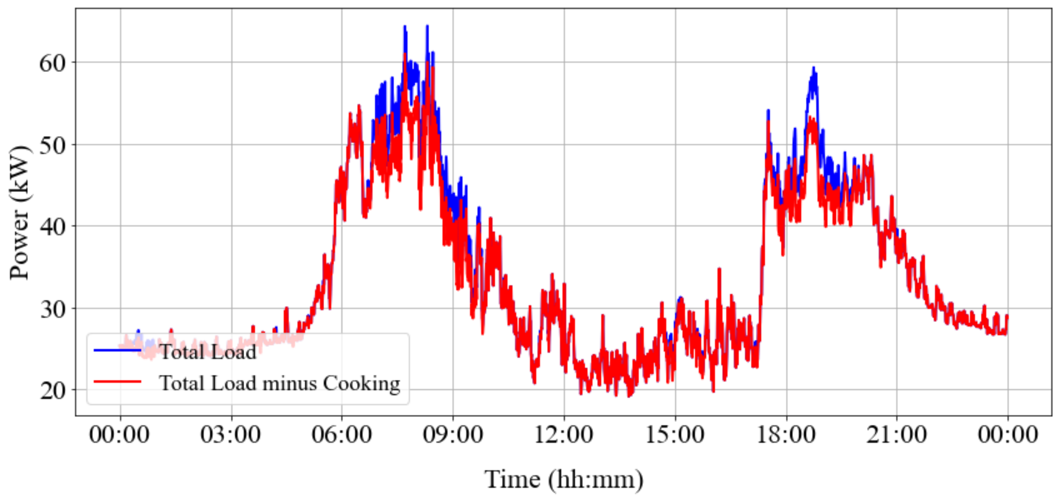

Figure 4.18: Total load and total load minus cooking load on 10th March 2021, during the Transition phase.

Focussing on the three study phases, the EPC contribution was on average around 2-3 kW in the transition and endline phases, with contributions of around 5 kW common upon inspection, rising to maxima of around 6 kW on certain days, while in the rollout phase it was only around 0.9 kW on average across the days, rising to a maximum of 3 kW, though contributions of 2-3 kW were common upon inspection. Therefore, it is very clear that other connections were mostly responsible for the increase in the total community load between the endline and rollout phases.

The ECO study revealed the ADMD of EPC cooking and how it varies, finding that 30 EPCs lead to total load profiles with peaks of around 3-10 kW, much less than the total coincident demand of the devices, which would be approximately 28.8 kW for 0.96 kW rated cookers. This result is very important for the planning of EPC trial projects and rollouts in similar contexts, as conservative, worst-case planning can be significantly relaxed. The rollout profiles show that the lack of diary study support and reduced power supply stability reduced EPC usage and the resulting total load of 20 EPCs significantly, to daily maxima of around 1-5 kW.

The study also showed that the timing of peak loads for cooking and in the community, within the same community, can vary, showing that it is important to understand how variable and coincident peak times are for both cooking and community loads, if planning study or rollout. Overall, the EPCs did contribute significantly to peak community loads on certain days, adding up to 7 kW, which is only just short of the maximum cooking ADMD measured of 10.2 kW. Contributions depend heavily on the timings of cooking and peak community activity, but load planning must consider the maximum likely contributions, close to the ADMD of the EPCs themselves.

Finally, in terms of scalability, the study revealed that the potential for increased uptake of EPCs is higher than that of induction cookers, as EPCs lead to lower ADMD for a given number of HHs, although this is partly due to their relatively limited usage. However, there was only enough power in the mini-grid for around 50 HHs to cook with EPCs in total, meaning that the scalability of electric cooking in the community, which is home to almost 1,100 HHs, is low.

4.5 Discussion

This chapter reported on a third cooking diary study, which focussed on EPCs, addressing research objectives 1-3 on current Nepali cooking practices and the transition to electric cooking, as well as objective 4 on exploring solutions which could enable increased uptake of electric cooking, in this case efficient cooking devices and community DSM measures. Research questions on the long-term acceptability of EPCs, rollout-style EPC usage, and effects on the mini-grid and community load profile, were explored. Overall, EPCs improved electric cooking scalability but their usage fractions were relatively low.

The ECO study was important for assessing the effectiveness of efficient cooking devices and community DSM measures. It had appeared, after the TRIID study, which was also conducted in Salyan, that there was no scalability for electric cooking in the community. However, the implemented community DSM measures reduced the total load by around 10-20 kW compared to pre-study levels, even though 30 EPCs had been introduced. Furthermore, the EPCs showed how shorter periods of full power cooking, and admittedly lower usage fractions, led to much higher scalability than envisaged, with almost 50 HHs actively using EPCs in the community. The mini-grid was less stable at the end of the data collection period, during the rollout phase, but the generated power could theoretically be increased beyond the measured 75 kW to improve stability.

Figure 4.19 compares the average load profiles of electric cooking from the TRIID and ECO studies, displaying greatly reduced demand for double the number of EPCs compared to induction cookers. The corresponding ADMD generally reached around 8 kW and 6 kW for induction and EPC cooking respectively.

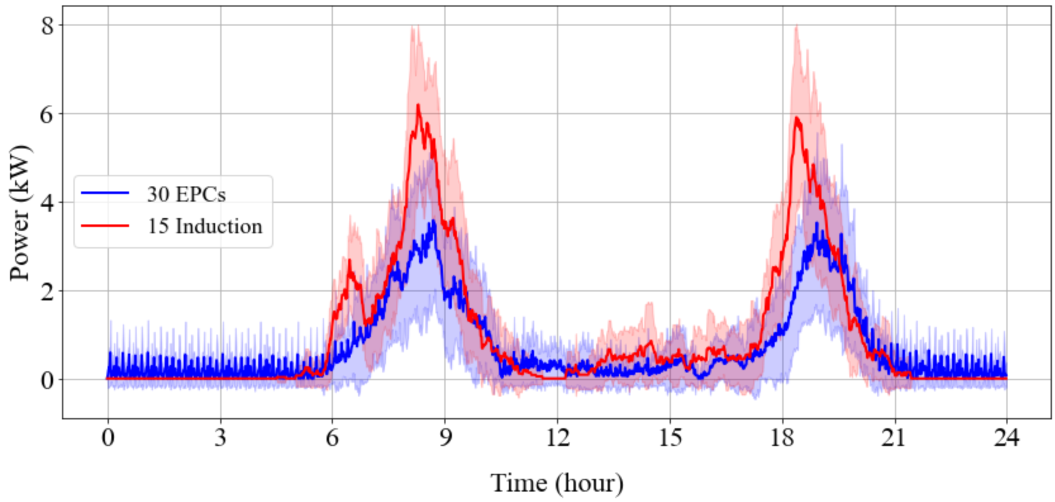

Figure 4.19: Average total load profiles of EPCs in ECO study and induction cookers in TRIID study, with variation of plus and minus one standard deviation.

Reduced usage was a key factor in the reduced cooking loads of the EPCs. Table 4.4 summarises stove usage in the TRIID and ECO diary studies, focussing on the endline phase for the ECO study, showing settled EPC usage habits. An accompanying factor was the nature of EPC usage, with rice the most commonly cooked dish, for which an EPC draws high power for only a short 10-15 minute preheat phase, and sometimes short 1-2 minute power pulses to maintain the temperature during the cooking phase, as opposed to induction cooking which, depending on power level setting, can draw high power for longer periods of time. Short periods of high-power draw reduce the likelihood of coincidence of cooking across HHs, leading to reduced ADMD. Frying in the EPC, which can draw power for longer periods, was rarely practiced by HHs, allowing the lower energy consumption of cooking boiling dishes in the EPC to affect the ADMD.

Table 4.4: Comparing electric cooking usage fractions across the TRIID and ECO studies.

Stove	**TRIID study usage (%)**	**ECO study usage (%)**
Induction cooker	77	-
Rice cooker	6	0
EPC	-	31
Electric kettle		1
Electric cooking total	**83**	**32**
Firewood	9	46
LPG	6	22

In the TRIID study, the mean daily electrical energy consumption for induction cooking was 1.63 kWh, far more than the 0.5 kWh calculated for EPCs. Nevertheless, one ECO study HH used their EPC for around 73% of their cooking in the endline phase, but still only consumed around 1 kWh of electrical energy for this per day, significantly less than the average requirement in the TRIID study, showing that EPCs do save energy compared to induction cookers, likely due to their shorter period of full power consumption. It was not possible to obtain dish level EPC energy consumption data but laboratory tests did capture this information, as presented in the full ECO project report [207].

The ECO cooking diary data is more likely to reveal realistic electric cooker usage fractions than the TRIID study, which may overestimate these. The TRIID exit surveys, which enabled calculation of approximate usage fractions over the three months following the project, showed that settled induction cooker usage did reduce to around 50% on average, although this was partly influenced by the reduced generation capacity in the dry season causing more frequent brownouts and blackouts, and wood stove usage for space heating, meaning that realistic and settled induction cooker usage is difficult to quantify with confidence. Other factors such as difficulty using the induction cookers, wanting to use existing stoves, electric cooking being too slow, or faults with the cookers, could also have contributed to reduced usage.

However, participants were mostly positive about the induction cookers and reported using them regularly, finding them to be fast, easy to use and versatile, able to cook a wide range of dishes. Therefore, the increased consecutive electric cooking seen during the TRIID study as compared to with EPCs in the ECO study is likely not only due to the study methodologies, with induction cookers representing a more complete solution for Nepali cooking than EPCs. Nevertheless, a longer study focussed on induction cooking and using the HH data loggers employed in the ECO study would have generated settled usage habits data and load profiles, enabling more direct comparison between cookers.

The TRIID and ECO studies showed that owning two electric cookers could enable HHs to use electricity for most of their cooking, while the use of electricity and LPG would constitute a clean stove stack. Pairing rice cookers with induction cookers or EPCs would be a least cost electric stove stack which can comfortably cover 2-3 dishes per meal, although HHs would be required to cook consecutively in the EPC to enable purely electric meal cooking. In all cases, the scalability of electric cooking would be significantly reduced by the extra load and electric cooking concurrency.

The fact that the TRIID and ECO studies were conducted in the same community could be viewed to reduce the usefulness of the data and the ability to generalise the results to other communities and contexts. While it is true that the ECO study did not contribute insights into a new community, the participating HHs were different, enabling understanding of variations in cooking practices within the community, which were generally small. Furthermore, direct comparison between induction cookers in the TRIID study and EPCs in the ECO study was possible. Also, the Simli study described in Chapter 3 captured data in a different MHP community and found that cooking practices were mostly similar.

Electric cooking adoption would reduce firewood consumption, as seen in the TRIID and ECO studies, but the use of wood for animal food cooking would prevent a total transition. Most HHs cooked food for animals on a separate stove, outside or in a different room, and it was found that animal food cooking does not require monitoring and can be left unattended, reducing the exposure of HH members to resultant smoke. However, temperatures can drop so low that outside cooking is impractical in winter, leading HHs to use inside stoves for animal food cooking, and therefore limiting the potential of transitioning to electric cooking to eradicate smoke in kitchens. Nevertheless, the ECO study showed improvements in HH smoke levels, suggesting that animal food cooking may not be a limiting factor. Furthermore, this study was able to provide evidence for a link between reduced smoke due to reduced wood stove usage and improved health. Longer term studies would be required to understand the effects of reduced smoke on health.

Overall, efficient devices and load shifting/demand reduction increase potential uptake of electric cooking, but people cook at the same time as peak community activity, and there is relatively little spare power in the community considering the total number of HHs, so its scalability remains limited. While 50 HHs being able to cook with EPCs was more than expected, it is a small fraction of the 1,100 HHs in the community. Therefore, energy storage must be explored to utilise unused energy generated during off-peak periods.

The improved cooking diary methodology employed for the ECO study enabled more and higher quality data to be collected in a more efficient way, although some HHs and enumerators grew tired of recording data due to the increased length of the study, while the use of KoboToolbox was challenging for some enumerators, necessitating support and data checking from the research team.

A key limitation of the study was the omission of exit surveys for rollout phase participants due to timescales and limited resources. Without participant feedback, it is unclear what the HHs thought of the EPCs and why their usage was generally lower compared to the diary study HHs. It is postulated that their reduced usage was due to lack of support, power supply instability due to the onset of the dry season, and/or increased wood stove usage for space heating, but surveys would have confirmed the influence of these factors. Nonetheless, electric cooking rollouts would benefit from providing cooks with some form of training and monitoring, perhaps through cooking demonstrations, videos, and television/radio campaigns, with data logger and surveys for samples of HHs. Furthermore, as found in the TRIID study, due to the flat rate tariff system in place in Salyan, it was not possible to directly assess electric cooking affordability and the influence of running costs on usage.

The HH data loggers were very useful and produced valuable data, but their interface meant that participants were generally unable to see and record voltage and energy readings, due to these not being automatically displayed. Such readings would have enabled participant understanding of the effect of voltage level on electric cooking and the capture of dish level energy data, rather than daily readings, although this would have increased the burden of data recording for participants. Furthermore, data loss in the HH loggers necessitated the creation of artificial events, as described in Appendix A2.5, with all data processing conducted by A2EI, and also led to repeated power spikes, although these were generally rare and small effects. The processing of data introduced a level of uncertainty about the accuracy of the load profiles. Some events had no valid power consumption values and therefore had to be approximated by an average power calculated from event energy consumption and duration. However, these events were rare, and generally the HH logger data appears sensible.

Further work should include deeper interrogation of the cooking diary, electrical system and HH logger datasets. The effect of powerhouse and HH voltage on electric cooking durations should be investigated. Voltage data could be integrated into a community electrical system model to understand voltage drops across transmission and distribution lines and how electric cooking loads affect power quality. HH logger and diary data could be combined to generate datasets of energy consumption of different dishes. Automated and intelligent analysis methods to identify ADMD and the contributions of cooking to community load profiles could be explored, to prevent erroneous power spikes skewing results and enable analysis of large datasets.

Further studies should be conducted to continue to investigate electric cooking adoption. Wider studies with scaled up electric cooker usage would generate data on cooking load profiles for large numbers of HHs, allowing more accurate estimation of large-scale electric cooking loads. Electric cooking rollouts including surveys to understand usage should be carried out, while studies and rollouts featuring multiple electric cookers, cooker combinations, and perhaps trialling different cookers in turn in the same HHs, would generate deeper insight into the potential of electric cooking to be assimilated in to Nepali HHs as a primary cooking method.

4.6 Summary

This chapter outlined the findings of the ECO study, which focussed on trialling EPCs in Salyan, the case study MHP community. During the cooking diary study, the long-term acceptability of EPCs for rural Nepali cooking was confirmed, with HHs generally integrating the devices into their daily cooking practices. However, the EPCs were used for a lower proportion of the menu than induction cookers, mostly for rice, which represented 80% of EPC dishes, and sometimes dal. Average usage across the seven-month diary study period was 1.5 times per day and 30% of cooking events. Usage reduced slightly over the monsoon season but was reasonably consistent, and highest during the transition and endline phases, at around 1.8 events per day. Willingness to experiment again led to higher usage fractions, with some HHs using the EPC for other dishes including noodles and potatoes, and for making tea and other water heating events.

The ability to let the EPC cook without needing to monitor it was a key benefit for participants, who were able to multitask, as was the reduction in smoke from wood cooking which resulted from a 55% reduction in firewood consumption across the study, although wood was still used for some dishes and for animal food cooking. Monthly EPC electricity costs, if the community used a tariff system based on consumption, would be lower than for induction cooking, partly due to reduced usage, and would be generally within reported affordability, but the price of the EPC itself was mostly seen as prohibitively expensive without subsidy or financing mechanisms. However, the EPC would generally provide savings on monthly cooking fuel costs compared to using LPG as a back-up fuel and the time value of collecting firewood.

Fuel stacking was common and occurred for many reasons including difficulty frying in the EPC, higher EPC cooking times, concurrent cooking enabling people to save time, worries about damaging the EPC with repair and maintenance capability low, and power supply instability. The rollout phase of the study revealed that the training, support and monitoring of the cooking diary methodology is likely to encourage higher electric cooking usage fractions, with rollout HHs only using their EPCs for an average of 1.1 events per day and fuel stacking for a higher proportion of their menu, although other drivers such as wood stoves providing warmth in winter and low voltage may have reduced their usage.

Brownouts were common throughout the study, contributing to fuel stacking. However, community DSM measures of load scheduling for mills and encouragement of HH electricity saving practices reduced the community load significantly while the EPCs were being introduced, freeing up spare power for electric cooking, and showing that DSM measures can increase its adoption potential.

Thirty EPCs led to total cooking load peaks of around 3-10 kW, depending on coincidence of cooker usage across HHs, with daily ADMD of around 6-7 kW common, while their contributions to community load peaks varied up to around 7 kW, with 5 kW contributions commonly observed in the data, revealing the higher scalability of EPC cooking compared to induction cooking. Overall, it was found that EPCs enable increased adoption of electric cooking compared to induction cookers, but are not a complete solution for Nepali cooking, as evidenced by their relatively low usage. The addition of another electric cooker, while enabling adoption of electricity as a primary cooking fuel, would reduce the limited scalability of electric cooking further. The datasets and knowledge generated in this chapter are taken forward to the techno-economic modelling outlined in Chapter 5, where they are used to model electric cooking loads, essential for understanding the impact of electric cooking on the financial sustainability of MHPs and the estimated load profile of increased adoption of electric cooking

Chapter 5
Techno-economic modelling of Nepali MHP communities

5.1 Introduction

Chapter 3 and Chapter 4 showed that electric cooking is feasible in MHP communities, albeit limited in scalability, and that efficient devices such as EPCs and load-shifting and demand reduction DSM measures could increase adoption potential. However, the effect of electric cooking on the financial status of the MHP had not been explored. The literature review and insight gained through the Simli, TRIID and ECO studies showed that the financial sustainability of MHP communities is often low.

During the TRIID and ECO studies in Salyan, it became clear that the MHP was struggling to generate sufficient income for economic viability. Therefore, a techno-economic model (TEM) of an MHP community, reported on in this chapter, was conceived for evaluating and improving the financial sustainability of MHPs. The literature review identified RAMP as the most suitable software for this task. RAMP, or Remote-Areas Multi-energy systems load Profiles, is an open-source bottom-up stochastic model for the generation of high-resolution multi-energy profiles, conceived for application in contexts where only rough information about users' behaviour are obtainable [161], [211]. RAMP and its earlier incarnation LoadProGen have already been used effectively to model cooking loads in several contexts [103], [172], [174].

Using RAMP, a realistic model of the electricity demand of an MHP community including electric cooking was developed, approximating the load breakdown of HHs and productive end uses (PEUs), to estimate their energy consumption, resulting payments, and the total income generated. This chapter uses the model to explore how tariffs can be set to balance the needs of the people and the plant, ensuring sufficient income while remaining fair and inclusive for consumers, as well as its potential to be used for load planning. It also addresses research objective 4 on exploring solutions which could enable increased uptake of electric cooking, aiming to understand the potential for income generation from electric cooking to increase the economic viability of MHP communities.

The case study for the TEM was Salyan, the community where the TRIID and ECO studies were conducted. In Salyan, there are 1093 HHs and 17 types of PEUs including business (BEUs), community (CEUs) and industrial end uses (IEUs). The MHP is community owned and currently most beneficiaries pay a flat rate of NPR 110 per month for electricity, while some IEU operators are charged according to their electricity consumption.

The TEM was originally created by the researcher in early 2021 using data from the TRIID study, including induction cooking data, before data from the ECO study had been obtained on the community electricity demand after the introduction of EPCs to the study participants [212]. Therefore, the model was originally validated using data that preceded the DSM measures implemented in the community, of load shifting of mills and HH electricity saving practices, as well as the EPCs. The model was subsequently updated using the latest data available from the ECO study, incorporating efficient electric cooking devices. The original model outlined and used in [212] is available in a publicly accessible repository in [213] while the updated version is also available in [214].

5.2 Methodology

In this chapter, a TEM is developed to calculate the overall plant income, profit, the income breakdown across consumers, and generate daily and average load profiles across a typical month. Figure 5.1 presents a flow chart of the methodology of the study. The model requires a breakdown of user energy consumption and realistic electricity demand profiles. RAMP is used to generate community load profiles and augmented to enable realistic modelling of electric cooking loads, incorporating extended cycle functionality to represent typical practices of cooking dishes sequentially at varying power levels. The RAMP model required data on the electricity demand of HHs and PEUs, recent powerhouse load profiles for model validation, and cooking diary data for specification and validation of RAMP electric cooking modelling. Together with this demand data, data was also required on plant costs, profit allocations, the proportion of paying consumers, and energy lost due to brownouts and blackouts. According to MHP bylaws 15% of total revenue should be allocated to repairs and maintenance, 25% of total profit should be allocated to a backup fund and 25% of total profit should be allocated to a community development fund [145]. The collected data, information and model outputs are then combined to understand the impact of different tariff structures and end uses on the techno-economic viability of the MHP.

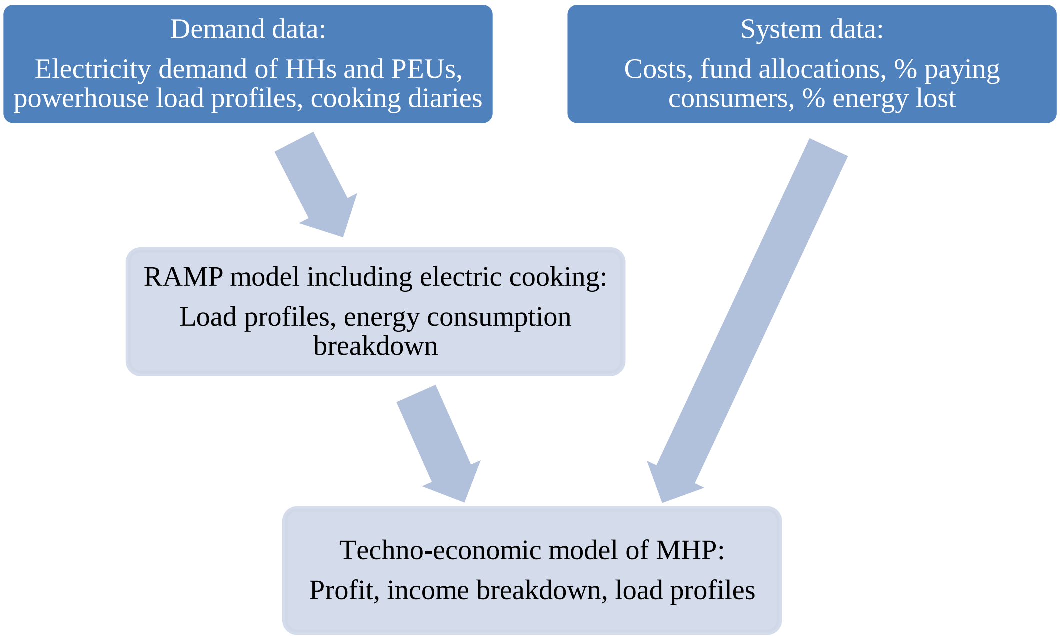

Figure 5.1: Flow chart of the study methodology.

5.3 Data collection

Data was collected from a number of sources between December 2020 and March 2021 in order to create and validate the RAMP model, understand the current and planned status of the MHP, and gain insight into consumer attitudes to the plant and their cultural cooking context. In addition, updated information was obtained during the ECO study, later in 2021, through its surveys and cooking diaries, while informal discussions with the research team and community members also contributed to the obtained understanding used to develop the model.

Firstly, an interview was conducted with the MHP secretary, see Appendix A3.1 on the plant status and end uses, contributing both system and demand data. Key insights included that the monthly plant income was low at around NPR 50,000 due to the flat rate and a large proportion of consumers not paying their bills. Originally, the tariff had been set according to what was deemed most acceptable for consumers, after community effort during MHP construction. It was found that many consumers were reluctant to pay due to having been involved in plant construction or currently being part of the MHP committee. Another section of consumers was unable to pay due to poverty while others were exempt due to family member involvement in the civil war or having donated land for the MHP.

Therefore, the plant was sometimes unable to cover the costs of repairs, maintenance and salaries of its three employees, and recently required financial assistance from the local government for maintenance works. To improve the situation the MHP committee plan to implement a new payment structure based on energy consumption and the process of making the transition to the system is underway. The new system will include tariff collection by staff members on the assumption that additional staff costs will be recuperated by increased revenue due to increased payments for some consumers and an increased percentage of consumers paying regularly.

The interview questionnaire also asked for information on the PEUs, their appliance ownership, and appliance power ratings, where possible, to generate electricity demand data. For IEUs such as mills, more detailed usage data was collected because high power machines have a large effect on the electricity demand profile, especially if several are in use at the same time. The interview data was complemented by a member of the research team at PEEDA visiting the PEUs to extend understanding of appliance ownership and usage. Table 5.1 shows the proposed tariff structure with end uses grouped by connection type and their numerosity in brackets e.g., there are two banks, both of which have a 16 A connection. Higher current connections will be charged more for electricity. An important insight was that the operators of the three phase rice mills had an agreement not to operate their mills after 5 PM to reduce the evening peak demand, which was subsequently extended during the ECO study to confine mill usage to an off-peak period, 10-4 PM. The results of all surveys, presented as RAMP inputs, are available in the data repositories [213], [214].

Table 5.1: Proposed payment structure by meter and breakdown of end uses.

Meter (Amps)	**3 A/6 A**	**10 A**	**16 A**	**32 A**
Minimum unit (kWh)	18	32	40	50
Minimum unit charge (NPR)	110	250	300	350
Per unit charge above min. (NPR)	7	8	8	8
End uses	HHs (99% of 1093) Shops (15)	HHs (1% of 1093) Schools (Primary) (9) MHP office (1) Government offices (2) Hotel (6) Police station (1) Poultry farms (4) Single phase mills (3)	Schools (Higher (3), Secondary (2) and Campus (2)) Cold storage (1) Health-post (1) Banks (2)	Crusher (1) 3 phase mills (8) Telecoms tower (1)

The number of HHs in the community (1093) implies that they are likely to dominate the electricity demand. Therefore, it was necessary to capture information on device ownership, power ratings, frequency of usage, usage windows and durations from a sample of HHs. Alongside the ECO study, a HH survey, presented in Appendix A3.2 was conducted in the thirty HHs, a suitable sample size for the data required. The survey collected data to a level of detail appropriate considering participant workload and inherent uncertainties, for example asking for periods of the day during which participants typically used devices. Figure 5.2 presents percentage ownership of domestic end uses among the sample.

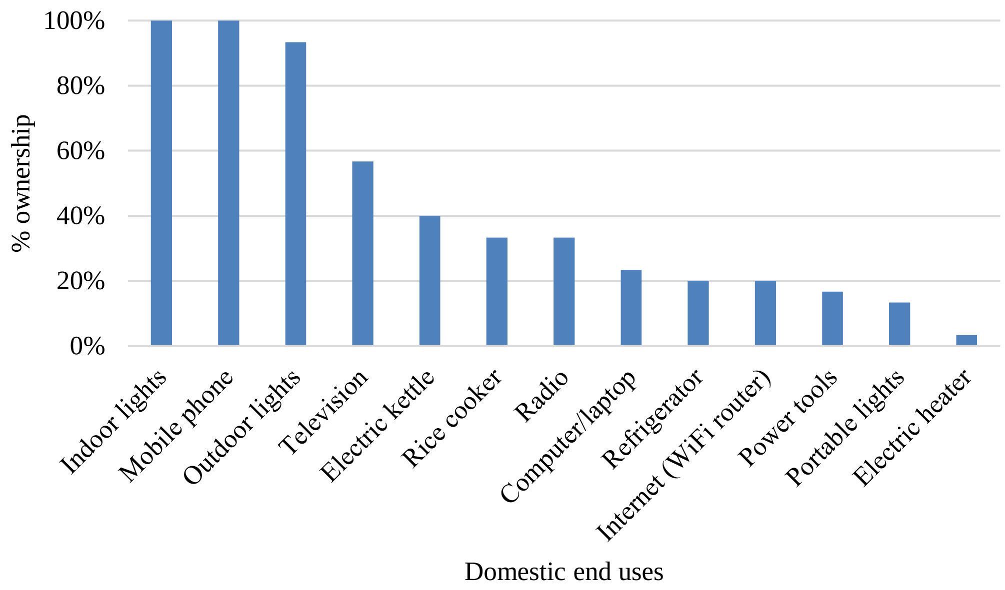

Figure 5.2: Percentage ownership of HH devices in the thirty HH sample.

Cooking diary data from the studies in the community was used to model cooking loads and for RAMP parameters for electric cooking appliances including rice cookers and electric kettles [140]. Powerhouse electrical data from these studies contributed system and demand data, including the frequency of brownouts and blackouts, the spare capacity at peak times, the load factor, and demand profiles for comparison to RAMP model outputs. The load factor was relatively high for an MHP, with the base load around 40 kW in off-peak times [145]. As outlined in Chapters 3 and 4, there is little spare power at peak times, and short blackouts and brownouts are frequent, the latter involving the voltage dropping to around 200 V and beyond.

5.4 Techno-economic model development and validation

The RAMP inputs and code files used in this study are available in [213], [214], with functionality fully explained in and the algorithm outlined in Appendix A3.3 [161]. RAMP version 0.2.1-pre was used and augmented for the study. The latest version of RAMP is freely accessible as “Remote-Areas Multi-energy systems load Profiles” (RAMP) from the GitHub repository, see [211]. Minor adaptations to the code were made, which were integrated into the latest version of RAMP by its developers, to adjust the probabilities of coincident switch-on of multiple numerosity appliances, such as lights and mobile phones, in on- and off-peak time windows [211]. In both cases the likelihood of the coincident switch-on of all instances of the appliance was increased. Full explanations are provided in the repository [211].

5.4.1 PEU and domestic load modelling

Table 5.1 presented the end uses, which correspond to user types in RAMP, and their numerosity. For each user type appliances were specified according to their numerosity, power rating, total daily usage, minimum usage per switch-on, windows of usage, weekly frequency of use where applicable, and duty cycles of varying power levels where required. These parameters were mostly specified from the collected survey data, and alternative sources used for power ratings where survey data was lacking using references [167], [172], [215], including a previous field study conducted by PEEDA in rural Nepal [215]. Generally, for simplicity, the rated power of all end uses was specified, rather than taking into account the effects of brownouts and voltage drops across lines on power consumption. As the community load data used for validation was measured in the powerhouse, it makes sense to exclude the effect of voltage drops across lines, while the effect of brownouts is taken into account during the economic calculations, as explained in Section 5.4.3.

Randomness factors which variate durations, windows, duty cycles, and powers according to uniform distributions were specified according to survey usage data, sensitivity analyses and research team member experiences. For each model run, RAMP creates and aggregates independent stochastic load profiles for every user within each user type, with multiple runs generating a series of daily load profiles. For the schools, offices, banks and police station weekend profiles are not created. In Salyan, Friday is a half-day for some community activities while Saturday is a holiday, therefore RAMP omitting two days for these end uses is a conservative measure but has little impact as HHs, BEUs and IEUs dominate demand.

The following is a description of the general RAMP algorithm, accessible in the Github repository in [211], and outlined fully in Appendix A3.3:

An input file for the RAMP algorithm consists of a list of user types (i.e. Hospital, Low Income Household, School, etc.). There is a certain number of users in each of the user types (minimum is one). Within each user type is an associated list of typical appliances. Almost all the usage parameters (specific power consumption, usage windows during a 24h period) are defined at the appliance level. For every stochastic computation i.e. of switch-on times, time frames, durations, power levels, etc, randomness factors are applied to the parameter using a uniform distribution. For example, for an appliance which is used for 10 minutes per day, if the randomness factor is 0.2, for every instance of the appliance a randomised duration of between 8 minutes and 12 minutes will be calculated and used. A theoretical load profile is computed from the list of user types and associated appliances via the following steps:

1. identify an expected peak time frame to allow differentiating between off- and on-peak switch-on events of appliances. See [211] for details.

2. for each type of appliance for each user within each user type, compute:

    i. the randomised appliance type's total time of use, based on the specified usage time and randomness factor and using on a uniform distribution

    ii. the randomised vector of time frames in which the appliance type is allowed to be switched on

    Subsequently, iterate over the following steps until the sum of the durations of all the switch-on events equals the randomised total time of use defined in step 2.i.:

    iii. generate a random switch-on time frame within the allowed time frames defined in step 2.ii

    iv. compute the randomised power required by the appliance type for the switch-on time frame defined in step 2.iii

    v. compute the actual power absorbed by the appliances of the type under consideration during the switch-on event considering a random numerosity of appliances

    Repeat step 2 N times to get a stochastic variation of the appliances' usage

3. Average the N profiles in the total load profile.

To understand and model the variation in HH appliance ownership and usage, HH user types were created based on HH survey results, representing degrees of income level within the community. Appliance numerosity and usage durations were varied around the mean across the groups, increasing with income level. Table 5.2 presents the HH types, percentage of the total 1093 HHs, and appliances owned, including the HHs with electric cookers which were part of the previous cooking diary study [140]. Type 5 is a small number of HHs owning all surveyed appliances. In reality, ownership varies widely across the community, e.g., some HHs own rice cookers but not electric kettles, but the user types created approximate clusters of HHs sufficiently for differentiating consumers.

Table 5.2: HH type groupings, percentage of HHs in Salyan, and appliances owned.

HH type	**Number** (% of total)	**Appliances owned**
1	437 (40)	Indoor and outdoor lights, Mobile phones
2	272 (25)	Indoor and outdoor lights, Mobile phones, TV
3	164 (15)	Indoor and outdoor lights, Mobile phones, TV, Radio, Rice cooker, Electric kettle
4	154 (14)	Indoor and outdoor lights, Mobile phones, TV, Radio, Rice cooker, Electric kettle, Laptop, Router, Refrigerator, Torch
5	10 (0.9)	Indoor and outdoor lights, Mobile phones, TV, Radio, Rice cooker, Electric kettle, Laptop, Router, Refrigerator, Torch, Heater, Power tools
Induction	7 (0.6)	HH type 2 plus induction cooker
Induction + rice cooker	1 (0.1)	HH type 2 plus induction cooker, rice cooker
EPC Endline	28 (2.6)	HH type 2 plus EPC based on ECO Endline
EPC Rollout	20 (1.8)	HH type 2 plus EPC based on ECO Rollout

Four separate groups were specified for HHs with electric cookers: those with induction cookers, those with induction cookers and rice cookers, those with EPCs who took part in the ECO cooking diary study, and those with EPCs who took part in the ECO rollout study. The numerosity of each HH group was specified according to the surveys and the latest data on electric cooker usage. Electric cooking HHs were all taken to be otherwise identical to HH type 2, to prevent confusion and complication with HHs regularly using rice cookers, electric kettles and other electric cookers. Specifying these HHs as members of type 2 also meant that the proportions of each HH type were preserved, with only electric cooking loads added, and that these HHs were using the most common devices and appliances, even though some of them would in reality be members of the other HH types in terms of device ownership and usage.

Frequency of use was specified for most appliances and varied across HH types. For example, type 4 was modelled to use their rice cookers and electric kettles around once every three days, to capture frequent but varying usage within the user type, whereas the frequency was lower at once every five days for type 3 to represent occasional usage. Varying the frequency of use also represents days where HHs are away from home and instances where brownouts might lead to reluctance to use electrical appliances.

5.4.2 Electric cooking load modelling and model testing

To model the HHs with electric cookers, data from the TRIID and ECO cooking diaries was used, alongside energy meter and HH data logger datasets, where available. Firstly, the induction cooker and rice cooker load modelling are outlined, which were based on the TRIID study, after which the EPC modelling, based on the ECO study, is specified. Subsequently, model testing is conducted to determine the level of detail required for setting up a useful techno-economic model.

Induction and rice cookers

During the TRIID study, 15 HHs were provided with induction cookers, with four HHs also provided with rice cookers [140]. RAMP was augmented with additional code functionality to enable realistic modelling of Nepali cooking loads using data from the diary study on durations, time windows, power levels and dish frequency. The main addition was an extension of the cycling functionality, enabling cycles of more than two parts with different durations and power levels. As identified in the diary studies, in Salyan, the most commonly cooked meal is lentil stew, rice and vegetables, known locally as dal bhat tarkari. Some HHs cooked two or three dishes sequentially on the induction cookers, and it was common to start the cooker at its maximum power of 1 kW and subsequently reduce it to a lower level while cooking each dish.

Table 5.3 presents the modelling specification for typical daily cooking practices in Salyan, based on TRIID study data, including cooking cycles, for typical HH sizes of 4-5 people. Time windows are 7-10 AM, 12-4 PM and 5-8 PM for breakfast, lunch and dinner respectively, while water heating events representing tea or drinking water are allowed to occur a varying number of times across the day. All induction cooker dishes can be represented as high power (HP) (1 kW) for an initial ten-minute preheat period followed by a reduced heat or simmering period at medium power (MP) (700 W). The induction cooker power is allowed to vary randomly by up to 20% around the specified level, accounting for different power level selections and cookers with higher maximum power than 1 kW, as the TRIID study revealed that participants adjust the power to varying levels during cooking [137], [140].

Table 5.3: RAMP induction cooking load modelling specification.

Meal (frequency)	No. dishes	Dishes	Frequency (%)	Cooking cycle / typology
Breakfast 1 (90%)	3	Dal, Rice, Vegetables	30 (or 50 for HHs with rice cookers)	Dal: HP 10 min (frying/boiling), MP 15 min (simmering) Rice: HP 10 min (boiling), MP 15 min (simmering). Or HP 25 min for HHs with rice cookers Vegetables: HP 10 min (frying), MP 20 min (lower heat)
	2	Rice, Vegetables	50 (or 30)	See above
	1	Dal or Rice	20	See above
Breakfast 2 (10%)	2	Meat, Rice	70	Meat: HP 10 min (frying), MP 25 min (lower heat)
	1	Meat or Rice	30	See above
Lunch 1 (50%)	1	Noodles	50	HP 10 min (boiling), MP 10 min (simmering)
Lunch 2 (50%)	1	Potatoes	50	HP 10 min (frying), MP 15 min (lower heat)
Dinner 1 (80%)				Same as Breakfast 1 except frequency 80%
Dinner 2 (20%)				Same as Breakfast 2 except frequency 20%

Another major addition to RAMP was the incorporation of “meal selector” parameters, similar to the user_pref factor already present in RAMP, allowing different meal options to be randomly selected with certain probabilities which translate to the frequencies in Table 5.3, chosen according to cooking diary data. For the TRIID study HHs, breakfast and dinner modelling included two layers of selectors, firstly between different meals and then for different numbers of dishes cooked on electric cookers. Fuel stacking is common, with participants cooking with different fuels to save time or out of preference for cooking experience or taste. In the TRIID study fuel stacking meant that 70-80% of dishes were cooked with electricity [140]. Therefore, the second selector chooses options where one, two or three dishes are cooked with electricity. Meat-rice meals could also represent roti-vegetables meals which are also a feature of cooking practices in Salyan. Single dish events could represent a wide range of dishes. For the lunchtime meal, the cooking diaries revealed that noodles or fried potatoes are the two most common meals, so only one selector is required. Fuel stacking was also accounted for by setting the overall appliance frequency of use at 90% to account for meals where HHs cooked entirely using wood or liquid petroleum gas (LPG), or did not cook at home.

HHs with rice cookers were modelled in a similar way as those without, except with the addition of a separate appliance representing rice cooked in the rice cooker, enabling the possibility of concurrent induction and rice cooker usage, as was often found in cooking diary data. A limitation of this is difficulty ensuring induction and rice cooker events happen in close proximity in time, as each appliance being independent means that RAMP can schedule them at opposite ends of a time window. Another difference was that the probability of cooking three dishes with electricity was increased, to 50% rather than 30%, and that of two dishes reduced to 30% from 50%, to reflect the increased likelihood of electric cooking when using two electric cookers, as seen in the TRIID study data.

Figure 5.3 presents an example HH electric cooking load profile: an early water heating event, a six-part cycle for breakfast representing three dishes, a single dish lunch, and finally a four-part cycle for dinner representing two dishes. Although not perfectly realistic as the power level varies between events, this stochastic power variation is more representative of consumer behaviour and differences between cookers than fixed power levels across the board. Two further changes were made to RAMP for modelling electric cooking, preventing a cycle repeating after duration randomisation, and ensuring sufficient time remaining in a time window for a full cooking cycle to be completed, explained in the code files in the data repositories [213], [214].

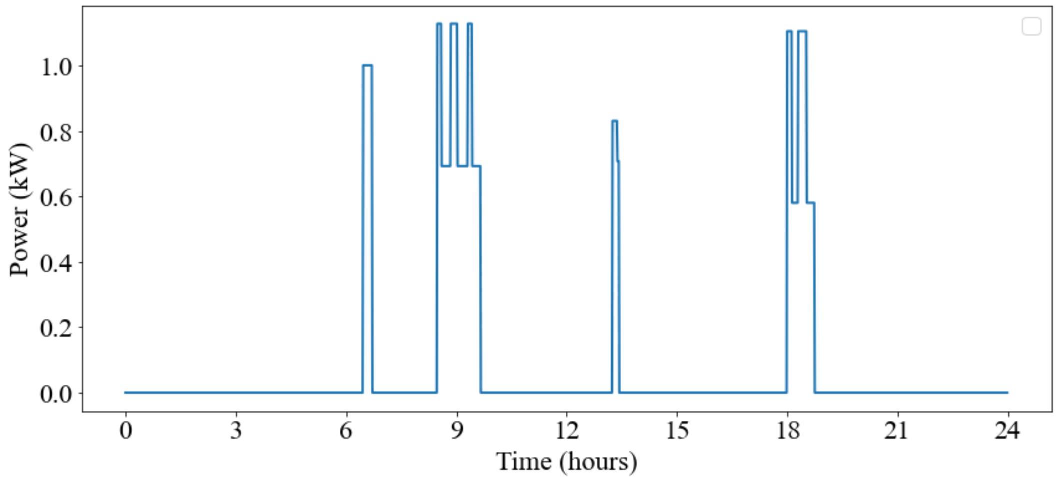

Figure 5.3: Example of RAMP output electric cooking load profile for one HH with an induction cooker.

The cooking load modelling was validated by comparing outputs to cooking diary data load profiles generated from energy meter readings and event durations during the TRIID study. Average power values during cooking events were aggregated across the HHs and then averaged to create an approximate daily load profile. Figure 5.4 compares the RAMP and diary curves for 15 HHs, showing reasonable agreement between the profiles. The maximum peaks across the 14-day period were 11.3 and 11.2 kW for the RAMP and diary profiles respectively, showing that similar variability was obtained with each method. The adherence of the generated profile to the measured data is also evaluated by means of the Normalised Root-Mean-Squared Error (NRMSE) (Equation (5.1)).

$$NRMSE = \frac{\sqrt{\frac{\sum_{x}^{N_t}(P_{RAMP}(x) - P_{diary}(x))^2}{N_t}}}{P_{diary,average}} \quad (5.1)$$

where $P_{RAMP}(x)$[kW] is the RAMP profile value at each timestep x, $P_{diary}(x)$[kW] is that of the diary profile, N_t is the total number of timesteps (1440 for one minute resolution), and $P_{diary,average}$[kW] is the mean of the diary profile. The NRMSE has been used to assess RAMP outputs previously [161], and normalizes the root-mean-squared-error by division by the mean of the measured profile, enabling comparison between datasets with different scales. The NRMSE is 0.35, indicating a strong level of adherence, with adherence higher for values closer to zero. Part of the difference between the profiles occurs in the lunchtime period. During the TRIID study transition phase, many HHs rarely ate their lunchtime meal at home due to work commitments, giving rise to a low afternoon electric cooking load. The RAMP cooking model accounts for an increased level of lunchtime electric cooking as other HH members may start to use the cooker after some time and more meals might be cooked at home during holiday periods.

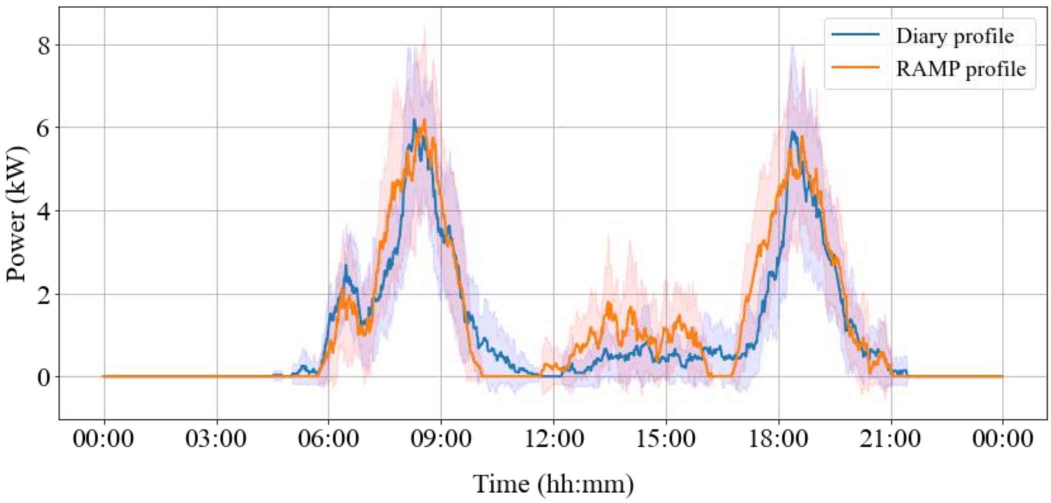

Figure 5.4: Comparison of average RAMP electric cooking load profile and cooking diary data profile for 15 HHs.

Electric pressure cookers

For the HHs with EPCs, the ECO study provided a dataset of HH data logger EPC load profiles covering a period of over nine months, although corresponding cooking diary data was only obtained for a month, during the transition and endline phases. As for the induction cookers and rice cookers, cooking diary data, this time from the ECO study cooking diaries, was used to specify RAMP parameters for EPC load modelling. This was first done for the transition phase, for 30 HHs, then adjusted for the endline phase, during which 27 HHs were actively using their EPCs, to model the latest cooking practices of the diary study group. A separate EPC modelling specification was created for the 19 active rollout HHs, adapted from the main group, according to their HH data logger load profiles, in the absence of cooking diary data.

The power drawn by the EPCs was affected by the HH voltage in the ECO study, sometimes dropping beneath the rated power during brownouts and due to voltage drops between the powerhouse and the HHs, along the transmission and distribution lines. As the data loggers were located in the HHs and used current and voltage readings to estimate power consumption, they captured these effects, measuring the local cooking load. Therefore, the EPC modelling specifications include slightly reduced rated power, by around 5%, to account for derating due to reduced voltage, with 10% random variation to allow for lower power levels when the voltage was low and variations in power draw between specific EPCs. The shared aspects of the modelling specification for the endline and rollout HH groups, which form part of the latest electricity demand picture in the community, are presented in Table 5.4.

Table 5.4: RAMP EPC cooking load modelling specification.

Meal	No. dishes	Dishes	Frequency (%)	Cooking cycle / typology
Breakfast	2	Dal, Rice (or other)	10	Dal: Preheat 15 min, OFF 5 min, ON 1 min, OFF 9 min, Changeover 20 min Rice: Preheat 15 min, OFF 5 min, ON 1 min, OFF 4-9 min, Release 10-15 min
	1	Rice or Dal (or other)	90	Preheat 15 min, OFF 5 min, ON 1 min, OFF 4-9 min, Release 10-15 min
Lunch	1	Noodles or Potatoes	100	ON 20 min
Dinner				Same as Breakfast

As for the TRIID HHs, water heating events representing tea or drinking water heated in the EPC or an electric kettle, if owned, are allowed to occur a varying number of times across the day. Time windows are similar to the TRIID HH windows, with slight differences specified to align with the cooking diary data and HH logger profiles. The lunchtime window remains 12-4 PM for all HHs, whereas the breakfast window is 7:15-10 AM and 6-10 AM for the endline and rollout phases respectively, and the corresponding dinner windows are 5:45-8:30 PM and 4:30-6:45 PM respectively, reflecting the differences seen between the groups in the total cooking profiles in Section 4.4.3. Generally, the EPC cooking modelling was simpler than that of induction cooking, due to the narrow usage of the EPCs seen in the data. Only dish level selectors were required, and only for breakfast and dinner, to choose between cooking one dish in the EPC, which was generally practiced 90% of the time, and two dishes in the EPC. The breakfast and dinner modelling could also represent other meals involving, for example, meat and vegetables, but rice and dal were by far the most cooked dishes in the EPC.

Fuel stacking was accounted for by setting the frequency of use for the events to 90% for breakfast and dinner, as cooking at least one dish in the EPC was very common, and just 10% for lunches, for which other fuels were often used. For the rollout HHs, the breakfast and dinner frequencies were reduced to 70% and 60% respectively, matching up to the HH logger profiles, as the logger data revealed that they used their EPCs less often. Fuel stacking was also built into EPC modelling by omitting a three-dish EPC cooking option, therefore representing a scenario where the third dish of the meal is cooked on another stove, as three-dish consecutive EPC cooking was almost never seen in the diary data and is unlikely compared to consecutive induction cooking due to the low versatility of EPCs.

The lunchtime meal represents frying of potatoes or open-lid non-pressurised boiling of noodles, which are both approximated as a short period of full power EPC cooking, as specified in Table 5.4. For breakfast and dinner, the one EPC dish option starts with a preheat phase of 15 minutes, which is allowed to vary in duration by 30%, as all total durations and cycle durations are, followed by an off period of 5 minutes, while the food is cooking. Then, during the cooking phase, a power pulse lasting 1 minute is specified, to model the case where extra power is required to keep the EPC contents above its temperature setpoint, and in line with Figure 4.2 in Section 4.3.1. For EPC cooking, in some cases a power pulse is not required, whereas in others more than one pulse is observed, therefore one pulse was deemed a reasonable approximation [207]. Following the pulse, the dish cooking would finish after a total of around 25-30 minutes, according to the dish (25 minutes for rice, 30 minutes for dal), based on the ECO study data, after which there would be a period of natural pressure release lasting 10-15 minutes. Therefore, after the power pulse, no further power consumption was modelled.

The preheat phase of EPC cooking for each dish, discussed in Chapter 4, was specified as 15 minutes on average, according to the laboratory tests conducted by PEEDA and referred to in Section 4.3.1, where it was found that the preheat phase for rice cooking requires 12 minutes at nominal voltage and 18 minutes at a reduced voltage of 180 V [207]. For two dishes it was most common in the ECO study data for dal to be cooked first, followed by rice, and so the first dish is as specified above, with the cooking complete after 30 minutes, followed by a natural pressure release period plus switchover time totalling 20 minutes. This period includes pressure release of 10-15 minutes plus 5-10 minutes of emptying the EPC into a hot case or other vessel, cleaning the inner pot, and preparing the rice for cooking, or any other kind of delay. After this, the rice dish is modelled as before.

The EPC cooking load modelling was validated against the HH data logger profiles and the NRMSE calculated to determine the level of adherence. Figure 5.5 compares the RAMP and logger profiles for the transition, endline and rollout phases, showing good agreement in each case, both between the average profiles and their standard deviations and therefore their maxima. The NRMSE for each phase was 0.32, 0.29 and 0.30 respectively (Equation (5.1)), with the close adherence obtained with the model for each phase providing additional validation.

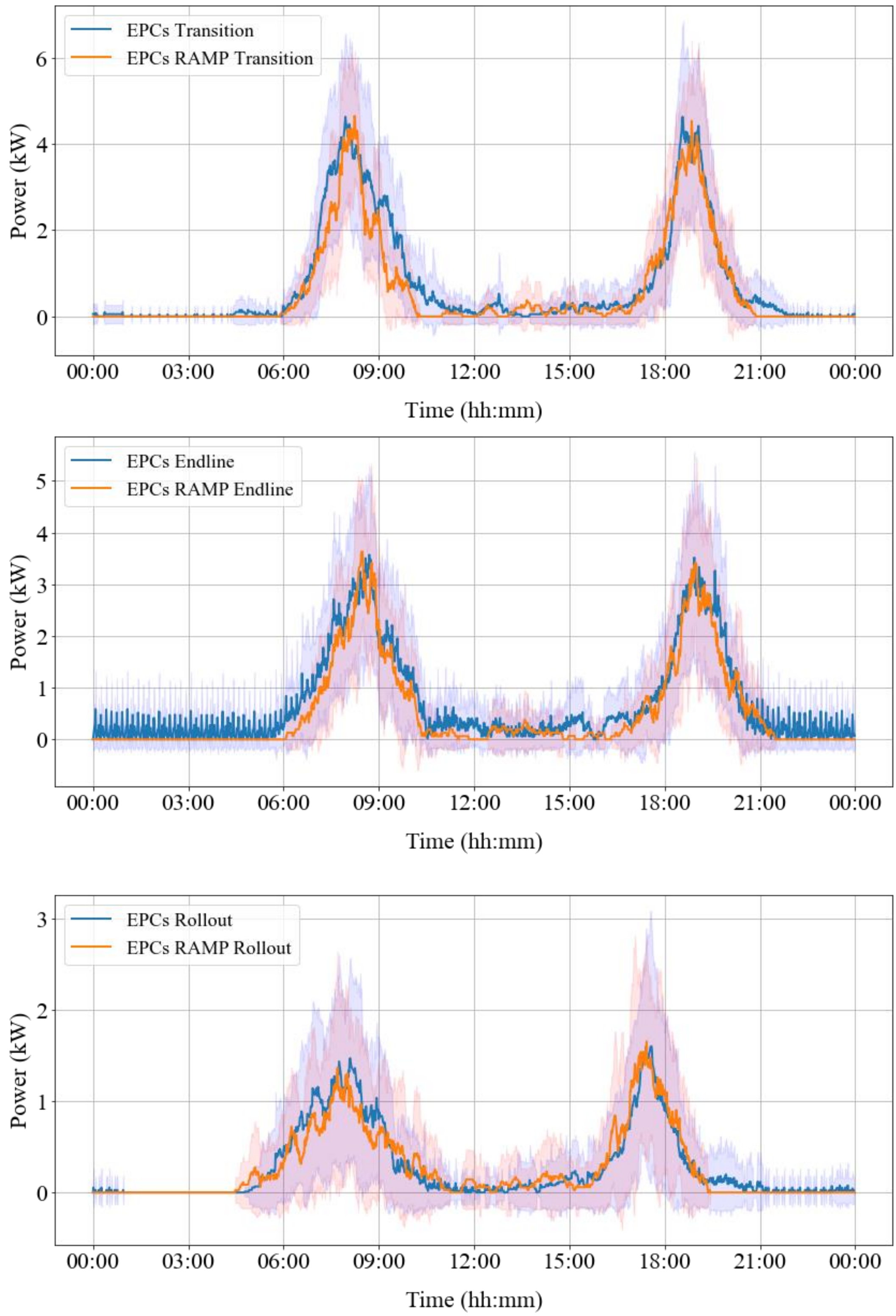

Figure 5.5: Comparison of measured and modelled load profiles for EPC cooking for the transition (top), endline (middle) and rollout (bottom) HHs.

To test the model and evaluate the level of detail of input data required to create a useful model, the electric cooking load modelling for the EPCs in the transition phase was specified with some of the detail obtained from the cooking diary data removed. This was done by imagining what assumptions might be made if some of the cooking diary insights were unknown. Firstly, each meal cooking window was assumed to be two hours around an approximate peak time which could be estimate by community members, and the randomness factors for the windows removed. Secondly, it was assumed that the EPC would be used for two consecutive dishes for each main meal, e.g. rice and dal, as these are the common staples suitable for EPC cooking which it might be predicted participants would cook in their EPCs. The cooking diaries revealed that single dish EPC cooking is actually the most common practice. Figure 5.6 compares the model and the adjusted version for EPCs in the transition phase of the ECO study.

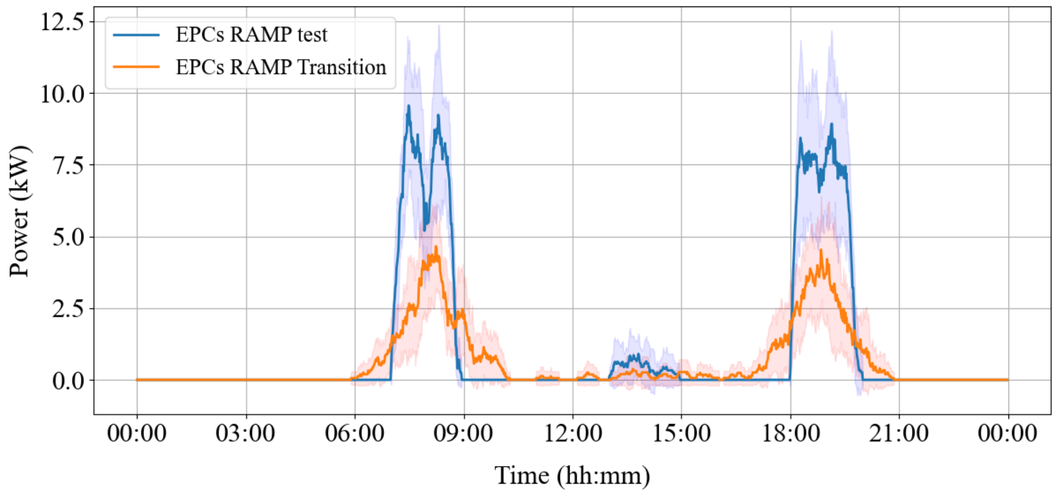

Figure 5.6: Comparison of the cooking load modelling for EPCs in the transition phase (orange) and an adjusted modelling specification for lower detail input data (blue).

The adjusted model produces profiles with much higher peaks, significantly higher than the measured data adhered to by the original modelling specification. In fact, the adjusted model still includes data on dish durations obtained from the diaries, which could be approximated, but nonetheless showing that all elements of the diary data were essential for specifying cooking practices accurately. Therefore, the level of detail of the data used to inform the model is justified and necessary for its initial setup in order to create a representative to model.

5.4.3 Community techno-economic model

After validating the electric cooking modelling, the community RAMP model was updated according to the latest data, with 7 TRIID study induction HHs and 1 TRIID study induction plus rice cooker HH, rather than 11 and 4 respectively, as recent surveys revealed that some cookers had broken down. The numbers of ECO HHs were updated to

28 and 20 for the main group and rollout group respectively. The frequency of use for the TRIID HHs was also reduced from 90% to 70% to represent more realistic fuel stacking than during the original two-week transition phase, when HHs were encouraged to use the cookers as often as possible, while the EPC HH frequencies were unaltered as the ECO study captured settled usage habits. The EPC modelled power consumption was increased to rated power in the community model so as to enable comparison with data measured in the powerhouse. Load profiles from the ECO study were used to validate the community RAMP model [140].

Figure 5.7 presents a comparison of thirty-day RAMP outputs and a community average load profile based on data from the rollout phase of the ECO study of 14 days in November and December 2021, during which the voltage was mostly stable, with brownouts occurring on some days. The blue line shows the average RAMP load profile across the thirty days of a typical month. The background clouds encompass one standard deviation either side of the mean, depicting the variation in daily profiles for each dataset. There is strong agreement between the average RAMP profile and the measured data, with the NRMSE calculated to be 0.11 (Equation (5.1)).

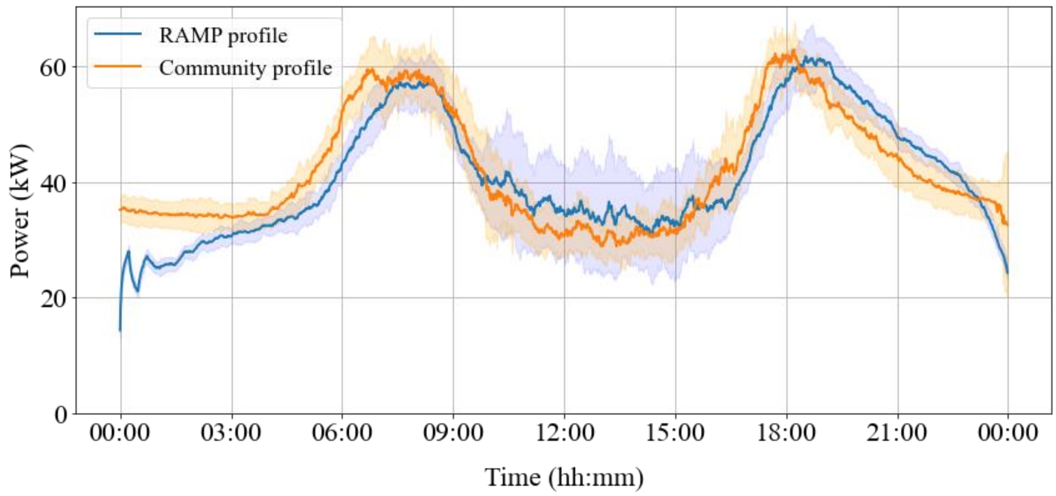

Figure 5.7: Comparison of community-wide RAMP and ECO study average load profiles.

The small peak and trough in the first hour of the RAMP profile, which have very little impact on the modelled energy consumption, can be attributed to an idiosyncrasy of RAMP, whereby each day is considered separately. This windowing means that appliances do not remain switched on across days, leading to lower modelled load just before and after midnight. The profiles mostly agree, with the variability during peak times similar, as evidenced by the background clouds reaching similar levels. There are slight differences in the timings of the peaks, the early morning and late evening load, the off-peak load between the morning and evening peaks, and the variability during this afternoon period. Firstly, the evening peak falling slightly later in the RAMP profile than the community profile is not problematic, as this peak occurred earlier in the endline phase and all other powerhouse data, suggesting that it can vary across the year and will vary as community activity varies. Furthermore, the load in the early and mid-morning is a slight underestimation, whereas that of the afternoon and late evening is slightly overestimated, exerting counteracting effects on the overall energy consumption, which affects the economic outcomes.

As outlined in Section 4.4.3, the community load in November and December 2021 was higher than a few months previously, perhaps partly due to the Tihar festival including connection of additional lights to the mini-grid. Therefore, the community load profile in Figure 5.7 may be a slight overestimation of the norm in peak times, meaning that the RAMP load profiles peaks are higher than necessary. However, the community profile includes the effect of brownouts on some constituent days, which would have lowered peak loads slightly. Their effect is not present in the model, meaning that the model output profiles being slightly higher than required make sense. The effect of brownouts on total energy consumption was taken into account in the model, as explained shortly.

The MHP secretary interview revealed that the MHP operators monitor the state of the mini-grid and request that mill operators switch off their machines when the total load nears capacity, which is difficult to model in RAMP while preserving its stochastic approach, potentially explaining the increased variability in the RAMP profiles seen in the afternoon period. Figure 5.8 shows the RAMP average output profiles and series broken down into HHs, commercial plus community end uses (ComEUs), and IEUs. HHs and IEUs produce the most variation, with IEUs peaks ranging from low to around 50 kW, showing that operator interventions could have a significant impact on the total load.

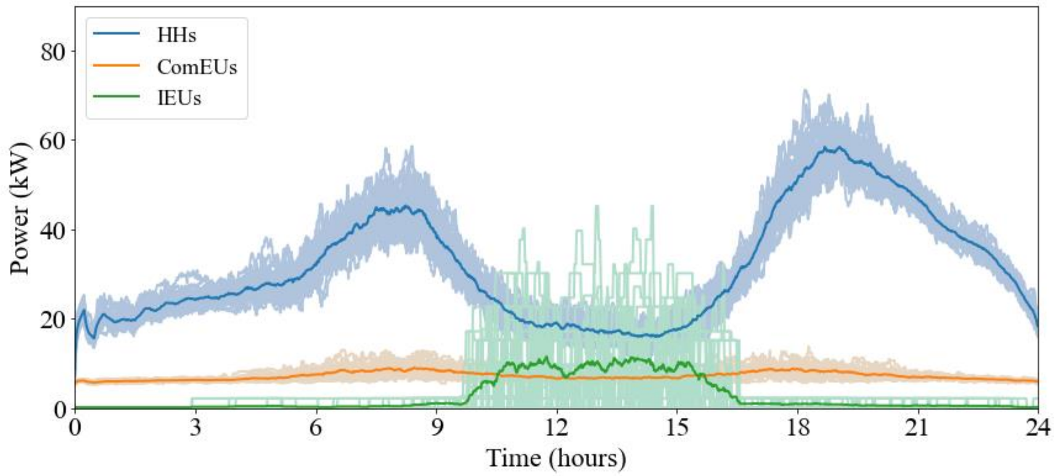

Figure 5.8: RAMP output profiles split by end use type. The solid lines are the average profiles and the background clouds depict all thirty days of profiles.

The model was originally validated against MHP electrical system data measured before the extension and introduction of the DSM measures. RAMP was then updated to reflect the measures, with the mills' agreement represented by confining usage to 10-4 PM, and HH RAMP parameters updated to reflect HH electricity saving practices, including reduced lights, TV and radio usage per day and, for HH types 4 and 5, reduced frequency of rice cooker and electric kettle usage. The updates were specified according to the opinions of the research team and experiences of field work in the case study community. These changes reduced the resulting RAMP profiles to around the level seen in the latest data obtained during the ECO study, showing that RAMP can be used to model and assess DSM measures.

The result of the testing of the cooking load modelling in Section 5.4.2 can be extended to the overall community model in that it would be impossible to create a realistic model of the community electricity demand without collecting detailed data on the end uses, appliances, and their typical usage patterns. It was also essential to gather the obtained data to enable HH level modelling to be specified, generating income and cost breakdowns by HH, necessary for understanding estimated monthly payments and electric cooking costs. The generated load profiles across a typical month were used to assess the potential economic status of the plant if the new tariff structure is introduced. A month of profiles rather than an entire year was deemed acceptable due to limited data on seasonality and computational resources. The MHP secretary survey, presented in Appendix A3.1, revealed that there is little variation in electricity demand across the year. Rather than storing the energy consumption of each individual user, the average consumption was calculated for each user type to save computational resources and focus results. Using the average consumption of a single user in each user type, the tariff system in Table 5.1 was applied and the resulting average single user income multiplied by the number of users in each type to calculate overall user type income and plant income.

Two factors are then applied during the economic calculations. Firstly, the total energy consumption of each user type is reduced by 10% to account for brownouts and blackouts, equating to three days of power outages in total across the month, which was deemed a conservative measure for resulting income but possible due to reported occasional shutdowns for maintenance or due to lightning and other external events. Approximately half of the HH survey participants reported frequent electricity supply disturbances.

Secondly, the calculated total income for each HH type excluding the electric cooking HHs is reduced by 20% to account for a proportion of consumers not paying their bills, both due to a sense of entitlement and exemption due to poverty. The percentage was chosen based on opinions of the MHP secretary and research team, and is deemed plausible as payments will be collected from HHs by MHP staff and consumers are generally supportive of the new system. The final income, calculated for the modelled month and scaled up to a year, is reduced by the fixed costs detailed in Table 5.5 to calculate overall plant monthly profit. Here profit refers to monthly running profits rather than also considering initial investment costs. NPR 10,000 was reported to be the likely expenditure on meter readers who will be paid per HH visited. There is a plan to hire field staff to attend to issues such as wooden distribution poles falling down.

Table 5.5: Breakdown of plant costs.

Cost	**Amount per month (NPR)**
Operator salary (2)	20,000
Admin staff salary	10,000
Meter readers payment	10,000
Field staff salary (2)	12,500
Maintenance budget	15% of total income

A metric for understanding the level of utilisation of MHP generation was defined as the total energy used across the simulated month divided by the total generated energy, assuming constant MHP power generation of 90 kW, which would be 64,800 kWh. This energy utilisation factor (EUF) reveals how well the community makes use of the available electricity, and how much energy is wasted by dumping it to ballast loads, and can be calculated according to Equation (5.2), below:

$$\text{EUF (\%)} = \frac{Energy\ used}{Energy\ generated} \qquad (5.2)$$

Generally, MHPs are operated below their rated power level, which is 100 kW in Salyan, and the TRIID study showed that the dry season can lead to reduced generation power, due to reduced flow and difficulty increasing the flow of water diverted to the plant at the intake due to the cold climate. Therefore, 90 kW represents a realistic maximum generation power in the community, according to the opinions of research team members, although in reality it is likely to vary around this level over the course of a year. Generally, the generated power can be maintained at a reasonably constant level with in a fully operational MHP.

5.5 Using the techno-economic model

5.5.1 Economic viability

The monthly revenue of the MHP in Salyan with the flat rate tariff system is only around NPR 50,000. The TEM was used to evaluate the potential economic status of the plant if the transition to the proposed payment structure detailed in Table 5.1 is completed while consumer behaviour remains as reported in the surveys and according to the DSM measures and latest data, Scenario P. The key results are presented in Table 5.6. The baseline scenario, B, is included, for which the technical parameters are the same as P, while the monthly profit is currently zero or less as the plant is struggling to cover costs. For all scenarios similar results were obtained over multiple model simulations.

Table 5.6: Key model results of proposed scenario P, compared to the baseline scenario, B.

Scenario	Energy (kWh)	Income (NPR)	Costs (NPR)	Profit (NPR)	Peak load mean (kW)	Peak load maximum (kW)	EUF (%)
B	26,400	50,000		0	61.7	76.8	40.7
P	26,400	203,600	115,500	88,100	61.7	76.8	40.7

The model returns a dramatic increase in monthly income from NPR 50,000 to around NPR 200,000, showing that, even if 20% of consumers do not pay, the new payment structure could significantly increase the financial sustainability of the plant, generating monthly profits of around NPR 90,000. Even after 50% of this remaining profit is allocated to backup and community development funds, NPR 45,000 would remain, and any funds not required for repairs and maintenance could go towards savings or community activities. Therefore, the proposed tariff system would improve the situation in the community significantly and its implementation is recommended.

Figure 5.9 and Figure 5.10 present the income sources and allocations, respectively. Overall, HHs contribute most of the total income, while BEUs and IEUs contribute a significant proportion, much of which comes from the Telecoms tower which is modelled to pay NPR 25,900 per month. The scenario shows that, even with HHs reducing their electricity usage relative to the time before the ECO study, the plant would be very profitable compared to the Baseline scenario, as shown in Figure 5.10.

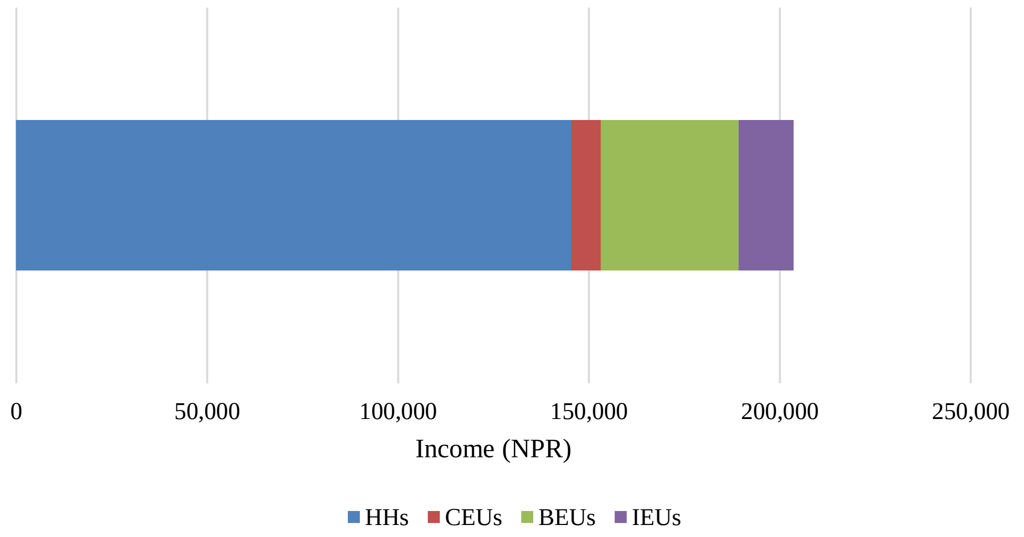

Figure 5.9: Income source breakdown for the proposed scenario.

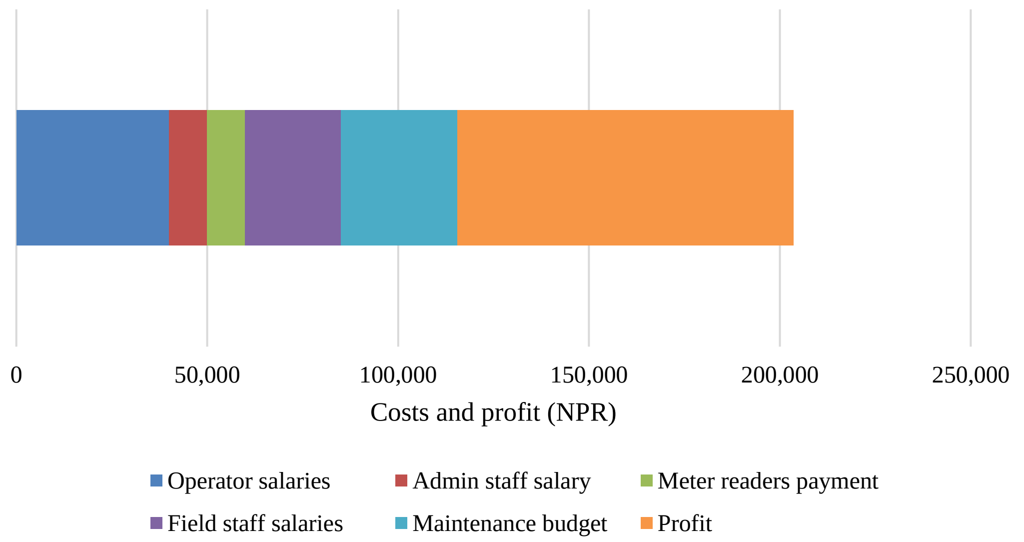

Figure 5.10: Costs and profit for the proposed scenario.

Figure 5.11 shows that HH types 1, 2 and 3 would pay the minimum of NPR 110, consuming less than 18 kWh in the month. In reality some HHs in type 3 would pay more than NPR 110, as the average energy consumption of the group was just short of the 18 kWh threshold. HH type 4 and 5 payments would increase to around NPR 439 and NPR 655 respectively, presenting the question of how willing these HHs will be to pay vastly increased sums for their electricity. HHs generally reported being comfortable paying less than NPR 400 in monthly bills, although, in the experience of the research team, some HHs in rural Nepal are comfortable paying more than NPR 400 and will pay high costs if they deem the service valuable enough. Furthermore, most HHs surveyed were supportive of the proposed payment structure, and there was an awareness that a change is required to improve the MHP financial viability. Another key result was that HH type 4 generates the most income, NPR 54,000, even though it includes only 15% of the total HHs.

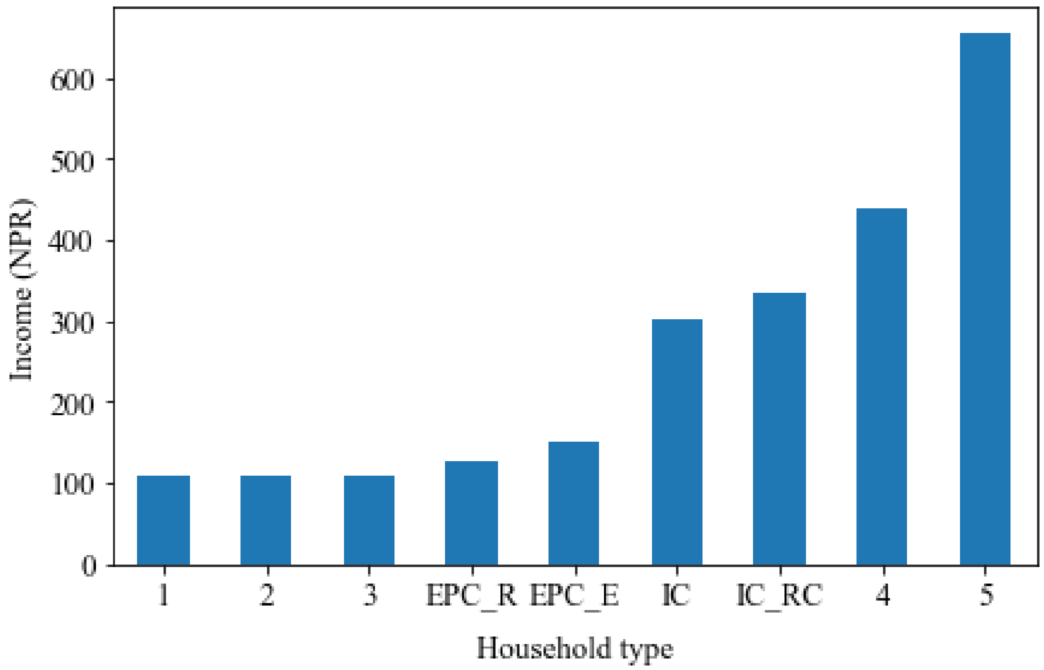

Figure 5.11: Single HH average income across HH types.

HHs with induction cookers would pay around NPR 303, of which around NPR 255 is for electric cooking, although these figures would vary according to cooker usage, with some HHs likely to pay around NPR 500 per month for induction electric cooking alone, as found in the TRIID study. The obtained average of NPR 255 is less than that found in the TRIID study, which was NPR 414, although this is partly due to the reduced settled usage assumed outside of the study context. The model calculated that the EPC HHs would pay around NPR 150 and NPR 126, for the main and rollout groups respectively, of which NPR 102 and NPR 79 would be for electric cooking, aligning with the ECO study data of

NPR 95 and NPR 90. The agreement between the model and the data from the studies provides further confidence in the electric cooking modelling and means that the modelled energy consumption is also comparable. As found in the studies, EPC costs and energy consumptions are much lower than those of induction cooking, largely due to their lower usage fractions.

Importantly, the model revealed how much income would be generated by electric cooking. In total, the income from the 56 HHs with induction cookers or EPCs would be NPR 9,188, almost 5% of the total monthly community income, showing that electric cooking can improve the financial viability of MHPs, even with only a low proportion of around 5% of HHs cooking with electricity.

The proposed tariff system is not more inclusive for lower income HHs than the flat rate system, as the minimum monthly payment is the same at NPR 110. To reduce bills for HHs who might be struggling to pay NPR 110 and using little electricity, and potentially enable HHs not currently paying due to poverty to contribute, the fixed minimum payment could be reduced from NPR 110 to, for example, NPR 50. This scenario generates an overall projected income of NPR 150,000, with total HH income reducing from NPR 145,000 to NPR 92,000. Although clearly a substantial decrease, there would still be sufficient revenue for a high profit of around NPR 43,000.

The model allows variation of key parameters to model extreme scenarios. If the increases in payments were unacceptable for consumers, the HH tariff could be set to NPR 50 for 18 kWh and NPR 6 per additional unit rather than NPR 7. With this reduced tariff, and even if 50% of consumers did not pay regularly, a percentage closer to the current proportion not paying under the flat rate system, the plant would still generate a profit of around NPR 11,000 per month, and monthly payments for HH type 4 would reduce to around NPR 332, perhaps more affordable for these HHs.

Figure 5.7 and Table 5.6 show that, with current consumer electricity usage patterns, the overall demand is high at peak times but much lower in the afternoon, with the EUF only around 40%. DSM measures can reduce peak loads, enabling connection of additional PEUs and appliances used during peak times, while excess energy generated in off-peak periods could also be exploited by new connections. Additional connections increase plant income and, therefore, financial sustainability. The TEM can be used to plan new connections and evaluate DSM measures.

5.5.2 Load planning and DSM measures

The model can be used for load planning, and for simulating DSM measures, as illustrated in the following example, in which the scalability of mills in the community is evaluated if all new mills are operated according to the DSM agreement of off-peak usage between 10 AM and 4 PM. Figure 5.12 presents Scenario M, the resulting load profiles if the number of mills in the community is tripled, connecting 16 extra 3 phase mills and six extra single-phase mills (orange line and cloud), compared to the proposed scenario, P (blue line and cloud). Table 5.7 presents the key results.

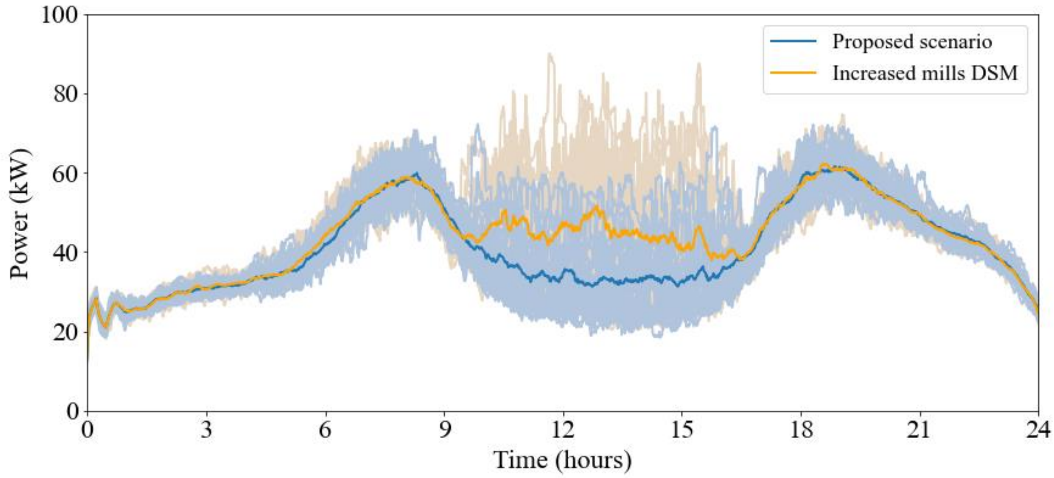

Figure 5.12: RAMP outputs for the addition of extra mills with the DSM agreement.

Table 5.7: Model outputs for Scenarios B, P and M, the latter including additional mills.

Scenario	Energy (kWh)	Income (NPR)	Costs (NPR)	Profit (NPR)	Peak load mean (kW)	Peak load maximum (kW)	EUF (%)
B	26,400	50,000		0	61.7	76.8	40.7
P	26,400	203,600	115,500	88,100	61.7	76.8	40.7
M	28,200	217,400	117,600	99,800	62.2	90.0	43.5

The simulation showed that there is sufficient spare power between the morning and evening that the community could triple the number of mills connected to the mini-grid with the power supply likely to remain largely stable, if the generated power can be increased to around 90 kW. The MHP powerhouse electrical system data analyses of the TRIID and ECO studies showed that, when the total load approaches the generated power, the voltage starts to drop, due to the torque on the generator slowing it down. Therefore, a reasonable threshold for the maximum load beneath which the system could retain stability was deemed to be 85 kW.

Scenario M, in the table above, led to a peak load maximum of 90 kW on one of the thirty simulated days, with the next highest peak across the month reaching around 87 kW, and all the remaining peaks falling short of 85 kW, while on average the off-peak afternoon load only reached around 50-60 kW. Therefore, theoretically, it is likely that the community could introduce the additional mills and mostly retain power supply stability in the off-peak period in question.

In fact, as seen in Section 5.4.3, the model slightly overestimated the average afternoon load and has a tendency to predict higher variability in the afternoon load of the IEUs than seen in the recent data. Therefore, it is possible that even more mills could be connected to the mini-grid than simulated in scenario M, the resulting load profiles if the number of mills in the community is tripled. Importantly, the MHP committee could have confidence in providing new mill operation licences to at least around twenty operators, as long as the generated power was increased to around 90 kW, and as long as the mill operators adhered to the DSM agreement. Of course, infrequent blackouts in the afternoon period would prevent mill usage, with the model useful for planning loads during normal operation of the MHP. Table 5.7 shows that the total income under scenario M would increase by around NPR 14,000, and that the EUF would increase to almost 44%, providing additional profit for the MHP. Overall, the TEM can be used for load planning, with or without DSM measures, to determine the scalability and economic impacts of additional end uses, including IEUs, as demonstrated, and electric cooking.

5.6 Discussion

This chapter developed and presented the results of techno-economic modelling of an MHP community to understand the impact of electric cooking on plant economic status, and explore how tariffs can be set to improve financial sustainability, while contributing a tool which can be used to address research objective 4 on exploring solutions which could enable increased uptake of electric cooking. Overall, the proposed tariff system could increase community income from around NPR 50,000-200,000, and is recommended to be implemented, while electric cooking would contribute almost NPR 10,000 with only 56 HHs with electric cookers in the community.

Previous studies have assessed the sustainability of MHP communities and characterised their electricity demand, but this is the first to create a detailed, adaptable model which approximates the load breakdown of HHs and PEUs, estimates energy consumption and plant economics, and enables load planning of new end uses including electric cooking. As the load factor in Salyan is relatively high, other communities may not generate similar profits with the same payment structure. The model can be used to assess and determine profitable, equitable payment structures for off-grid communities in Nepal and elsewhere, which meet the needs of the people and the plant, ensuring sufficient income while remaining fair and inclusive for consumers.

It would be especially useful for communities wanting to switch to a tariff system based on consumption and/or generating insufficient income, although an MHP community in which expectations on payments have solidified may face difficulties implementing increased tariffs [9]. The model could also be used in the MHP planning stage, with data on the likely numbers of HHs, BEUs, CEUs and IEUs, to estimate income with different tariffs. This chapter also provides valuable data from the surveys on HH appliance ownership and usage, IEUs usage patterns, and appliances used in BEUs and CEUs.

The model was tested by imagining an adjusted version based on lower detail input data, resulting in cooking load profiles with peaks of around double those measured by the HH data loggers in the ECO study. Therefore, the level of detail of the data obtained for the model specification was required in order to create a useful model. However, now that the model specifies the electricity demand of HH groups, business and community end uses, and industrial machines, including typical appliance usage, it can be adapted to other similar communities and contexts based on limited detail input data such as typical daily electricity demand patterns, numbers of households and productive end uses and appliances owned, and usage patterns for industrial machines.

Under the proposed payment structure, the model predicts that around 20-30% HHs will be required to pay significantly more than the flat rate of NPR 110, although this percentage could be higher in reality. High income HHs will likely owe around NPR 400-700 per month, depending on usage and response to the change. Over half of the participating HHs in each of the TRIID and ECO studies reported that they would be willing to pay in excess of NPR 400 for electricity for cooking, but this was after the provision of electric cookers, rather than a large increase in payment for using devices already owned [137], [140]. Therefore, it is possible that a large proportion HHs would be reluctant to pay the increased bills. However, the model showed that if the tariff was reduced so that HH type 4 payments reduced to NPR 332, and 50% of consumers were still unwilling to pay, the system would nevertheless generate sufficient income to cover costs and make relatively small monthly profits.

Comparing the proposed tariff system to other MHP payment structures reveals that it is cheaper than most, which are often NPR 8-10 per kWh above a certain number of units.

[145]. For high energy consuming HHs, such as HH types 4 and 5, the MHP tariff is cheaper than grid electricity, which is NPR 8 or more for over 30 units [216]. The proposed structure could also be adjusted to enable poorer HHs to pay less than the flat rate while the plant remains profitable, increasing the equitability of the system. Overall, as in the TRIID and ECO studies, it is difficult to assess the willingness of consumers to pay increase bills while they still pay a low, flat rate. Alongside the introduction of new tariff systems, communities could run education campaigns for consumers on MHPs and electricity consumption, encouraging appliance usage while explaining that energy saving can reduce bills and peak loads, increasing system stability.

The model showed that the spare energy in the mini-grid could be used for PEUs such as additional mills or other machines, or for the introduction of electric cookers and other high power devices, all of which would increase economic viability further. DSM measures must be specified with convenience for consumers in mind and according to cultural behaviour patterns to ensure effectiveness. The model showed that the number of mills could be tripled if additional operators adhered to the 10 AM to 4 PM restriction. After their introduction, monitoring would be required to identify whether there were windows of concentrated usage within the off-peak period and, if required, the agreement could be extended to restrict usage to different windows for different groups of mill operators, and the model used to approximate the resulting load profiles. As is currently practiced in Salyan, MHP operators could communicate with mill operators to prevent high levels of coincident mill operation by monitoring mini-grid status.

The TEM provides detailed insight into the electricity demand and economics of MHPs but is not without limitations. In its current form, the RAMP demand model does not store individual user profiles within each user type, leading to average energy consumption and income for user types rather than ranges across user instances. The model could be adapted to store profiles of each user if greater detail were of interest. Furthermore, specifying HH user types based on survey results from a sample of thirty HHs carries inherent uncertainty, although detailed information can be obtained on BEUs, CEUs and IEUs due to their lower numerosity, enabling HH demand to be characterised and adjusted so that community-wide outputs match measured data.

Large communities without detailed bookkeeping inevitably require assumptions on the proportion of paying consumers, energy losses and seasonality. The energy loss measure for brownouts and blackouts could be specified more accurately with increased data interrogation. However, overall, with surveys conducted in thirty HHs and the aforementioned assumptions, a close adherence was obtained for the community-wide profiles to measured data, with a low NRMSE. Therefore, the model can be used to generate sufficiently realistic demand profiles based on limited demand data.

The induction cooking load modelling is limited by a lack of measured load profiles for data validation, whereas the EPC modelling benefitted from comparison to HH logger data on power consumption. Modelling HHs with induction cookers and rice cookers presented the difficulty of ensuring each cooker is used at similar times. However, using cooking diary data to inform the cooking load models specification produced similar profiles to the average diary profiles, with low NRMSE in each case. As the diary data from each study was examined to determine inputs to RAMP's bottom-up modelling approach such as approximate cooking windows, durations, dish frequencies and fuel stacking, and outputs subsequently validated against cooking diary average load profiles generated from recorded cooking events, there can be confidence in the validity of the cooking load models. They could be easily adapted to other contexts with similar information on the cooking context due to its generic structure, specifying up to three dishes for each meal, and already provide reasonable models for communities across rural Nepal where cooking practices are comparable [137].The model assumes that electricity usage patterns remain the same after electricity consumption is metered. However, even if consumers reduced their electricity consumption further, which may be unlikely for some HHs as they have already done so when asked to during the ECO study, the plant is likely to remain profitable due to the high projected revenue. Furthermore, the model can be used to assess the effect of introducing additional end uses such as electric cooking and industrial machines, which could increase revenue further. The model scenarios were simulated for one month and did not include load evolution projections such as increasing appliance ownership. RAMP is adaptable and parameters adjustable to enable easy addition of devices, increased timescales, and sensitivity analyses to reduce uncertainties.

Even with DSM measures, in MHP communities of hundreds of HHs, electric cooking scalability is very limited. The TEM can be used to generate realistic community-wide demand profiles including cooking, enabling simulation and specification of energy storage systems which could increase the uptake of electric cooking, as explored in Chapter 6. Finally, Chapter 7 uses the TEM to assess the scalability of electric cooking in the community, through direct cooking with different types of electric cookers, including DSM agreements around cooking, and through energy storage systems for electric cooking.

5.7 Summary

This chapter developed a RAMP based stochastic techno-economic model for evaluating the economic viability of off-grid communities and improving their financial sustainability by introducing new appliances, PEUs and DSM measures. The model can be used to understand community electricity demand, assess economic status, and determine equitable and profitable tariff structures. This is the first study to develop a detailed techno-economic model of a Nepali MHP community. The model showed that a payment structure based on electricity consumption rather than a flat tariff could increase the income of a case study community in Eastern Nepal by approximately 300%, although increased monthly payments for certain HHs from NPR 110 to NPR 400-700 could present difficulty. However, lower and more equitable tariffs could be chosen while preserving plant profitability.

The chapter contributes validated electric cooking load models for Nepali cooking, scalable to approximate widespread uptake of electric cooking, and adaptable to other cookers and contexts. The income generated by 56 HHs with electric cookers in the community amounted to around 5% of total income, revealing the potential of electric cooking to improve the financial sustainability of MHP communities. The model can also be used to plan new connections such as electric cookers and industrial machines and test DSM measures to utilise the spare energy in MHP mini-grids. It was found that the number of mills in the community could be tripled. Generated load profiles could be used for realistic sizing of energy storage systems to enable increased uptake of electric cooking. Energy storage for increased electric cooking is explored in Chapter 6, using load profiles generated by the techno-economic model, before the scalability and economic viability of electric cooking and solutions for increasing its adoption is evaluated in Chapter 7 through the techno-economic model.

Model testing showed that the high level of detail of the obtained input data was justified. However, the model can be adapted to other similar communities and contexts based on limited detail input data such as typical daily electricity demand patterns, numbers of households and productive end uses and appliances owned, and usage patterns for industrial machines.

Chapter 6

Modelling and sizing of battery storage systems in MHP mini-grids

6.1 Introduction and control system modelling

As identified in the literature review, battery storage could be integrated into MHP mini-grids in central, distributed or HH topologies to support increased penetration of electric cooking. The load factor, which is the ratio of the average load to the peak load in a specified time period, is relatively high for Salyan at around 60% with the off-peak load around 40 kW, compared to factors as low as 20% in many MHPs in Nepal [145]. However, it could still be vastly improved if energy generated in off-peak periods could be stored, improving the usage of the generated energy and enabling higher peak loads.

This chapter mostly focusses on modelling to estimate the required battery capacities for enabling increased adoption of electric cooking in MHP mini-grids, addressing objective 5. To inform this modelling, control system modelling of the integration of battery energy storage systems (BESS) into MHP mini-grids was conducted, generating understanding of how the generated power is used to charge BESS, how BESS could interact with the electronic load controller (ELC), and how the BESS could discharge to provide power for increased peak loads due to the introduction of electric cooking. The control system modelling is presented in detail in Appendix 4.

The modelling provided a proof of concept for reverse droop control for BESS, based on the literature, in a new context of an MHP mini-grid, where the centralised or distributed BESS is/are required to work alongside the generator and ELC, charging with excess generated power and discharging when the total load surpasses the generated power to meet the extra load. Reverse droop was selected as the most suitable control method as it enables BESS to respond to changes in grid frequency and voltage, sinking or providing the required power, enabling the generated power to remain reasonably constant.

The simulations showed that the reverse droop control system works as intended. During the discharge phase, when the total load exceeds the generation, the system operation is straightforward, with the frequency dropping below nominal, enabling the BESS to discharge the required amount of power according to its droop curve, alongside the generated power. The key difference presented by the context is the ELC, which uses frequency control to dump excess generated power when the total load is less than the generation. The ELC frequency setpoint was increased above nominal so that, rather than dumping all of the spare power, the BESS charges with some of the spare power, according to its droop characteristic, while the ELC maintains the frequency at a desirable level. Therefore, the reverse droop control system enables full charging and discharging of the BESS.

The control system was shown to work for both centralised and distributed BESS topologies, and revealed important differences between them. Due to the distributed BESS being located at the consumer end, with the distribution transformers, the load carrying requirements of the initial lines around the powerhouse and the step-up transformer are reduced to around the nominal generated power, as, during the discharge phase, there is no centralised BESS outputting power at the powerhouse alongside the generator.

In the distributed BESS topology, the voltage-reactive power, V-Q, droop enables the BESS to prop up the voltage at their locations in the network by outputting reactive power according to the local voltage drop, which is not possible in the centralised topology. Therefore, distributed BESS can improve power quality, although this is at the expense of injecting extra current into the mini-grid.

Overall, tt was found that the generator sends power to the loads in proportion to their magnitude, with the BESS meeting the extra demand that the generator is unable to serve. AThe understanding gained can be transferred to BESS sizing through simplified modelling. Figure 6.1 depicts a snapshot of the modelled electricity demand in the case study mini-grid, showing that, if the generated power is assumed constant at 90 kW, there is a lot of spare power that could be used for charging central and HH batteries to enable increased electric cooking, rather than being dumped by the ELC to ballast heaters.

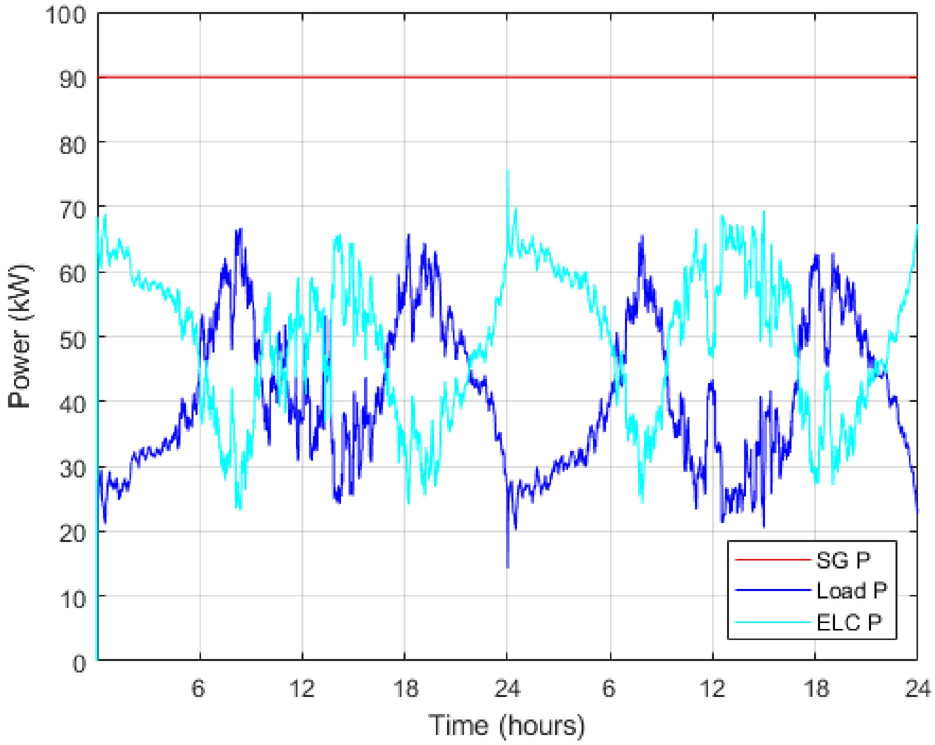

Figure 6.1: Modelled electricity demand and dumped power, using TEM load modelling.

The central BESS topology was taken forward as the simplest illustration of the potential of energy storage in MHP mini-grids, while the HH battery topology demonstrates storage at the opposite end of the scale. Further work could use the knowledge obtained on distributed storage topologies gained from the control system modelling to simulate and specify distributed battery capacities for increased electric cooking.

The literature outlined in Section 2.6.3 showed that modelling of power flows in mini-grids is common and that HH batteries are already being explored for supporting electric cooking. Various studies have used simplified power flow modelling to estimate required capacities for centralised BESS in mini-grid contexts, based on energy dispatch strategies whereby the BESS charges and discharges according to the electricity demand and power generation [171], [172], [197]. Studies on electric cooking penetration in solar mini-grids included modelling of the network topology and electrical parameters throughout the grids, using OpenDSS software, enabling understanding of the voltage levels and load requirements of mini-grid infrastructure [49], [121].

In this chapter, some of these concepts are applied to the new context of an MHP mini-grid, with its unique constant power generation capability. The power flows model described in this chapter was originally conceived as part of the TRIID study [140] and is improved here by incorporation of realistic electric cooking loads generated by the TEM.

Overall, this chapter investigates research objective 5 on energy storage in MHP mini-grids, estimating the required battery capacities for BESS at central and HH levels, through mini-grid power flows modelling and HH battery specification, using simplified models and calculations. It aims specify BESS for different topologies and for different penetrations of electric cooking, determining the approximate scalability of BESS-supported electric cooking in the case study MHP community, Salyan.

6.2 Methods for battery storage modelling

6.2.1 Electric cooking energy and load profiles specification

To estimate the battery capacities required for increased electric cooking at central and HH levels, data and modelling from the cooking diary studies and TEM specification were utilised. It was necessary to quantify the amount of electrical energy required for HH electric cooking, for the HH topology, and the load profiles of multiple HHs cooking with electricity, for the central topology. Generally, it was decided to estimate battery sizes for a high level of electric cooking penetration. On a HH level, it was envisaged that a HH battery should contain enough energy so as to enable 2-3 dishes to be cooked with electricity before needing to be recharged. For induction cookers, this was often seen in the TRIID study data, with some HHs regularly cooking three dishes consecutively on their hobs. Even though induction cooker usage reduced for some HHs over the months following the study, some HHs maintained a high usage fraction. For EPCs, although most HHs only used the device for one dish per meal, some used it for two dishes, and it was decided that it should be possible for HHs to do the latter using battery power, rather than restricting usage to a low level.

For both HH and centralised BESS topologies, the nature of the MHP community electricity demand and reasonably constant power generation meant that the two main demand peaks, during which cooking takes place, could be considered as separate events that the BESS must cater for, before being recharged during the afternoon or overnight off-peak period so that they can be used again for the next meal. Therefore, based on cooking diary data, the morning and evening electrical energy consumption requirements for induction cooking were each estimated at 1 kWh. The mean daily electrical energy consumption in the TRIID study for all-electric days was 2.06 kWh, which generally covered 4-6 dishes depending on HH practices, while the mean dish energy consumption was 0.35 kWh, justifying 1 kWh as a reasonable energy requirement of 2-3 dishes on an induction hob. For EPC cooking, the requirement was set at 0.6 kWh, to enable two dishes to be cooked in the EPC during a meal, based on the ECO study finding that HHs cooking around 1.8 dishes per day in the EPC required on average 0.5 kWh.

For a centralised BESS, the idea of enabling high electric cooker usage was also applied. Thirty-day community load profiles with increased electric cooking were created using the TEM outlined in Chapter 5. Two scenarios were created: one with an increased number of HHs with induction cookers, and one with an increased number of HHs with EPCs. For these scenarios, new RAMP users with cooking appliances were created, based on those specified from the data obtained from the cooking diary studies. Changes included that the frequency of use of the cookers was set to 90%, to represent high usage, as seen in TRIID study for the induction cookers and the cooking diary phases for the EPCs; that the EPC cooking windows were specified as a compromise between the ECO endline and rollout phase groups; and that the EPC dish selectors were reversed so that two EPC dishes were cooked for 90% of meals and one dish for 10%, rather than vice versa. These changes were made to create generalised electric cooking HHs using their cookers for a high proportion of their menu, so that the required central battery capacity for high penetrations of electric cooking could be investigated. Detailed specifications are available in the RAMP input file in the latest version of the TEM data repository [214].

6.2.2 Power flows and centralised BESS modelling

A logic and calculation-based MATLAB model for analysis of real power flows and energy in the MHP mini-grid over a month was created in order to assess how energy storage could enable the uptake of electric cooking by large numbers of HHs, using the rules obtained through the control system modellingon how BESS could operate in a reverse droop control system. It was assumed that the droop characteristics would be specified so that the frequency and voltage would stay within their prescribed limits. Overall, the battery charges through an inverter when there is spare energy in the mini-grid and discharges, if possible, to meet any load that exceeds the generated power. Unused power is dumped to a ballast load of electric heaters. Specifically:

- Charging phase: If the load is less than the nominal generated power, 90 kW, the generator meets the load and the spare generated power is used to charge the battery and/or dumped to the ballast loads, depending on the SoC of the battery
- Discharging phase: If the load is greater than the generated power, the generator and battery combine to meet the load, if possible, the generator providing its maximum nominal power of 90 kW and the battery providing the rest. If the

battery runs out of energy or the required battery power is higher than its maximum discharge power, some of the load will be unmet

Figure 6.2 illustrates the model algorithm, in which ‘excess load’ refers to the load above the nominal generated power, 90 kW, for example 30 kW if the total load is 120 kW.

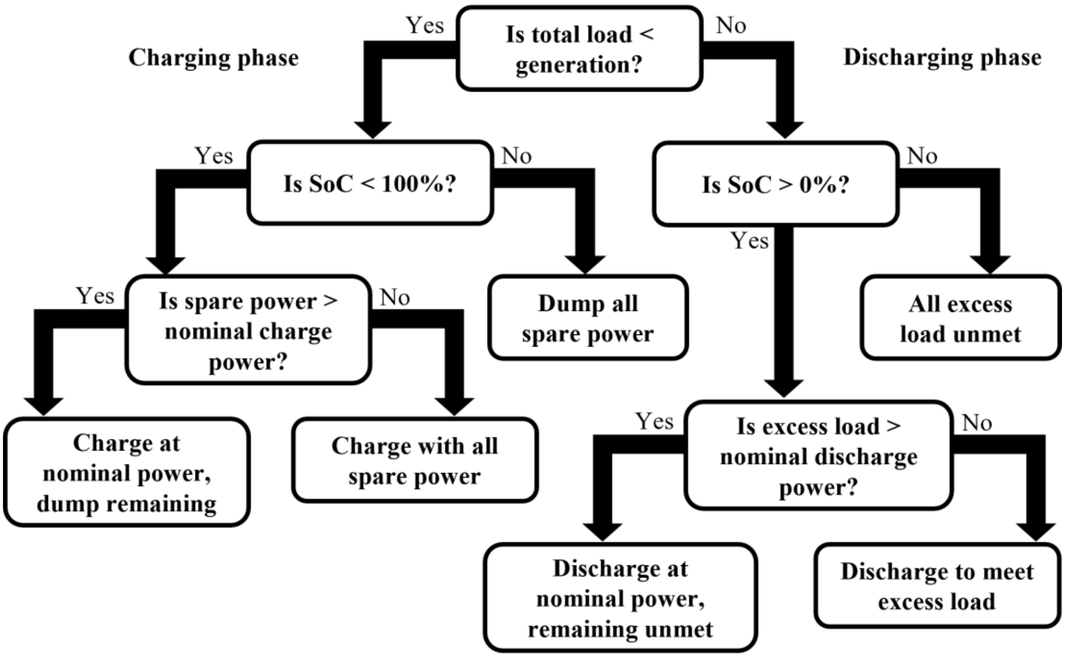

Figure 6.2: Power flows model algorithm.

An idealised battery storage model representative of some lithium-ion batteries was used which assumes a flat discharge curve and uses a round-trip efficiency to determine charging and discharging losses. It does not take into account factors such as capacity reduction at high discharge, capacity fade, temperature and cycle life. An inverter efficiency of 90% and battery round-trip efficiency of 95% were assumed [168], [247], [248]. Lithium batteries are reported to charge and discharge very efficiently and therefore this measure could also include cable losses in the powerhouse [185]. As the demand profiles were specified for nominal voltage, it was assumed unnecessary to consider line losses. As outlined in Section 5.4.3, the maximum generated power was set at 90 kW, a realistic upper bound considering system health and season. Reactive power is not considered.

The charging C rate was limited to a maximum of 0.5C, which would theoretically charge a fully depleted battery in two hours, while the discharging C rate was allowed to vary. High-power charge and discharge reduce available capacity and affect cycle life [187]. The end of life of a battery is sometimes considered to be when its capacity decays to 80% of its original capacity [168]. The cycle life depends on the operating temperature, current drawn and depth of discharge (DoD), with a typical lifetime considered to be around 2,300 cycles or just over 6 years of daily use at a C rate of 0.5C and average DoD of 80% [168]. Higher C rate discharge would likely lead to reduced lifetimes [186]. As the BESS is modelled to charge and discharge twice per day, for each mealtime, the expected lifetime may be limited to a maximum of just over three years, rather than six, depending on C rate and DoD. The battery capacity could be increased by measures to account for decay and capacity loss at high discharge, increasing the cycle life by reducing the required C rate and DoD and by increasing the number of cycles until the capacity decays to 80% of its original level. However, this would incur higher costs.

The model can be used as a guide for sizing a central battery by identifying the minimum capacity required to meet the maximum meal excess load – the highest extra energy above 90 kW, which occurs during a mealtime – while maintaining the battery SoC above a desired level e.g. 20%, and scaled up by converter and battery discharging efficiencies. The model identifies this maximum meal excess load and calculates the required battery capacity to meet it and therefore all other meals, as long as there is sufficient time and power in between community load peaks for the battery to recharge sufficiently. Therefore, the battery SoC generally remains significantly higher than 20% after mealtimes, as the capacity is calculated to cover the worst-case peak load.

6.2.3 HH battery storage modelling

The potential of HH level batteries for electric cooking was also explored. The eCook Modelling Spreadsheet [168], kindly provided by Professor Matthew Leach, was used to size HH batteries according to the induction and EPC cooking energy requirements specified in Section 6.2.1. Firstly, the cooking energy requirement is scaled up by the assumed inverter efficiency η, 90%, and cable losses μ, 5%, as in Equation (6.1) [168]:

$$E_{discharge} = \frac{E_{cooking}}{\eta_{inverter}} \times (1 + \mu_{cables}) \tag{6.1}$$

where $E_{discharge}$ is the amount of energy the battery needs to be able to provide in order to meet $E_{cooking}$, the cooking energy requirement. Then factors are applied for DoD and decay, to prevent the battery from needing to be discharged beneath a minimum SoC of 20%, i.e. a maximum DoD of 80% (DoD_{max}), and to add extra capacity to mitigate the effect of capacity decay over its lifetime, with the default measure to add half the capacity lost by end of life. Therefore, the decay factor, F_{decay}, adds an extra 10% in Equation (6.2), below [168]:

$$C_{battery} = E_{discharge} \times \frac{1}{1 - DoD_{max}} \times (1 + F_{decay}) \quad (6.2)$$

where $C_{battery}$ is the final calculated HH BESS capacity. After useful HH battery capacities for each type of electric cooker were estimated, simple calculations were performed alongside the MATLAB power flows model to assess the scalability of HH battery electric cooking in the community. Two scenarios were assessed. In the first, HHs use their batteries for each of the two main meals and, in between each meal, charge their batteries at constant power over a seven-hour period, i.e. 10-5 AM overnight and 10-5 PM in the afternoon. The off-peak load was estimated at 50 kW, which was around the measured maximum in the latest data from the ECO study, and the number of HH batteries that could be connected to the mini-grid was evaluated. The maximum permissible load was taken to be 85 kW, as in Section 5.5.2.

This scenario approximates the use of a system where BESS are charged during off-peak periods, while not in use for cooking, possibly using reverse droop control, and discharged during peak times if the connected cooker is in use. It could also represent an agreement where community members charge their batteries during these periods, or scheduling technology where charging begins and ends at these times, or an algorithm which begins charging when the battery voltage reaches a minimum level, representing the minimum SOC, although the latter would lead to more varied charging patterns as some HHs would use different amounts of energy for cooking and cook at different times. Therefore, this scenario represents the maximum scalability of HH battery electric cooking without the integration of the batteries into a control system requiring communication links. The seven-hour charging periods enable the lowest possible charging power consumption, given the typical timings of the two main meals. Charging power levels were scaled up by the square root of the assumed BESS round-trip efficiency and the inverter efficiency.

The second scenario explored the maximum possible usage of the available generated energy, calculating the number of HHs that could use their HH batteries or cook directly from the grid in an ideal scenario by dividing the total spare energy in the mini-grid on each day by the chosen daily cooking energy requirement for each cooker i.e. 2 kWh for induction cookers and 1.2 kWh for EPCs. The load profiles created using the TEM in Chapter 5 modelling the current community electricity demand, were used. This scenario ignores losses, instead simply calculating the maximum possible number of times the MHP could provide the cooking energy requirements each day of the month.

The scenario could loosely represent an intelligent control system that schedules HH battery charging and adjusts charging power according to the state of the mini-grid and battery SoC, thus making use of all of the spare power in the network, including during peak times, although HHs would mostly be cooking during peak times. It could also approximate an intelligent system in which communication links enable a combination of MHP and HH BESS power to be used for cooking, with the control discharging some batteries with high SoC, while grid power meets other HH cooking loads, making the best use of the spare power at peak times. Finally, it could loosely represent a UPS-style system with a bypass feature whereby the grid and HH batteries share HH cooking loads, although intelligent control may be required to decide how much grid power and how much battery power should be used in each HH.

6.3 Using models

6.3.1 Centralised storage

The centralised storage model was first run for load profiles with increased induction cooking. Table 6.1 below presents the key results for the addition of induction cookers to 400 HHs in the community, compared to the proposed scenario, P, first outlined in Section 5.4.3, showing what BESS capacity would be required to keep the SoC above 20% during the month of modelled load profiles, as well as providing information on how the electricity demand in the community and electrical system would change.

The model showed that a centralised battery with a capacity of 135 kWh could be integrated into the mini-grid and provide enough energy for the connection of around 400 additional induction cookers, if HHs used them regularly, for around 2-3 dishes per main meal. It calculated that a capacity of between 134 kWh and 135 kWh would be required to maintain the SoC above 20% across the modelled month. With this capacity, the SoC was often much higher than 20% after meals, generally between 30% and 50% depending on the variation in load estimated by the TEM, meaning that the DoD was usually between 50% and 70%, only almost reaching 80% during the maximum load peak.

Table 6.1: Power flows model results on required central BESS capacities and peak loads.

Scenario	Battery capacity (kWh)	Peak load mean (kW)	Peak load max (kW)	Minimum SoC (%)	C rate max (C)
P		61.7	76.8		
400 Induction	135	131.4	153.7	20.3	0.54
400 EPC	45	109.5	138.7	21.8	1.23
800 EPC	201	156.7	182.7	20.6	0.53

Figure 6.3 portrays the behaviour of the model for a two-day period depicting a snapshot of the modelled power flows, showing how the BESS charges (positive power) with the spare power in off-peak periods, and discharges (negative power) to meet the increased cooking loads during peak times. The SoC remains above 20% such that no load is unmet, while any spare power when the BESS is full dumped by the ELC. The maximum discharging C rate was just over 0.5C, which occurred when the required discharge power reached just over 70 kW during the particular mealtime where the load peaked.

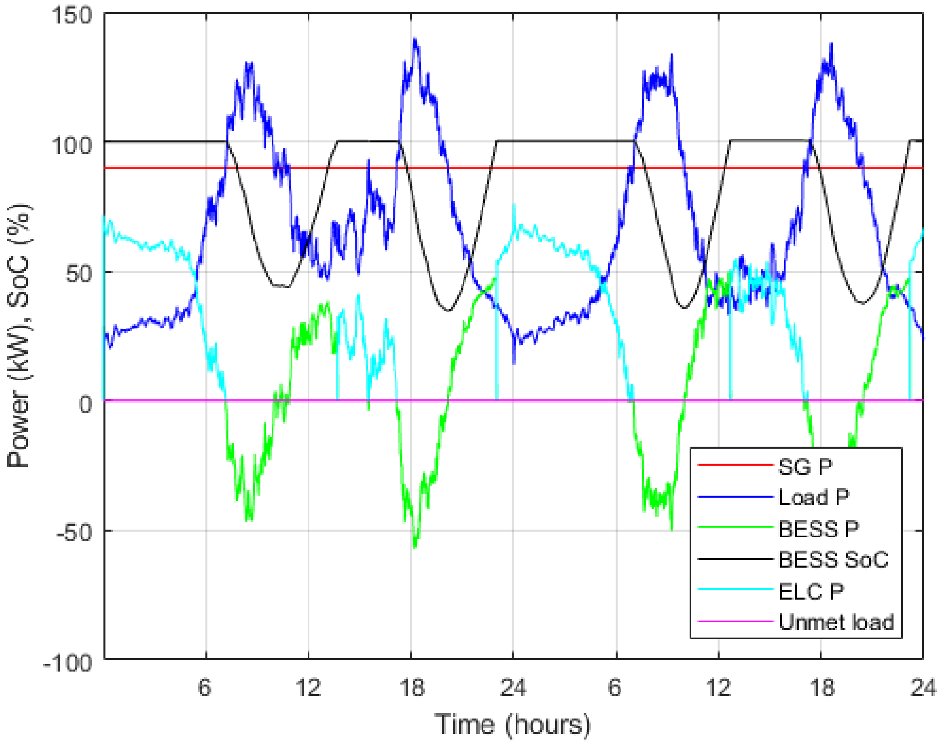

Figure 6.3: Power flows and BESS SoC for load profiles with 400 extra induction cookers.

Importantly, while the BESS could enable this high level of induction cooking in the community, the mini-grid infrastructure would potentially need to be upgraded to accommodate the increased load during peak times, depending on the ratings of the existing infrastructure, with the load reaching almost 155 kW in one instance and regularly surpassing 130 kW. As the model does not include specification of transformers, lines or location of electric cookers in the mini-grid system, it is unable to specify the required load capabilities of the distribution transformers and distribution lines, only calculating the overall peak load. If the ratings were exceeded and relevant upgrades not implemented, the lines and transformers would overheat and fail. Furthermore, the model assumes there are no blackouts during the simulated month. In reality, these would occur on occasion, after which it would be necessary to ensure the BESS could be fully recharged during the next off-peak period.

When the load was increased to 500 HHs cooking with induction hobs the battery sizing rule of covering the maximum meal excess load broke down, as illustrated in Figure 6.4.

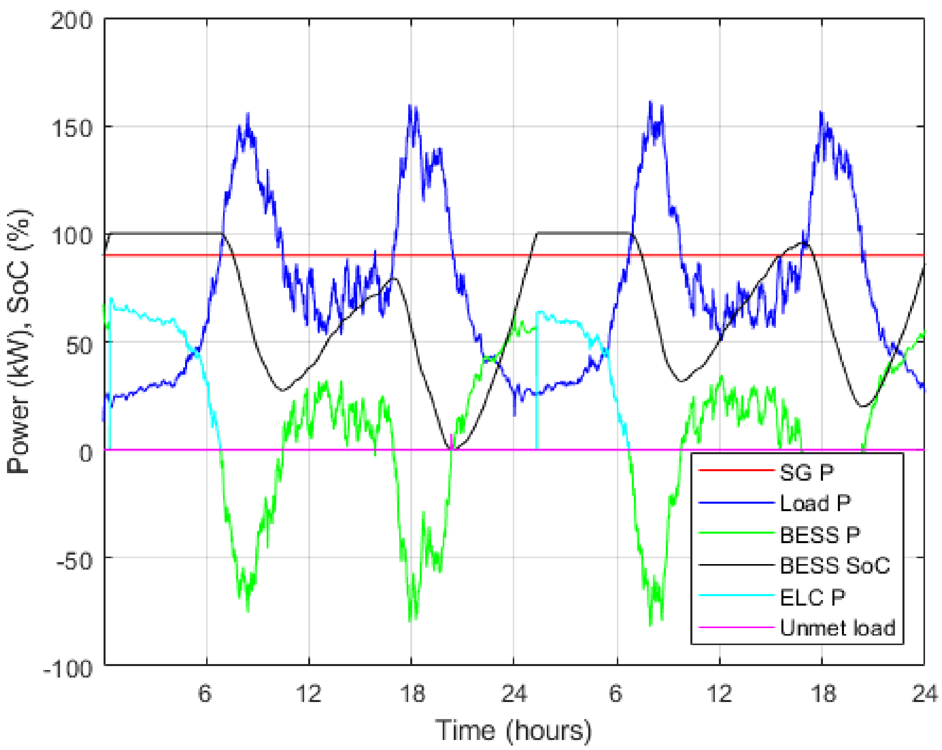

Figure 6.4: Power flows and BESS SoC for load profiles with 500 extra induction cookers.

The calculated required battery capacity was so high that there was sometimes insufficient spare power during off-peak periods to recharge it, meaning that it could not reach full charge between every meal, and therefore ran out of stored energy. Figure 6.4 shows that the SoC drops to zero on one day towards the end of the modelled month and a small amount of load is therefore unmet.

The capacity had to be increased from the calculated value of 195 kWh to 245 kWh to prevent the SoC dropping beneath 20%, but this meant that the SoC did not reach 100% after every charging period. Therefore, the realistic scalability of induction cooking supported by centralised battery storage is limited to between 400 and 500 HHs. The afternoon off-peak period load for the increased induction cooking load profiles was high compared to scenario P, the existing electricity demand based on the latest data, due to water heating events taking place at varying times throughout the day, according to the TEM specification. If HHs did not use their electric cookers or kettles in the afternoon periods there would be more spare power for recharging the centralised BESS. The model was also run for the addition of 400 EPCs to the community, with results presented in Table 6.1, and behaviour presented in Figure 6.5.

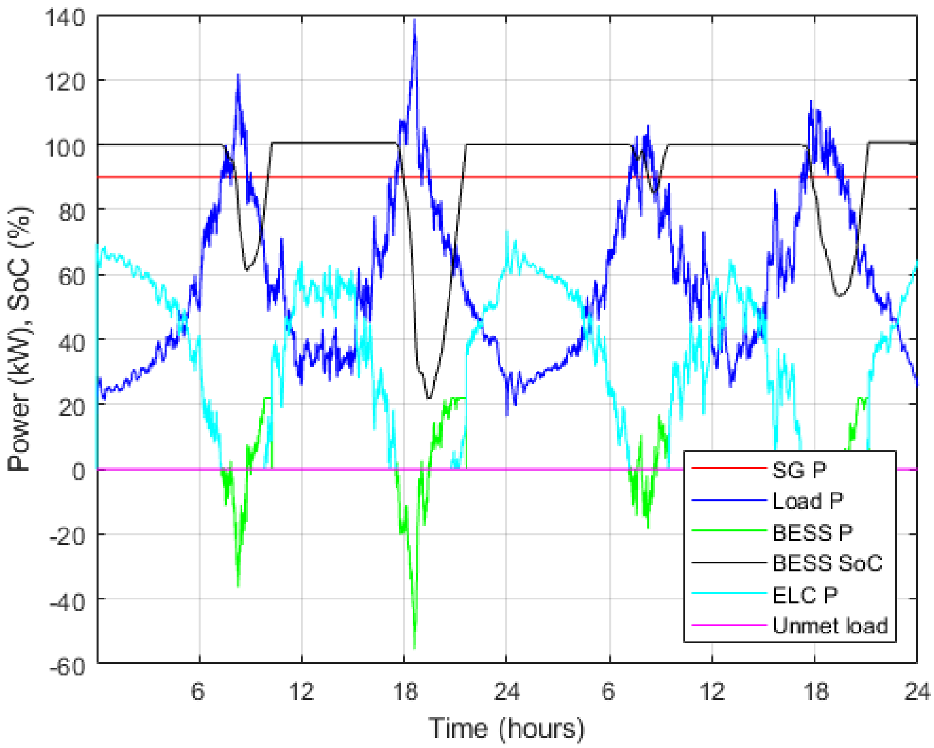

Figure 6.5: Power flows and BESS SoC for load profiles with 400 extra EPCs.

The battery sizing rule calculated a much smaller required BESS capacity of around 45 kWh to maintain the SoC above 20% across a month of simulated load profiles. The peak load the system would need to withstand also reduced to just under 140 kW, with daily peaks regularly reaching around 110 kW. The reduced BESS capacity is as expected due to: the EPC cooking load model representing a maximum of two EPC dishes per meal, rather than three, as three consecutive EPC dishes is unrealistic according to the cooking diary studies; and the short EPC preheat phase leading to lower ADMD of EPC cooking as compared to induction cooking, as seen in Section 4.4.3. The C rate reached just over 1.2C, due to the lower capacity of the BESS relative to the discharge requirements. Therefore, the cycle life would be reduced relative to the induction cooking BESS unless a higher capacity was specified, although once again the SoC generally remained between 30% and 50% after mealtimes, limiting the DoD to around 70%.

Figure 6.5 shows how the SoC remains just above 20% during the evening mealtime on the first day and also displays the reduced peak loads, requiring less power from the

BESS than for the same number of HHs with induction cookers. Therefore, an increased capacity BESS would allow a much higher number than 400 HHs to cook with EPCs. The number of EPC HHs was increased in increments of one hundred until it was found that, beyond 800 HHs, for 900 HHs, the sizing rule broke down as before, suggesting that the upper limit of EPC cooking supported by a centralised BESS is between 800 and 900 HHs, beyond which the BESS is unable to recharge fully between meals. Figure 6.6 presents the system behaviour for 800 HHs cooking with EPCs.

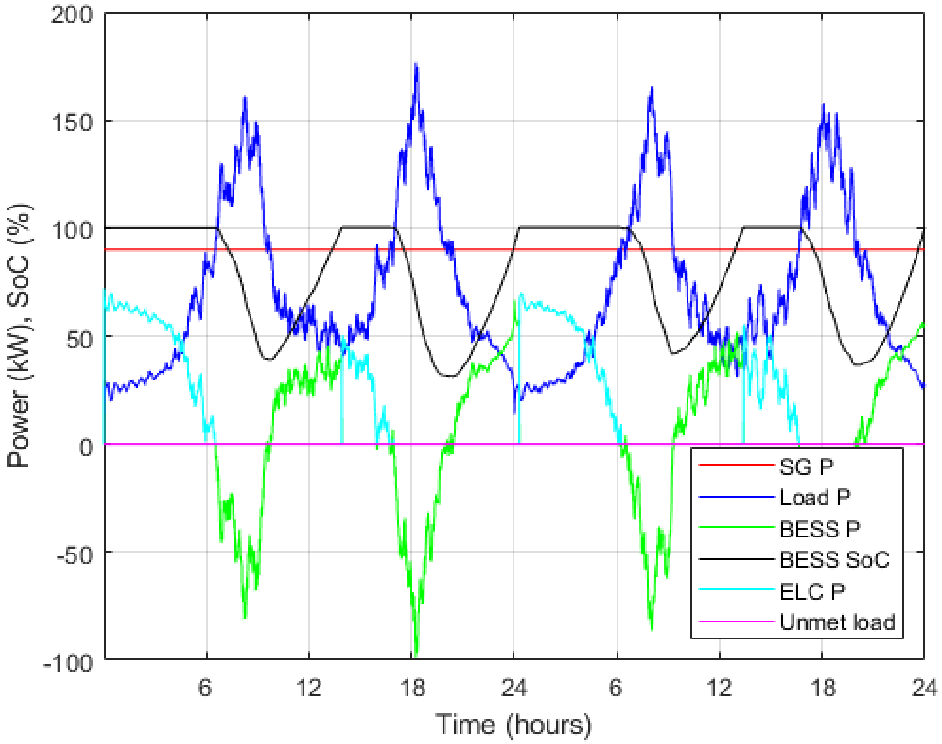

Figure 6.6: Power flows and BESS SoC for load profiles with 800 extra EPCs.

A 201 kWh BESS would be required, while the load reached a maximum of just over 180 kW and daily peaks generally fell just short of 160 kW, representing the load bearing requirements of the mini-grid, as presented in Table 6.1. The maximum C rate was just over 0.5C, similar to that calculated for the 400 induction cooker HHs BESS, while the SoC also generally remained between 30% and 50% after mealtimes, reducing the typical DoD to around 50-70% except for during the maximum load peak.

The scalability of centralised BESS-supported electric cooking was investigated by calculating the required BESS capacities to maintain the SoC above the minimum level for increasing numbers of HHs, as presented in Figure 6.7. The graph shows that the relationship between required BESS capacity and number of HHs is reasonably linear while the sizing rule holds until, once the calculated capacity increases so much that there is insufficient spare power to always recharge the BESS, the required capacity increases more than before, especially in the case of induction cooking HHs, between 400 and 500 HHs. It can be surmised that the scalability limit is closer to 400 than 500 HHs for induction cooking, and closer to 900 than 800 HHs for EPC cooking, due to the larger increase in gradient of the line between 400 and 500 induction cooking HHs. The required capacity continues to increase at higher gradients beyond the scalability limits, evident here for 600 induction cooking HHs and 1,000 EPC cooking HHs.

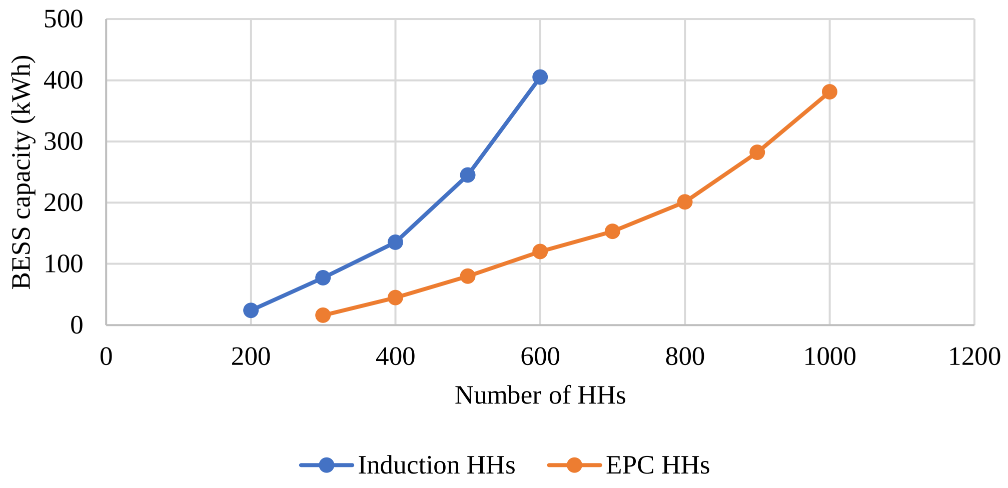

Figure 6.7: Relationship between required central BESS capacity and electric cooking HHs.

6.3.2 HH storage

HH battery modelling enabled understanding of the potential for HHs in the community to cook from batteries in their own homes, both in terms of suitable battery capacities for electric cooking, and the scalability of HH battery electric cooking. Table 6.2 presents the results of the investigation into HH battery electric cooking potential. The eCook modelling spreadsheet was used to calculate useful battery capacities of 1.6 kWh and 0.96 kWh for induction and EPC cooking respectively, based on the meal cooking energy requirements of 1 kWh and 0.6 kWh [168]. The resulting nominal discharge C rates can be calculated as 0.625 and 1 respectively. Although these C rates are high, especially the latter for EPC cooking, the HH BESS sizing calculation included the decay factor to increase the capacity, reducing the required DoD and increasing cycle life. Battery discharge at 1C is also likely to lead to reduced usable capacity, even at the beginning of its lifetime [187]. However, the EPC cooking energy requirement is conservative, as HHs generally used 0.5 kWh for around two EPC dishes. Therefore, an effective capacity of less than 0.96 kWh may still be sufficient for high EPC usage.

Table 6.2: Key HH BESS parameters and scalability indicators.

HH type	HH battery capacity (kWh)	Nominal charge power (kW)	Nominal charge C rate (C)	Nominal discharge power (kW)	Nominal discharge C rate (C)	Max HH batteries stacked	Ideal max cooking HHs (mean)
Induction	1.6	0.23	0.14	1	0.625	134	531
EPC	0.96	0.14	0.14	0.96	1	224	885

The calculations showed that around 134 induction cookers and 224 EPCs could be connected to HH batteries which could be charged simultaneously in off-peak periods using the spare energy in the mini-grid. If four-hour charging were specified instead of seven-hour charging, the scalability would be reduced to 77 and 128 respectively. Depending on the infrastructure capabilities in the mini-grid, and location of the HHs with cookers, infrastructure upgrade requirements may be reduced compared to those required for centralised BESS integration, as the peak load should not exceed the generated power, although fewer HHs would be supported. However, some elements of the mini-grid infrastructure may require upgrading, for example, if many HHs are co-located under the same distribution transformer. The model does not include consideration of upgrade requirements. Furthermore, as found in the cooking diary studies, HH electrical wiring would require upgrading to support the increased HH electricity demand due to electric cooking. If the HH batteries were integrated into the mini-grid control system such that they could send power back through the system, lines and transformers could require additional upgrades.

The results on the maximum numbers of cookers whose charging could be stacked in off-peak periods show reduced uptake potential compared to the results of the power flows model for a centralised BESS. This is partly due to the centralised BESS system utilising more of the spare power surrounding cooking times, either side of the peaks in Figure 6.5, rather than only using the two seven-hour off-peak periods for charging, in the way that the HH BESS charging system does.

The final column in Table 6.2 presents an upper limit for the number of HHs that could cook with each electric cooker, based on the cooking energy requirements and the total spare energy in the mini-grid, showing that high electric cooking penetration is theoretically possible, although this would require an intelligent charging/discharging system which fully utilises the available energy, and slightly reduced cooking energy requirements, as the calculation does not consider losses nor battery DoD. The calculated numbers of HHs, 531 and 885 for those cooking with induction cookers and EPCs respectively, are averages across the thirty days of modelled load profiles. As the cooking energy requirements are conservative and many HHs would likely require less energy, compared to the maximum stacked charging HH battery potential, intermediate numbers of HHs would likely be able to cook from HH batteries, if they were used for fewer dishes, fewer meals or specified to a lower capacity.

6.4 Discussion

This chapter addressed objective 5 on investigating how energy storage could enable increased uptake of electric cooking, focussing on the sizing of BESS for centralised and HH topologies. Overall, the models provide useful, simplified approximations of the requirements and limits of central and HH BESS in MHP mini-grids. High electric cooking usage fractions were assumed to understand potential, with the models adaptable to represent lower usage scenarios which could be enabled by lower capacity BESS. Simple power flows modelling enabled estimation of central battery capacities for widespread adoption of electric cooking and their scalability, while HH cooking energy requirements and community electricity demand data enabled estimation of HH battery requirements and their charging scalability during off-peak periods.

Initially, an approximation of constant current constant voltage (CC CV) charging was specified in the power flows model, where the battery is charged with a constant current at first until the voltage reaches its maximum, at which point the charging current is reduced [185]. For this, the charging C rate was set at 0.5C until the battery reaches 80% state of charge, at which point it drops to 0.1C. The approximation charges the battery in four hours. However, the approximation was deemed unnecessary, as there was generally insufficient spare power for 0.5C charging, so the battery was charged with the available spare power instead, and the approximation had no impact on the obtained results.

The power flows model assumes that the mini-grid infrastructure is upgraded to tolerate the increased loads in the system as, otherwise, the load would be downrated by reduced voltage due to increased losses. Therefore, the model is able to predict the maximum load, and how it varies, and the required BESS capacity to support the increased load in a mini-grid functioning within nominal voltage limits. It is unable to describe how the voltage varies in the mini-grid. Furthermore, it does not consider reactive power, knowledge of which would be required when determining the maximum current throughout the system. The model concepts could be extended and refined into an electrical system model, perhaps using specialist software such as OpenDSS, using data on the mini-grid layout and topology to incorporate electrical parameters and components such as line impedances and transformers, enabling simulation of the reverse droop control system and understanding of real and reactive power, current, voltage and frequency levels throughout the system, as well as specification of infrastructure upgrade requirements. This would enable evaluation of the load requirements and resulting voltage deviations throughout the network, before and after the required upgrades to transformers and cables.

The power flows model showed that 400 induction cooking HHs and 800 EPC HHs load scenarios are around the upper limits of feasibility without central BESS SoC sometimes falling beneath the minimum of 20%. For higher numbers of HHs, the high load significantly depleted the battery during each meal and there was sometimes insufficient spare power, especially during the afternoon period, for it to recharge in time to meet the load of the next meal without being fully depleted, down to 0% SoC. More precise estimates of scalability could be determined as part of future work. The battery capacity could be increased so that, even though it may not always return to 100% SoC during charging, it can provide enough energy for cooking. However, for high numbers of HHs this would require a very high-capacity BESS, at high cost, which would gradually reduce in SoC over time due to there being insufficient recharging power available.

For both BESS topologies, in stable load scenarios, higher BESS capacities could be specified for autonomy, so that one or two days, rather than a single meal, can be provided for by the BESS, in the event of blackouts or system downtime reducing the availability of the MHP. However, these would require oversized batteries at significantly higher costs than for the calculated capacity BESS. Batteries sized to cover one meal would be unusable at times, due to blackouts preventing charging, but HHs would simply fuel stack to meet their cooking needs.

The typical C rates and DoD calculated for each central and HH BESS varied. If used twice per day at around 80% DoD, BESS lifetimes may be limited to a maximum of just over three years for those operated at around 0.5C, and even less for higher C rates, before battery replacement is required [168]. Generally, the central BESS SoC remained higher than 20% after mealtimes, with the DoD typically reaching between 50% and 70%. However, as high discharge can reduce usable capacity, in reality the DoD may be higher than calculated [187]. Lifetimes could be increased if the BESS were used less often, for example for one meal per day instead of two, or if extra capacity was added, as was done in the HH BESS sizing calculations, although this would increase costs. Furthermore, with increased capacity or and/or reduced cooking loads, and as the modelled cooking loads and energy requirements are conservative and for high usage, the cycle life definition could be revised to consider a lower remaining capacity than 80% as the end-of-life capacity, such as 60%, for example, increasing the effective lifetime. Higher BESS capacities specified for autonomy could enable one charge and discharge cycle to cover both mealtimes, rather than two, but would incur significantly higher costs. Other battery technologies and chemistries could be explored. Detailed battery modelling, including other BESS components such as inverters, would enable better quantification of system lifetimes and required replacement frequencies.

The HH BESS modelling provides an indication of suitable battery sizes and approximates scalability. The seven-hour charging scenario could be implemented, either with charging droop control and switching circuitry for discharging for cooking, or through an agreement, depending on consumer willingness, but in reality there would be more variation in BESS charging windows, which would sometimes include peak times, depending on cooking habits, thereby slightly reducing the likely scalability of HH BESS.

The integration of HH batteries into a mini-grid control system such that the MHP and BESS combine to provide power to cooking loads could be explored, as the spare power at peak times is unused in the seven-hour off-peak charging scenario. However, implementation of this may require a sophisticated control system, likely to be more complicated than the reverse droop control system explored in the control system modelling, and the ECO study revealed that HH voltage levels vary widely across the community and across the day, presenting difficulty if using voltage as a control parameter. Improved HH BESS modelling could be incorporated into the aforementioned expanded electrical system modelling, using more realistic CC CV charging, and either by simulating charging loads, or by integration into a control system based on voltage or frequency. Distributed BESS could also be incorporated into an improved model, to determine capacity requirements and enable direct comparison between central, distributed and HH topologies.

For both centralised and HH BESS topologies, further work includes refining and improving the battery model to include more accurate efficiencies and the effects of high-power discharge on cycle life and usable capacity. An electrical model of battery storage could be incorporated into an MHP electrical system model. Nevertheless, the modelling tools presented could be used to estimate BESS potential in other mini-grids using data on generated power, community load and electric cooking loads.

6.5 Summary

In this chapter, the potential of battery storage to enable increased adoption of electric cooking was investigated. Using understanding obtained from the control system modelling, an MHP mini-grid power flows model was created in MATLAB and used with load profiles generated by the TEM described in Chapter 5 to understand how a centralised BESS could be integrated into the case study mini-grid. Community load profiles with 400 extra electric cookers were simulated in the model and the required centralised battery capacities to support the excess load determined while maintaining the battery SoC above 20%. BESS capacities of 135 kWh and 45 kWh were calculated for increased induction and EPC cooking respectively, for which the mini-grid infrastructure would require upgrading to support maximum loads of just under 155 kW and 140 kW respectively, across the simulated month. The addition of 400 extra induction cookers represented an approximate upper limit, as increased penetration would require BESS for which there would sometimes be insufficient spare power to fully recharge, while around 800 EPCs, which could be supported by a 201 kWh BESS with peak loads reaching just over 180 kW, could be connected before the same issue was encountered.

HH battery electric cooking potential was assessed by sizing batteries for HH cooking energy requirements representing high usage of 2-3 dishes per meal for both induction and EPC cooking. Capacities of 1.6 kWh and 0.96 kWh were calculated for enabling induction and EPC cooking estimated to consume 1 kWh and 0.6 kWh respectively for each of the main meals, with the batteries charged during off-peak periods. If the HH BESS were charged slowly over seven-hour periods, it was estimated that around 134 and 224 HH BESS could be introduced in the community. For both central and HH topologies, high C rates and usage twice per day could limit BESS lifetimes to a maximum of just over three years, although detailed modelling is required to accurately quantify battery cycle life. Overall, the models provide useful tools to understand and estimate battery storage requirements to enable increased uptake of electric cooking on central and HH levels, but further data and more detailed modelling would be required to specify more realistic systems. However, this is the first research work to estimate BESS requirements in different topologies and for modelled electric cooking loads in MHP mini-grids.

Chapter 7

Evaluating solutions for increasing electric cooking adoption in MHPs

7.1 Introduction

This chapter aims to update and use the techno-economic model (TEM) to assess the scalability of the identified solutions, their economic impacts on the community, and their resulting feasibility. In doing so, it shows how the TEM can be used for load planning. The chapter also draws on lessons from the cooking diary studies by considering how combinations of electric cookers could enable the adoption of electric cooking as a primary cooking fuel and investigating the associated scalability and economic effects.

The previous chapters identified and evaluated solutions for increasing the potential adoption of electric cooking in MHP mini-grids by: trialling efficient devices in the form of EPCs in the case study community; evaluating the effects of load scheduling and demand reduction DSM measures on the community electricity demand; and investigating the control and sizing of battery storage systems at centralised and HH levels. Chapter 5 outlined the creation of a TEM which was used to understand how a tariff system based on electricity consumption could improve the financial sustainability of the MHP in Salyan, how DSM measures could increase the scalability of industrial machines, and the income generation potential of electric cooking.

7.2 Techno-economic modelling of solutions

The TEM is used to assess the scalability, income generation potential and economic viability of the following:

- Direct electric cooking with EPCs, as compared with induction cookers
- HHs agreeing to a cooking DSM measure
- Centralised and HH battery storage for electric cooking
- HHs cooking with combinations of electric cookers

The TEM provides the ability to evaluate the scalability of these solutions by generating the resulting load profiles, which are simulated to produce the relevant technical and economic outputs. The same method for scalability assessment as exemplified by increasing the number of mills in the community in Section 5.5.2 was employed, with the number of each cooker or battery varied until the simulated peak load across the month exceeded the stability limit of 85 kW. As explained in Section 5.4.3, it is possible that the RAMP model load profile peaks are slightly higher than required, due to the community load being higher than usual in late 2021 during the Tihar festival. Therefore, scalability assessments of loads during peak times may produce slightly conservative estimates. However, it may be that additional end uses also caused the increased community load in late 2021, and that these have continued to be connected since, so that the model load profiles are representative of the demand. Overall, obtaining a reasonable match to measured data was considered important, as was conservativeness in estimates. Generally, multiple runs of the same simulations produced similar results, with the resulting peak load across the month varying within ranges of around 3-4 kW.

7.2.1 Solutions

Table 7.1 provides information on the scenarios evaluated for each of the solutions, including the electric cooker combination scenarios.

Table 7.1: Evaluated solutions with constituent scenarios and explanations.

Solution type	Scenario	Notes
Direct electric cooking	Induction realistic	Frequency of use 70%, based on projected reduced usage after TRIID study
	Induction TRIID	Frequency of use 90%, based on TRIID study data and usage levels
	EPC rollout	Frequency of use 70%, unmonitored
	EPC monitored	Frequency of use 90%, based on ECO study endline phase data
	EPC high	Frequency of use 90% and dish selectors reversed – two EPC dishes most likely
Direct electric cooking with cooking DSM agreement	Induction TRIID DSM	As above scenarios with extended windows
	EPC monitored DSM	See above
	EPC high DSM	See above
Battery storage-supported electric cooking	Induction central BESS	Uses ‘Induction TRIID’ scenario profiles
	EPC central BESS	Uses ‘EPC high’ scenario profiles
	Induction HH BESS	RAMP appliances representing 1.6 kWh HH BESS using parameters in Table 6.2
	EPC HH BESS	RAMP appliances representing 0.96 kWh HH BESS using parameters in Table 6.2

Electric cooker combinations	Induction TRIID + rice cooker	As in Table 5.3 but with rice cooked concurrently for the 2- and 3-dish options
	EPC monitored + rice cooker	See Table 7.2, concurrent EPC and rice cooker usage

For the assessment of direct EPC cooking as the efficient devices solution, as compared with induction cooking, simulations of the TEM including the electric cooking modelling explained in Section 6.2.1, used in the power flows model, were conducted, and the number of HHs with each cooker varied to determine the upper limit before the resulting community load peaks exceed 85 kW during the simulated month of load profiles. In Table 7.1, frequency of use refers to how often a cooker is used for a meal, reflecting levels of fuel stacking. For induction cooking HHs, more ‘realistic’ usage than observed during the TRIID study was assessed, while high usage was also evaluated. For EPC cooking, the 70% frequency of use case represents HHs cooking with similar EPC usage fractions as observed in the rollout phase of the ECO study, modelling users who are not monitored and supported during their adoption of electric cooking. The 90% frequency of use case was also run, representing HHs who took part in the cooking diary phases of the ECO study. Finally, a simulation to capture high EPC usage was conducted, with 90% frequency of use and where two EPCs dishes per meal, rather than one, is most likely, to assess the impact on the resulting scalability of EPC cooking.

DSM measures could increase electric cooking scalability further. The induction and EPC cooking model specifications were adapted by specification of wider cooking windows, extended by an hour in both directions, to represent the effect of a DSM measure such as an agreement that HHs only start cooking if the voltage is stable, encouraging cooking over wider periods of time, as implemented successfully in Myanmar [155]. Such an agreement is potentially feasible if HH meters displayed the supply voltage and training was provided, although meters would present additional costs. Simulations were conducted for 90% frequency of use and for high EPC usage.

For assessing centralised battery storage, the results of the power flows model were analysed through the TEM to determine the associated income generated by the increased electric cooking, which was compared with approximate BESS costs. For HH batteries, new RAMP users and appliances were specified to represent the stacked off-peak HH battery charging outlined in Section 6.2.3, with the details accessible in the latest TEM data repository [214]. The parameters were set according to the specification, with charging windows of 10-5 AM and 10-5 PM, charging powers calculated as specified in Section 6.3.2 and scaled up for inverter and battery round-trip efficiencies. For these appliances, RAMP variability factors were kept low, to represent HHs agreeing to charge their batteries at certain times, scheduled charging, or a control system which charges batteries in off-peak periods and switches to discharging for cooking as required. The TEM was then used to verify the findings of the HH storage modelling in Section 6.3.2 and determine the economic impacts, which were then assessed against estimated costs. For both centralised and HH BESS, battery lifetime is an important consideration. The TEM enabled calculation of approximate payback periods for BESS if MHP profits were used to cover initial costs, which were compared to likely battery lifetimes, to assess the viability of increasing electric cooking adoption through the introduction of BESS.

7.2.2 Electric cooker combinations

Electric cooker combinations were evaluated as the cooking diary studies revealed that owning an extra cooker would make adoption of electric cooking as a primary cooking fuel much more likely. As rice cookers were used successfully by HHs in the TRIID study alongside induction cookers, and due to their lower cost as compared to induction cookers and EPCs, two new RAMP users were specified, the first representing a general case of HHs with induction cookers and rice cookers, and the second representing HHs with EPCs and rice cookers, as specified in Table 7.2, with further details accessible in the latest TEM data repository [214]. A combination of induction cooker and EPC would also be very effective, although it would be much more expensive than the rice cooker combinations, and the EPC would likely be used mostly as a rice cooker anyway, as found in the ECO study, with the induction cooker preferred for other dishes such as dal, vegetables, roti, etc, due to its fast cooking and easier frying capability.

The HHs with induction cookers and rice cookers were modelled in the same way as specified in Table 5.3 in Section 5.4.2 except that, rather than modelling rice cooker usage as a separate appliance which allows the rice dish timing to vary, concurrent electric cooking was made inevitable, so that the two and three dish options included simultaneous usage of the induction and rice cookers. This was done as the aim of simulating electric cooker combinations was to understand how high electric cooker usage, including concurrent electric cooking, affects the resulting load profiles and ADMD of electric cooking HHs. For the three-dish option, the most common occurrence seen in the data was for dal to be cooked first, followed by rice and vegetables concurrently. Therefore, the power consumption for the second dish was increased by 900 W, the rice cooker power rating, to represent simultaneous cooking of rice and vegetables, while the two-dish option simply excluded the first dish.

For the induction plus rice cooker HHs, the three-dish option was already covered, with the rice switched to being cooked in the rice cooker. However, for the EPC plus rice cooker HHs, the original EPC modelling only included up to two EPC dishes. With the advent of a rice cooker, an option of two EPC dishes plus one rice cooker dish was now relevant. Therefore, the EPC cooking load modelling was adapted according to Table 7.3.

Table 7.3: RAMP modelling specification for HHs with EPCs and rice cookers.

Meal	No. dishes	Dishes	Frequency (%)	Cooking cycle / typology
Breakfast	3	Dal, Rice, Vegetables (or other)	20	Dal: Preheat 15 min, OFF 5 min, ON 1 min, OFF 9 min, Changeover 20 min Veg: ON 5 min then repeat OFF 3 min and ON 2 min until 25 min reached Rice: HP (900 W) 25 min, concurrently
	2	Dal, Rice (or other)	70	Dal: Preheat 15 min, OFF 5 min, ON 1 min, OFF 4 min, Release 10-15 min Rice: HP (900 W) 25 min, concurrently
	1	Rice or Dal (or other)	10	HP (900 W) 25 min, rice cooker. Could also loosely represent one EPC dish
Lunch	1	Noodles or Potatoes	100	ON 20 min (EPC)
Dinner				Same as Breakfast

The aim when modelling these HHs was not to represent the highest possible electric cooker usage, but rather to predict the most likely usage of each cooker and the resulting load profiles. If HHs owned both an EPC and a rice cooker, it was deemed most likely that they would use them both once per meal, cooking dal and rice with the EPC and rice cooker concurrently, and so this option was assigned the highest probability, 70%, for the main meals. This is due to the fact that HHs mostly cooked only one dish in their EPCs. Cooking only one dish with an electric cooker was deemed unlikely for HHs with two cookers, with the associated probability set to 10%. Finally, cooking three dishes, two in the EPC and one in the rice cooker, was deemed likely to happen around 20% of the time, as it requires consecutive EPC dish cooking, which was uncommon in the ECO study.

Modelling the use of the EPC to cook vegetables represented a new type of EPC cooking, that of frying, and used the ECO study diary data to specify the duration of cooking, which was found to be around 25 minutes. Laboratory tests on cooking vegetables were conducted during the ECO study, during which spices and onions were fried in oil with the EPC lid off, before the addition of vegetables to the process [207]. It was common to see pulsing of power, with the EPC temperature oscillating around a setpoint, with an initial ON period of around 3-5 minutes, followed by OFF and ON periods of 3 minutes and 1-2 minutes respectively, with longer power pulses when the voltage was lower. Therefore, the RAMP vegetables dish was specified as in Table 7.3, with pulsing occurring until the 25-minute duration is reached, aligning with a rice dished cooked in the rice cooker for the same duration. The dal dish specification could also represent the cooking of meat in the EPC. The centralised and HH battery storage modelling outlined in Chapter 6 could also be used to specify batteries for electric cooker combination HHs.

7.3 Results of techno-economic modelling

7.3.1 Electric cooking scalability and efficient devices

Table 7.4 presents the results output by the TEM for assessing the scalability of cooking with induction cookers and EPCs in the community, comparing to Scenario P, the potential economic status of the plant if the transition to the proposed payment structure is completed while consumer behaviour remains as reported in the surveys and according to the DSM measures and latest data.

Table 7.4: Key TEM results for direct electric cooking scenarios.

Scenario	HHs	Energy (kWh)	Income (NPR)	Income cooking HHs (NPR)	Income single HH (NPR)	Profit (NPR)	Peak load max (kW)	EUF (%)
P		26,400	203,600			88,100	76.8	40.7
Induction realistic	50	28,300	216,200	13,600	272.6	98,800	85.8	43.7
Induction TRIID	40	27,900	212,800	12,800	320.7	95,900	86.3	43.1
EPC rollout	100	28,000	210,600	13,600	136.5	94,000	85.8	43.2
EPC monitored	85	28,100	211,400	13,200	155.4	94,700	83.4	43.3
EPC high	60	28,100	213,900	13,300	221.1	96,800	85.7	43.4

The results show that around 40-50 and 85-100 induction cookers and EPCs could be connected to the mini-grid respectively, depending on the level of usage. If EPCs were used for 90% of main meals and most often for two dishes per meal, there would be enough spare power for around 60 to be introduced in the community. The ‘EPC rollout’ scenario represents the most likely usage level, although higher usage would become likely with training and monitoring. Overall, although the maximum load peak observed in the latest measured powerhouse data from the ECO study was 75.6 kW (see Section

4.4.3), and that of the TEM scenario P was 76.8 kW, the model predicts that it would still be possible to connect a large number of electric cookers to the mini-grid. Furthermore, the solution of efficient cooking devices increases the scalability of electric cooking significantly, with an additional twenty high usage EPCs usable in the community compared to high usage induction cookers, and higher numbers of additional EPCs for more realistic usage.

Figure 7.1 shows the average and standard deviation of the modelled electricity demand for scenario P and with 40 additional induction cookers with high usage i.e. ‘Induction TRIID’ scenario. The equivalent profiles for the other scenarios are not presented as they were all very similar to that of the ‘Induction TRIID’ scenario, with the peak loads in Table 7.4 all around 85 kW. Although the existing load sometimes reached around 75 kW, it was generally lower, on average around 60 kW during peak times, which meant that there was often sufficient spare power for the electric cookers. However, with almost 1,100 HHs, the results in Table 7.4 reiterate that the scalability of direct electric cooking in the community is limited.

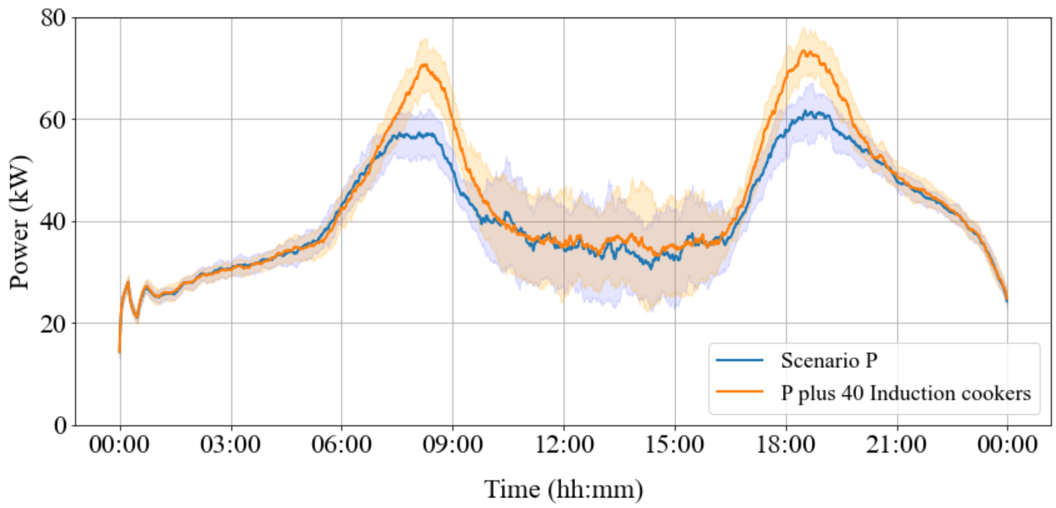

Figure 7.1: Average load profiles and variation for increased induction cooking.

In each scenario the increased cooking is modelled to contribute approximately 6% of the total increased income, around NPR 13,000, leading to increased monthly profits, with the EUF increasing in each case. The required monthly payments are higher for higher electric cooker usage, as expected. There is broad agreement between the modelled monthly bills and those found in the cooking diary studies and scenario P, as discussed in Section 5.5.1. The running costs of electric cooking are generally within the reported affordability of the diary study HHs, which was NPR 200-600 for most HHs in both the TRIID and ECO studies.

However, the upfront costs were found to present the biggest barrier to electric cooking adoption. If the MHP committee used MHP profits to cover the purchase costs of the cooking systems (including cookware for induction cookers) for the HHs, who then paid for their electricity usage, those purchase costs could be recovered over periods of between 4.6 and 8 months for the five scenarios in Table 7.4, or 6.3 months on average. These figures were calculated by dividing the total cost of the specified number of cookers in each scenario by the modelled monthly profits in Table 7.4, with the induction cooker plus cookware costing NPR 13,000 and EPC costing NPR 7,500. Discount rates are not considered here for simplicity, with the aim to obtain approximate estimates.

However, this would use the entirety of the generated monthly profits, whereas the periods would be doubled if 50% of profits were allocated to funds. After costs were recovered, the increased electricity demand of increased electric cooking would generate higher profits. Therefore, the TEM can be used for load planning and for determining the economic viability of financial mechanisms for enabling electric cooking.

7.3.2 Demand-side management measures

Table 7.5 presents results of scaling up electric cooking with the cooking DSM agreement, where HHs agree to only start cooking when the mini-grid voltage is stable, which would be likely to spread out cooking events across wider cooking windows. It shows that the DSM measure enables increased electric cooking penetration, improving scalability, by enabling the addition of an extra 20 induction cookers and an extra 35 EPCs, compared to the scalability without the DSM agreement.

Table 7.5: Key TEM results for direct electric cooking with DSM scenarios.

Scenario, plus DSM	HHs	Energy (kWh)	Income (NPR)	Income cooking HHs (NPR)	Income single HH (NPR)	Profit (NPR)	Peak load max (kW)	EUF (%)
P		26,400	203,600			88,100	76.8	40.7
Induction TRIID	60	28,800	218,000	19,200	320.0	100,300	87.1	44.4
EPC monitored	120	28,200	211,800	18,900	157.6	95,100	84.8	43.5
EPC high	95	28,700	215,500	20,800	219.2	98,100	86.0	44.3

Figure 7.2 shows that induction cooking scalability is increased from 40 HHs to 60 HHs, for high usage, and features flatter load peaks as compared to Figure 7.1 due to the DSM measure spreading out cooking times across wider windows.

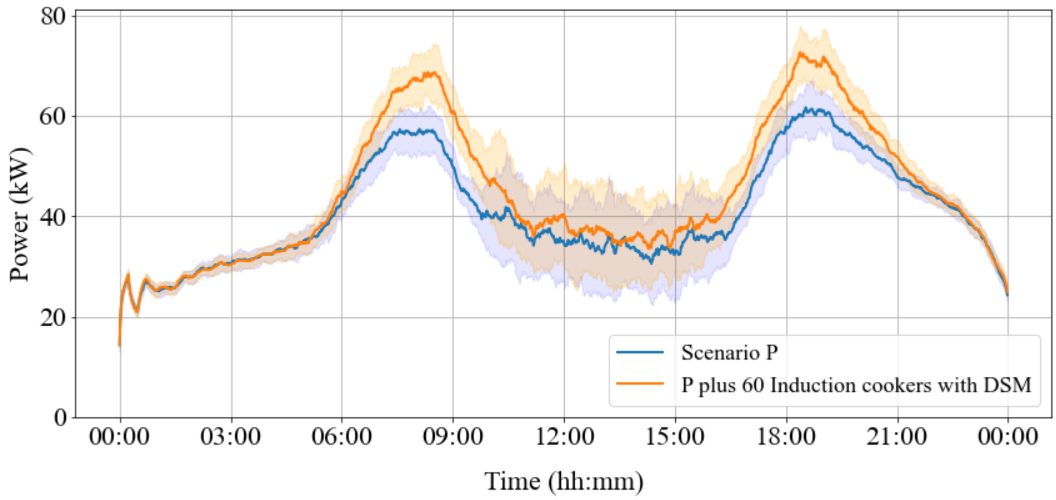

Figure 7.2: Average load profiles and variation for increased induction cooking with DSM.

The income generated from the HHs with the additional electric cookers is increased from around NPR 13,000 in Table 7.4 to NPR 20,000 for DSM cooking, with corresponding increases in the EUF. Therefore, the TEM can be used to assess DSM measures in terms of scalability and economic impact. However, this particular cooking DSM measure could cause inconvenience for HHs and necessitate excessive behavioural change. Furthermore, the experience of the cooking diary studies research team showed that HHs usually want to be finished with cooking by 8 PM and would therefore be unlikely to agree to such a measure, unless there was a financial incentive, although this too may not guarantee adherence. Participants of the ECO cooking diary study were asked how willing they would be to cook slightly earlier or later than usual, when the voltage is stable, to reduce the strain on the system. On a scale of 1 to 5, with 1 meaning unwilling and 5 meaning very willing, the mean score was 2.5, showing that there was little appetite for such a change. They were also asked the same question with the addition that they would pay less, but the average scored only increased slightly, to 2.9. Regardless, in communities of hundreds of HHs, widespread electric cooking adoption remains unfeasible without more drastic DSM measures or, more feasibly, energy storage.

7.3.3 Battery storage systems

Focussing first on centralised BESS and comparing to Scenario P, the potential economic status of the plant if the transition to the proposed payment structure is completed and the electricity demand remains as is, the results in Table 7.6 show that the scalability of electric cooking is significantly increased by the use of energy storage. The total number of HHs that could start using electric cookers could be increased from around 50 and 100 induction cookers and EPCs respectively to around 400 induction cookers and 800 EPCs. The 400 HH scenarios are considered first, enabling direct comparison.

Table 7.6: Key TEM results for central and HH battery storage scenarios.

Scenario	HHs	Energy (kWh)	Income (NPR)	Income cooking HHs (NPR)	Income single HH (NPR)	Profit (NPR)	Peak load max (kW)	EUF (%)
P		26,400	203,600			88,100	76.8	40.7
Induction BESS	400	42,200	307,400	129,900	324.7	176,300	153.7	65.1
EPC BESS	400	36,400	265,500	88,400	221.0	140,700	138.7	56.1
EPC BESS 2	800	46,200	329,300	176,300	220.4	194,900	182.7	71.4
Induction HH BESS	134	38,100	277,200	86,400	645.1	150,700	101.1	58.8
EPC HH BESS	224	38,000	273,200	90,400	403.7	147,200	99.1	58.6

Widespread adoption of electric cooking enabled by battery storage would drastically increase the income of the plant, with the total income from the 400 HHs with the additional electric cookers reaching around NPR 130,000 and NPR 90,000 for induction and EPC cooking respectively. The EUF would also increase dramatically, from around 40% to over 55%.

The high profits enabled by the centralised BESS could be used to regenerate the money spent on the 135 kWh and 45 kWh systems for induction and EPC cooking respectively. At a cost of $255.27/kWh for lithium ion batteries in 2022, or NPR 32,659/kWh as of July 2022, as specified in [168], these centralised BESS would require investments of NPR 4,409,000 and NPR 1,470,000, respectively. If these costs represent 75% of the total BESS cost including the inverter, control system, and cabling [168], the total costs would be NPR 5,879,000 and NPR 1,960,000, respectively. Further costs for upgrading infrastructure such as transmission and distribution lines and transformers would be required but are not specified here. The 15% of MHP total profits allocated to repairs and maintenance could contribute further to such costs.

Comparing the estimated costs to the generated profits, if the entirety of each monthly profit was used to recover costs, it would take around 33 months and 14 months respectively for the induction BESS and EPC BESS. If 50% of monthly profits were allocated to funds, around 67 months and 28 months would be required respectively. If recovering the costs of the cookers too, these periods would be approximately doubled. Therefore, centralised BESS for electric cooking would require high initial costs but these could be recovered over a period of around 1-3 years depending on cooker type and penetration, although infrastructure upgrades, electric cooker costs and any profit allocations would extend these periods. After costs are recovered the increased electricity demand enabled by centralised BESS would generate increased profits for the plant. The calculated BESS capacity requirement for 800 EPC HHs was 201 kWh, as presented in Table 7.6, which would require approximately 50% higher costs than for the 135 kWh BESS and a minimum payback period of 45 months, almost four years.

With likely battery lifetimes of up to 3-4 years, the economic viability of centralised BESS is limited. If pre-existing savings, government subsidy or other funding were available, the profitability would be increased, with the benefits of enabling widespread adoption of electric cooking clear. BESS lifetimes could be increased with reduced usage or increased capacities, though the latter would require higher initial costs.

Focussing on HH batteries, the results in Table 7.6 show that HH battery storage also significantly increases the scalability of electric cooking, as found in Section 6.3.2, with enough spare power during off-peak periods for 134 and 224 HH batteries to be charged for induction and EPC cooking respectively. The plant income would be increased significantly, by around NPR 90,000 per month, generating high profits. The EUF would also be improved due to the usage of off-peak energy, as shown in Figure 7.3, which shows how the batteries could be charged outside of cooking windows, and also depicts the high variation in the afternoon cooking load across the simulated days.

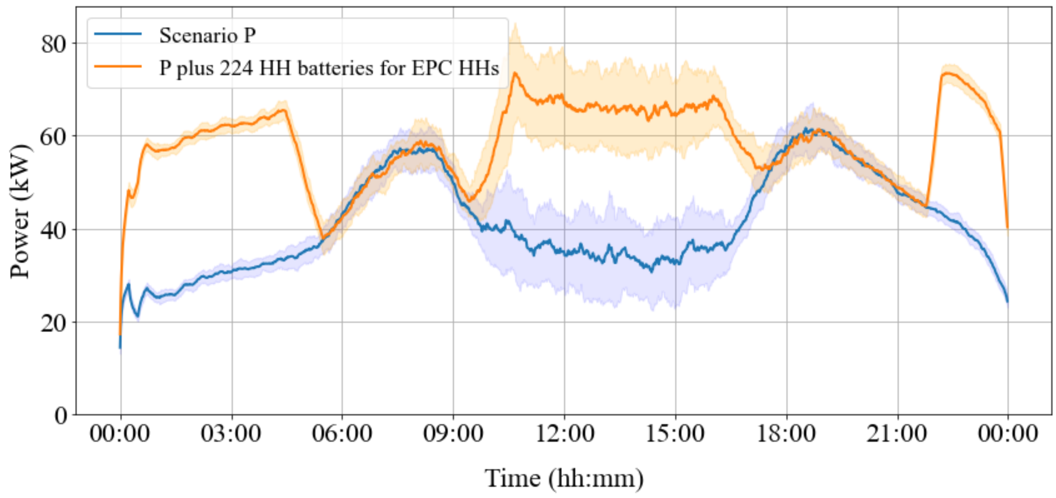

Figure 7.3: Load profiles and variation for increased HH BESS-supported EPC cooking.

As presented in Table 7.6, the peak load across the simulated month actually reached around 100 kW for each of the HH battery scenarios, well above the 85 kW stability limit. However, this is due to the high variability in IEU load which occurred in these periods, as depicted in Figure 5.8 in Section 5.4.3. The afternoon load varied up to around 70 kW in the TEM, Scenario P, while maxima of around 50 kW were observed in the latest measured powerhouse data from the ECO study. Therefore, the stability limit for the afternoon period, during which the mills are operational can reasonably be increased by 20 kW, to 105 kW. The modelling in Section 6.2.3 showed that, assuming a maximum afternoon load of 50 kW, the specified numbers of HH batteries could be connected.

HH battery charging for high penetration of electric cooking would consume more energy than direct cooking, evident in the increased monthly payments that would be required from HHs, of around NPR 645 and NPR 404 for induction and EPC cooking respectively. These payments would possibly be beyond affordability for some HHs, although over half of the participating HHs in each of the TRIID and ECO studies reported that they would be willing to pay more than NPR 400 for electricity for cooking. In reality, HHs may not use as much energy as specified in the cooking energy requirements for HH battery sizing, potentially charging their batteries less often or for shorter periods of time, reducing payments.

If MHP profits were used to recover the costs of the HH BESS, in a similar way as for the centralised BESS, for 134 induction HH BESS and 224 EPC HH BESS, the payback periods would be around 60 and 70 months if all profits were used [168]. These figures were calculated using costs generated by the eCook modelling spreadsheet of the induction and EPC BESS of $529 (NPR 67,700) and $357 (NPR 45,700) respectively, which include the costs of inverters and cabling, with conversion rates valid in July 2022. Including the costs of the cookers, the periods would be extended to 72 and 81 months, respectively, while each period would be doubled if 50% of profits were allocated to funds. Therefore, periods of at least five years would be required to cover HH BESS costs, possibly much longer. Although the sizing calculations included upscaling to mitigate capacity fade, compared to approximate battery lifetimes of around 3-4 years, HH BESS appear less economically viable than central BESS unless usage is reduced.

According to the eCook Modelling Spreadsheet and accounting for the proposed electricity tariff in Salyan, the 1.6 kWh and 0.96 kWh HH BESS for induction and EPC cooking respectively could be paid for on a monthly basis at NPR 2,205 and NPR 1,569 per month respectively, over 5 years and considering discount rates, including cooker costs and electricity usage [168]. These monthly rates would drop to NPR 1,456 and NPR 980 for a twenty-year period, respectively, including discounted system component replacement costs. All the calculated monthly costs are beyond the reported affordability of the ECO study HHs. Therefore, other financial arrangements, such as loans for the cookers which could be repaid by MHP profits, may be more suitable. Overall, battery supported cooking requires large investments for both HH level and centralised storage, but would lead to high profits which could be used to recover costs, and would increase the scalability of electric cooking in MHP communities drastically. However, limited battery lifetimes reduce economic viability. As discussed in Section 6.4, BESS could be sized for 1-2 days of autonomy, rather than one meal, but this would increase the calculated costs and payback periods further, reducing feasibility.

7.3.4 Electric cooker combinations

Table 7.7 presents the results output by the TEM for assessing the scalability of cooking with two electric cookers per HH in the community. The obtained load profiles appeared very similar to those in Figure 7.1 and are therefore omitted.

Table 7.7: Key TEM results for electric cooker combination scenarios.

Scenario, plus rice cooker	HHs	Energy (kWh)	Income (NPR)	Income cooking HHs (NPR)	Income single HH (NPR)	Profit (NPR)	Peak load max (kW)	EUF (%)
P		26,400	203,600			88,100	76.8	40.7
Induction TRIID	30	28,100	214,400	9,500	380.0	97,200	85.4	43.4
EPC monitored	35	27,300	209,300	9,200	262.5	92,900	86.8	42.2

It was found that the scalability of these HHs was reduced as compared to HHs with only one electric cooker, as expected. In particular, the addition of a rice cooker to a HH with an EPC reduced scalability by 50 HHs, from 85 HHs to 35 HHs, due to the change from mostly cooking one dish with electricity per meal to mostly cooking two, concurrently. The reduction in scalability was less pronounced for HHs with induction cookers, from 40 HHs to 30 HHs, as they were specified to already cook 2-3 dishes with electricity per meal, usually, with the addition of the rice cooker only changing the means by which one of these dishes is cooked. However, the concurrency of induction and rice cooking did reduce scalability by 10 HHs.

Interestingly, a TEM simulation was performed of the original TRIID HHs who owned induction and rice cookers, for which the timing of the rice cooker dish was allowed to vary during the cooking window, leading to mostly consecutive rather than concurrent electric cooking. The frequency of use increased to 90% to represent comparably high usage. It was found that the scalability was around 35 HHs, only slightly increased from the result in Table 7.7, with the peak load reaching a comparable maximum of 85.8 kW. Figure 7.4 presents the resulting load profile, which is similar to that of Figure 7.1,

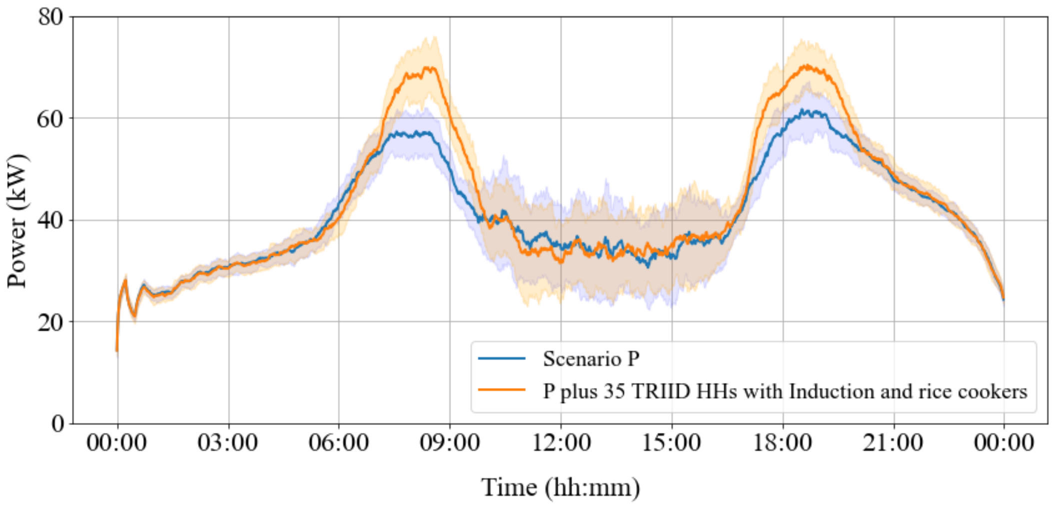

Figure 7.4: Average load profiles and variation for increased TRIID HHs with induction and rice cookers.

Therefore, forced concurrency of the two cookers only led to a small increase in the ADMD of these HHs, likely due to consecutive electric cooking also causing high ADMD due to high total cooking times causing high coincidence of cooking across HHs. Overall, the TEM can be used to assess the scalability of electric cooking through different combinations of cookers, which is important for load planning, both for studies or rollouts in which HHs purchase or are provided with multiple cookers, and for modelling load evolution: some HHs are likely to add a second electric cooker to their stove stack over time, particularly rice cookers, which are common in rural areas.

7.4 Discussion

The scalability of electric cooking for different usage levels was revealed, with realistic induction and EPC usage at around 50 and 85-100 HHs respectively. It was also important to compare high induction cooker usage, which was mostly 2-3 dishes per main meal and a high frequency of use of 90% for the 'Induction TRIID' scenario, with high EPC usage, to assess the effectiveness of efficient devices as a solution for enabling increased adoption of electric cooking. The model revealed high usage scalability to be around 40 and 60 HHs for induction and EPC cooking respectively, showing that EPCs do increase scalability for comparably high usage. However, the ECO study revealed that people would require support to use EPCs for more than one dish consistently, and would mostly use them as rice cookers. Therefore, the likely usage scalability of EPCs is much higher than that of induction cookers, but for limited usage.

If considering introducing a set of electric cookers to their community, an MHP committee could enable adoption by using savings to cover initial costs and start to make profit on those costs during the first year of usage, according to the modelled scenarios. HHs could pay back initial costs in instalments. Other arrangements where HHs contribute to initial costs, repay through on-bill financing, or pay their own way entirely can be envisaged. The model showed that electric cooking can contribute significantly to MHP income.

DSM measures for cooking can increase the scalability of electric cooking. However, they are unlikely to be agreed to without financial incentive, and even then, would present inconvenience to users, and would be difficult to monitor. DSM measures for other end uses, like the mills agreement, may be more practical. Other methods of freeing up spare power during peak times and enabling increased electric cooking could include, for example, limiting the usage of lights and high-power devices such as electric kettles in BEUs and CEUs, as well as HHs.

The energy storage sizing and scalability assessments, presented in Chapter 6 and this chapter, are intended to provide an indication of the technical and economic feasibility of battery storage for increased electric cooking. The sizing models were simplified, as were the economic calculations. The calculations should be improved by specifying all required components, such as inverters and chargers, and building on extended mini-grid modelling discussed previouslyby estimating infrastructure upgrade costs. Reactive power including power factors of devices could be considered to determine more accurate current flows in the mini-grid. Distributed storage topologies should be specified and compared to the centralised topology. Improved models could enable accurate technical and economic specifications of BESS, including of battery lifetimes, which could be incorporated into the TEM to calculate improved estimates of electric cooking scalability, costs and payback periods.

A limitation of the TEM is that it has a tendency to overestimate the variation in electricity demand in the off-peak afternoon period, making scalability assessments of HH battery charging, or other end uses, more difficult. As explained in Section 7.3.3, this limitation can be mitigated by reconsidering the maximum load stability limit. The MATLAB model described in Section 6.2.3 was able to estimate scalability using assumptions on load levels. Further work could investigate the limitation in more depth to identify its root causes. Other HH battery topologies could also be investigated, including integration into an intelligent mini-grid control system, although gradual purchase of HH BESS for cooking and usage without such integration appears likely, to minimise cost and complexity, and due to the unreliability of HH voltage in the community.

For centralised BESS, the purchase mechanism of using a loan or MHP profits to cover initial costs and recovering these costs with the increased income from new electric cooker usage is easy to imagine. For HH BESS, it is perhaps more likely that HHs would purchase their own systems, with payment mechanisms over periods of years reducing initial costs. Otherwise, as postulated for direct electric cooking without energy storage, MHPs could purchase the HH BESS, with or without contributions from HHs, and the increased income from electric cooking used to recover costs. For all of these scenarios, the plant would need to switch tariff system and operate profitably over a period of time until a level of stability and financial viability is achieved, before considering mechanisms and plans for increasing electric cooking adoption. The economic viability of central and HH BESS appears limited without pre-existing savings, subsidy or other financial mechanisms, due to approximate battery lifetimes of around 3-4 years for high usage and higher calculated BESS payback periods depending on topology and capacity.

The simulations with electric cooker combination HHs showed that, if HHs cooked concurrently with two electric cookers, the scalability of electric cooking in the community would be reduced. Furthermore, the upfront cost of the cooking system would obviously increase. However, as found in the cooking diary studies, electric cooking usage fractions would most likely be higher, with reduced fuel stacking.

It was shown that consecutive electric cooking also causes high ADMD for a group of HHs, if slightly lower than concurrent electric cooking, and that the differences varied between the cookers. For EPCs, the scalability when a rice cooker was added to the stove stack reduced significantly, even for the high EPC usage case, from 60 HHs to 35 HHs. Therefore, for comparable electric cooker usage fractions comprising mostly two dishes per meal, using two cookers simultaneously leads to higher ADMD for a group of HHs than the coincidence of consecutive cooking across HHs. This is due to EPCs demanding full power for short, preheat periods, making coincidence across HHs less likely.

For induction cookers, the scalability when a rice cooker was added reduced by only 10 HHs, because induction cookers demand high power for longer periods, increasing the likelihood of coincidence across HHs, so that the ADMD of consecutive cooking is high and only slightly lower than that of concurrent cooking. In HHs, it is likely that a mix of behaviours would be observed, with some HHs cooking concurrently across stoves to save time, while others cook consecutively. Some HHs might cook consecutively with electric cookers for fear of causing power supply instability, while others might do so according to preference for cooking dishes in a certain order, perhaps fuel stacking at the same time as the second dish, thereby completing meal cooking in the time it takes to cook only two dishes. The TEM can be used to simulate varieties of cooking practices within and across different user groups.

7.5 Summary

In this chapter, the scalability and economic impacts of solutions to enable increased adoption of electric cooking in MHP communities were evaluated. Firstly, it was found that efficient devices such as EPCs can increase the scalability of electric cooking, but widespread adoption of any electric cooker is impossible if cooking directly from the mini-grid. Between 60 and 100 EPCs could be introduced in the community, depending on usage levels, compared to 40-50 induction cookers. Scaling up electric cooking to make full use of the spare power at peak times would generate around NPR 13,000 in extra income, which could be used to recover cooker costs in around 5-8 months. A cooking DSM agreement could increase scalability by around 20 induction cookers and 35 EPCs, although its implementation would present difficulties and inconvenience for cooks. Other DSM measures could be assessed using the TEM and introduced.

Energy storage could enable widespread adoption of electric cooking, with around 400 HHs with induction cookers or 800 HHs with EPCs able to cook if supported by a centralised BESS, generating around NPR 150,000 in extra income, although this would require a period of 3-4 years for cost recovery. The scalability of HH battery charging for electric cooking was estimated at over 100 HHs and over 200 HHs for induction cookers and EPCs respectively, generating an extra NPR 90,000 for the plant, although HHs would face higher monthly bills, especially if repaying costs for their HH BESS on a monthly basis. Battery sizing models and economic calculations should be refined to generate accurate feasibility indicators including cycle life estimation. The economic viability of both central and HH BESS is limited by low battery lifetimes of around 3-4 years or less as compared to similar or longer payback periods, if using MHP profits alone, depending on BESS topology and capacity.

Owning combinations of electric cookers could enable and encourage HHs to adopt electric cooking for a high proportion of their menu, but this would reduce scalability in terms of the number of HHs who could transition to electric cooking, especially for HHs with EPCs, whose scalability could reduce from around 60 to 35 HHs if provided with a rice cooker, as opposed to a reduction of around 40 to 30 HHs for those with induction cookers. The TEM can be used for technical and economic aspects of load planning, to understand which cookers and combinations of cookers could be introduced to communities and to what degree, and how DSM measures and energy storage could enable increased adoption of electric cooking.

Chapter 8

Conclusions and Further Work

8.1 Discussion

In this thesis, the transition to electric cooking in rural Nepali MHP communities has been investigated from social and technical viewpoints, collecting data and insights on how to enable community members to integrate electric cookers into their daily practices as much as possible, and evaluating solutions to increase the potential adoption of electric cooking in mini-grids with constrained capacities.

The review of literature identified that electric cooking is rare in MHP communities and could improve life for community members, as well as MHP financial sustainability, which is often low due to insufficient usage of the generated energy and low tariffs. Detailed monitoring and understanding of rural Nepali cooking practices had not yet been conducted, while there was a lack of data on MHP electrical systems, such as generation, load and voltage profiles, and on electric cooking loads. MHP mini-grids are often weak, operating close to capacity at peak times. In communities of hundreds or thousands of HHs, the scalability of connection of electric cookers, which typically draw around 1 kW, is limited. Solutions to increase it were identified, including efficient electric cooking devices, DSM measures, and battery energy storage. Methods including data collection and modelling were specified to investigate the transition to electric cooking and evaluate measures for increasing its potential adoption, according to the research objectives.

Three electric cooking trial studies were conducted, including cooking diaries and collection of MHP electrical system data and electric cooking load data, to understand and characterise the current rural Nepali cooking context, investigate the acceptability and suitability of electric cookers for Nepali cooks, and explore how efficient cooking devices and DSM measures could increase the limited scalability of electric cooking in constrained grids. The initial studies showed that electric cooking is well received in rural Nepal, with participants appreciating cooker usability, time savings, firewood savings, and reductions in smoke. However, its scalability was very limited, with the mini-grids struggling to cope with the connection of 10-15 induction cookers. Therefore, EPCs were investigated in the ECO study to understand how lower cooking energy and power demand could increase scalability. Crucially, as the community load in Salyan was near capacity during the TRIID study due to the induction cookers, community DSM measures of load scheduling for mills and encouragement of HH electricity saving practices were implemented, reducing the community load peaks by 10-20 kW, thereby freeing up spare power, and showing that DSM measures can increase electric cooking adoption potential.

Cooking diaries revealed that the EPCs were used mostly for rice, dal and water heating, and for only around 30% of cooking events, whereas induction hobs were used much more, for all staple dishes including rice, dal, vegetables, tea, noodles and potatoes: around 80% of cooking events in the TRIID study. A caveat is that HHs with induction cookers were asked to use them as much as possible to help them with the two-week transition period, whereas the seven-month EPC monitoring period aimed to capture settled usage habits. However, although the TRIID study may have overestimated usage, consecutive dish cooking was much more common with induction cookers than EPCs, and participants reported being comfortable cooking most dishes with induction cookers, including frying dishes, as opposed to preferring to cook mainly rice with EPCs, for which cooking durations were longer due to a pressure release period.

Fuel stacking between electricity, firewood and LPG was common for reasons including:

- Being more comfortable with existing cookers and practices
- Unsuitability of electric cooking for certain dishes, such as roti and meat stews (for induction cookers) and all frying dishes (for EPCs)
- To save time by cooking concurrently across stoves, encouraged by the addition of the electric cooker and, for some HHs in the TRIID study, a rice cooker
- For the warmth provided by burning firewood for cooking in winter months
- Power supply instability due to high community loads and dry season

With double the cookers (all ~1 kW), the ADMD of the total EPC cooking load profile was lower than that of induction cooking, due to lower EPC usage and lower EPC energy consumption, commonly reaching around 8 kW and 6 kW for 15 induction cookers and 30 EPCs respectively – important data for electric cooking load planning. Mini-grid electrical system data revealed that the total community load is high in the morning and evening, and low at other times, and that people cook at the same time as each other *and* as community load peaks. The high resulting loads can cause supply instability, including brownouts, forcing people to revert to wood/gas stoves. Contributions of electric cooking to community load peaks varied day to day due to diversity affecting coincidence: additions of 5 kW were common for both 15 induction cookers and 30 EPCs. Improved induction cooking load profile data gathering, using HH data loggers, is required, to better understand its ADMD and coincidence with community load peaks. The ECO study reiterated that electric cooking scalability is limited, as there is little spare power available at peak times with 56 HHs of 1,100 cooking with electricity.

Induction cookers represent a more versatile and complete solution for Nepali cooking than EPCs, although longer studies are required to understand settled induction cooker usage habits. Higher induction cooking energy requirements would mean higher running costs under a consumption-based tariff system, although these were comparable to those of LPG as back-up fuel, generally less than equivalent time costs of wood cooking, and often within reported affordability. In each study, electric cooker usage fractions varied between HHs, with those more willing to experiment cooking a wider range of dishes with electricity, including roti with the induction cooker, and noodles and potatoes with the EPC. Such HHs often chose to cook consecutively with electric cookers to reduce firewood usage and resulting smoke levels, rather than saving time by cooking multiple dishes concurrently. These HHs are more likely to adopt electric cooking as a primary cooking fuel, especially if provided with two electric cookers, such as an induction cooker or EPC and an additional rice cooker, which enabled high electric cooking usage fractions in the TRIID study. HHs willing to experiment and cook consecutively with an EPC could cook entire three-dish meals with electricity, if provided with a rice cooker, although this would require some EPC frying of staple dishes such as vegetables, which presented difficulty for some ECO study participants. An electric and LPG stove stack also enables reduced firewood usage while preserving the convenience of fast gas cooking and concurrent cooking for HHs with one electric cooker rather than two.

The rollout phase of the study revealed that the training, support and monitoring of the cooking diary methodology is likely to encourage higher electric cooking usage fractions, although other drivers such as wood stoves providing warmth in winter and low voltage may have reduced their usage. For rollouts, cooking demonstrations, remote training through videos, and recipes, including EPC times and water quantities for different foods, will be essential for enabling maximum possible usage levels, while remote monitoring and surveys of samples of HHs would enable understanding of usage levels. For induction cooker rollouts, naturally higher usage is likely due to easier, more versatile cooking and higher cooker usability than EPCs. Overall, the cooking trial studies provided key insights and datasets applicable to other similar communities and cultures in Nepal and beyond.

The cooking trial studies showed that electric cooking is possible in rural Nepal and can become a key element of the cooking fuel mix, supporting government targets for its adoption such as that of the Second Nationally Determined Contributions (NDCs) Policy which aims for 25% of Nepalese HHs cooking with electricity by 2030, outlined in Section 1.3.1 [46]. The rollout aspect of the ECO study showed that training on using electric cookers is essential for enabling maximised electric cooker usage and should be a key part of policy in efforts to scale up electric cooking. Furthermore, MHP mini-grids should be considered an important sector in national policy as hydro mini-grids provide renewable electricity to 12% of HHs in Nepal which could be used for electric cooking [35].

The obtained knowledge and understanding from the trial studies were used to create a techno-economic model (TEM) of an MHP community which aimed to understand the potential of income generation from electric cooking to improve MHP plant financial sustainability, enable evaluation of different tariff structures, and enable evaluation of solutions for increasing electric cooking adoption potential. Overall, the proposed tariff system could increase community income in Salyan from around NPR 50,000 to NPR 200,000, and is recommended to be implemented, while electric cooking would contribute almost NPR 10,000 with only 56 HHs with electric cookers in the community. Monthly payments would increase for around 20-30% of HHs from NPR 110 to NPR 400-700. However, lower and more equitable tariffs, reducing minimum payments for lower income HHs, could be chosen while preserving plant profitability.

Without additional data following the introduction of the new tariff system, it is difficult to predict electricity usage and willingness to pay increased bills, but the TEM can simulate various tariff, demand, and payment percentage scenarios, and could be used in off-grid communities in Nepal and elsewhere with limited input data. It also includes validated electric cooking load models for Nepali cooking, scalable to approximate widespread uptake of electric cooking, and adaptable to other cookers and contexts. The cooking load models would benefit from further studies with higher numbers of cookers to provide additional confidence in generated load profiles for increased electric cooking.

The model was tested by imagining an adjusted version based on lower detail input data, resulting in cooking load profiles with peaks of around double those measured by the HH data loggers in the ECO study. Therefore, the level of detail of the data obtained for the model specification was required in order to create a useful model. However, now that the model specifies the electricity demand of HH groups, business and community end uses, and industrial machines, including typical appliance usage, it can be adapted to other similar communities and contexts based on limited detail input data such as typical daily electricity demand patterns, numbers of households and productive end uses and appliances owned, and usage patterns for industrial machines.

In this way, the model can support government policies of increasing per capita energy consumption and adoption of electric cooking outlined in Section 1.3.1, by enabling improved financial sustainability of MHP communities and load planning for the introduction of electric cooking. The model should be used by Nepali organisations such as the Alternative Energy Promotion Centre (AEPC) for mini-grid communities in Nepal, and can also be adapted to other similar contexts in Nepal and beyond. The model can be used in these communities and contexts to evaluate the scalability and economic viability of electric cooking and plan its introduction. It can also be used to increase electricity usage and therefore plant income by enabling the connection of electric cookers and other end uses such as industrial machines, and by simulating DSM measures for maximising generated energy usage.

The control of battery storage integrated into MHP mini-grids was investigated to understand how off-peak generated energy could be stored and used during peak times to enable increased electric cooking adoptions. Existing reverse droop control principles were applied, generating understanding of system behaviour, and enabling comparison of different topologies of battery storage integration. The ELC frequency setpoint was increased above nominal so that, rather than dumping all of the spare power during off-peak periods, the central or distributed BESS charge with some of the spare power, according to their droop characteristics, while the ELC maintains the frequency at a desirable level. During peak times, the generator sends power to the loads in proportion to their magnitude, with the BESS meeting the extra demand that the generator is unable to serve.

Due to the distributed BESS being located at the consumer end, with the distribution transformers, mini-grid infrastructure upgrade requirements upstream of the distribution BESS are reduced compared to a centralised topology. Furthermore, distributed BESS can improve power quality through voltage-reactive power droop at the expense of increasing the current in the mini-grid. However, a central BESS could be managed by MHP operators. For HH BESS, reverse droop control could be applied during charging only and, when the cookers are switched on, the batteries could provide power to their cookers as required. The modelling provided proof of concept for reverse droop control for BESS, based on the literature, in a new context of an MHP mini-grid.

The obtained understanding of active power flows in an MHP mini-grid with integrated BESS under reverse droop control was applied to create a model for estimation of battery storage capacity requirements for increased electric cooking adoption using realistic electric cooking load profiles generated using the TEM. The power flows model showed that 400 induction cooking HHs and 800 EPC HHs load scenarios are around the upper limits of feasibility without the central BESS SoC sometimes falling beneath the minimum of 20% and there being insufficient spare power to fully recharge after mealtimes. BESS capacities of 135 kWh and 201 kWh were calculated for these increased induction and EPC cooking scenarios respectively, for which the mini-grid infrastructure would require upgrading to support maximum loads of just under 155 kW and just over 180 kW respectively. HH battery electric cooking capacities of 1.6 kWh and 0.96 kWh were calculated for enabling induction and EPC cooking representing high usage of 2-3 dishes per meal. If the HH BESS were charged slowly over seven-hour periods, it was estimated that around 134 and 224 HH BESS could be introduced in the community. For both central and HH topologies, high C rates and usage twice per day could limit BESS lifetimes to a maximum of just over three years, although detailed modelling is required to accurately quantify battery cycle life.

The TEM was updated to evaluate the identified solutions for enabling increased electric cooking adoption in terms of scalability and economic viability, assessing direct electric cooking with different cookers and usage levels, DSM measures for spreading out cooking loads, BESS in centralised and HH topologies, and electric cooker combinations, drawing on the knowledge obtained from the cooking trial studies and modelling work. Realistic induction and EPC usage scalability was estimated at around 50 and 85-100 HHs respectively, while high usage scalability was around 40 and 60 HHs respectively, showing that EPCs do increase scalability for comparably high usage, although it is unlikely that the majority of HHs would regularly use EPCs for more than one dish per meal, with induction cookers seen as more useful and easier to use for more dishes. Maximum electric cooking penetration would generate around NPR 13,000 in extra income per month, which could be used to recover cooker costs in around 5-8 months across cookers and usage levels.

Electric cooker combinations, while increasing likely levels of electric cooking, would reduce scalability from around 60 to 35 HHs for an EPC plus rice cooker combination around 40 to 30 HHs for an induction cooker plus rice cooker combination. A cooking DSM agreement could increase scalability by around 20 induction cookers and 35 EPCs, although it may be difficult for HHs to accept, with the load scheduling and demand reduction measures implemented during the ECO study likely to be more acceptable while still effective.

The specified centralised BESS would generate around NPR 150,000 in extra income but would require a period of 3-4 years for cost recovery, while the maximum addition of HH BESS would generate an extra NPR 90,000 for the plant, although HHs would face higher monthly bills, especially if repaying costs for their HH BESS on a monthly basis. The economic viability of central and HH BESS appears limited without pre-existing savings, subsidy or other financial mechanisms, due to approximate battery lifetimes of around 3-4 years for high penetrations of electric cooking, and comparable or higher calculated BESS payback periods, if using MHP profits alone, depending on topology and capacity.

Overall, the TEM can be used for technical and economic aspects of load planning for similar communities, to understand which cookers and combinations of cookers could be introduced and to what degree, and how DSM measures and energy storage could enable increased adoption of electric cooking. It was demonstrated that efficient cooking devices, DSM measures and battery storage can all enable increased adoption of electric cooking, although widespread uptake would require expensive BESS.

This thesis investigated how the transition to electric cooking in rural Nepali MHP mini-grids could be enabled. Three electric cooking trial studies generated datasets and understanding of the current Nepali cooking context and the effect of electric cooking on MHP electrical systems, finding that induction cookers and EPCs are suitable for Nepali cooking and assimilated into daily cooking practices, albeit to different degrees, and that the scalability of electric cooking in constrained grids is limited. Techno-economic modelling showed that MHP financial sustainability can be improved by consumption-based tariff systems and the introduction of electric cooking, while demand-side management measures can reduce peak loads. It was shown that battery energy storage could be integrated into MHP mini-grids in central and distributed topologies using reverse droop control. Overall, efficient cooking devices such as EPCs can significantly increase electric cooking scalability, although induction cookers are used more often by Nepali cooks, while widespread adoption of electric cookers would require expensive battery storage systems, with payback periods of at least three years reducing feasibility.

The data and models contributed by this thesis support government targets for electric cooking and energy consumption, showing that electric cooking is feasible and acceptable in rural Nepal, and that techno-economic modelling can improve the financial sustainability of MHP communities, as well as enabling load planning including evaluation of the scalability and economic viability of introducing electric cooking and solutions to enable its widespread adoption.

8.2 Key research outcomes and contributions

The main contributions of this research are described as follows and related to research objectives specified in Section 1.4:

- Two electric cooking studies trialling induction cookers were conducted, using cooking diaries and MHP electrical system data collection, generating detailed understanding and datasets on the current Nepali cooking context in MHP communities **(Objective 1).** The studies investigated the transition to electric cooking from social and technical perspectives **(Objectives 2, 3)**, finding that induction cookers are well received and compatible with most Nepali dishes, but that a total switch to electric cooking is unrealistic, with fuel stacking inevitable. The scalability of electric cooking was found to be limited, with very little spare power available at peaks times after the connection of only 10-15 electric cookers in communities of several hundreds of households.
- An electric pressure cooker trial study was conducted, assessing the long-term acceptability of EPCs and collecting cooking load profile data to understand the potential of efficient cooking devices to increase electric cooking adoption potential **(Objectives 1-4)**. EPCs were appreciated by participants but mostly used to cook rice, for a total of only 30% of cooking events, although 6 kW load peaks for 30 EPCs compared to 8 kW peaks for 15 induction cookers showed increased scalability. DSM measures reduced peak loads by 10-20 kW through industrial load scheduling and HH electricity demand reduction.
- A techno-economic model (TEM) of an MHP community was created in Python to understand the impact of electric cooking on plant economic status, explore how tariffs can be set to improve financial sustainability, and enable evaluation of solutions to increase the adoption potential of electric cooking **(Objective 4)**. The introduction of a tariff system based on consumption in a case study community could increase community income from NPR 50,000 to NPR 200,000, while electric cooking would contribute almost NPR 10,000 with only 56 HHs with

electric cookers in the community. The model includes validated electric cooking load models for Nepali cooking, scalable to approximate widespread uptake of electric cooking, and adaptable to other cookers and contexts. The model was tested with lower detail input data, finding that it required the detailed data collection conducted. However, it can be adapted to other similar communities and contexts in Nepal and beyond based on limited detail input data such as typical daily electricity demand patterns, numbers of households and productive end uses and appliances owned, and usage patterns for industrial machines. It should be used by organisations such as the Alternative Energy Promotion Centre for enabling increased electric cooking adoption and improving mini-grid financial sustainability.

- A model of an MHP mini-grid integrating centralised and distributed batteries energy storage systems (BESS) using reverse droop control was created, providing a proof of concept **(Objective 5)**. Electronic load controller frequency setpoint adjustment enabled full BESS charging and discharging. Simulations showed that the generated power is shared proportionally between load branches, while the central or distributed BESS meet the extra load. Distributed BESS could improve power quality and reduce mini-grid infrastructure upgrade requirements although operation and maintenance of a centralised BESS could be managed alongside the MHP by trained operators. The control system modelling enabled conception of a power flows model and HH battery sizing model to specify central and HH BESS, determining the approximate scalability of BESS-supported electric cooking **(Objective 5)**. BESS capacities of 135 kWh and 201 kWh were calculated for high usage of 400 induction cookers and 800 EPCs respectively, using the TEM for realistic electric cooking load modelling, representing approximate scalability limits without oversizing. HH BESS capacities of 1.6 kWh and 0.96 kWh were calculated for enabling high induction cooker and EPC usage, with the corresponding scalability of off-peak charging calculated at 134 and 224 HH BESS respectively. The models can be used to estimate BESS requirements for supporting electric cooking adoption, based on realistic electric cooking modelling validated against measured data, in other MHP communities and further similar contexts.
- The TEM was updated to evaluate solutions for enabling increased electric cooking adoption in terms of scalability and economic viability (**Objective 6).** All solutions would enable increased electric cooking adoption, with the high

usage scalability of EPC and induction cooking calculated at 60 and 40 HHs respectively, confirming that EPCs are more scalable, although widespread uptake of electric cooking would require expensive BESS with payback periods of three or more years, comparable to battery lifetimes. The TEM can be adapted to other communities and contexts and used to evaluate measures for maximised electric cooking adoption.

8.3 Further Work

Several areas of further work are derived from the research conducted in this thesis, summarised here:

- A follow-up study in the case study community once the new tariff system is implemented to understand HH willingness to pay increased bills, and data collection on their electricity consumption and resulting payments, determining whether the new system causes HHs to reduce their electricity usage. The TEM could subsequently be updated to assess plant economics, inform load planning decisions, and simulate DSM measures. The study could include surveys with cooking diary study participants to determine electric cooking costs under the new tariff system and their affordability for HHs
- Further electric cooking studies and rollouts including: longer induction cooking studies to capture settled usage habits; multiple electric cookers, cooker combinations, and perhaps trialling different cookers in turn within HHs to understand typical usage levels and cooker preferences; and electric cooking rollouts including limited remote training, monitoring and surveys to understand typical usage levels and dishes cooked with electricity, along with corresponding reasons for usage patterns provided by cooks. Rollouts could include remote data logging of cooking load profiles for large numbers of HHs, allowing more accurate estimation of large-scale electric cooking loads, enabling comparison to TEM electric cooking load modelling output profiles
- Adaptation of the TEM to other off-grid communities in Nepal and elsewhere in both the planning and operational stages to assess and determine profitable, equitable payment structures, which meet the needs of the people and the plant, ensuring sufficient income while remaining fair and inclusive for consumers. The TEM could also be used to inform load planning decisions and simulate DSM measures, including extension to model other electric cookers and cooking practices in differing cultures. The model adaptation could be based on similar data collection as conducted in Chapter 5 in a new community, or using limited input data such as: typical electricity demand peaks and troughs; number of HHs and typical appliances owned; number and type of productive end uses; and typical usage patterns for industrial machines. The model described in this thesis could be adapted based on this data and matched to local knowledge on typical electricity demand, enabling a shortcut to a useful techno-economic model

- A tool to enable a macro assessment of MHP mini-grids could be developed, which uses indicators such as spare power availability, mini-grid stability, cooking fuels, etc, to identify MHP sites that are currently capable of supporting electric cooking, and determine pathways for other MHP sites to become suitable for integration of electric cooking
- A full electrical system model of an MHP mini-grid using alternative software, such as OpenDSS, incorporating case study mini-grid data on site layout and mini-grid architecture and including realistic load profiles generated by the TEM. The model could incorporate all electrical components and parameters such as line impedances, transformers, and improved modelling of batteries, inverters and the ELC, enabling: realistic simulation of reverse droop-controlled BESS and comparison of different topologies including HH batteries; determination of mini-grid infrastructure upgrade requirements for each topology and for different electric cooking penetrations; understanding of voltage drops throughout the network and how distributed BESS could improve power quality; accurate estimation of BESS capacities including the effects of high power discharge on cycle life and usable capacity, leading to improved estimation of cycle life and resulting battery lifetimes and payback periods
- Generally, in Nepal, electric cooking adoption would benefit from: awareness campaigns and cooking demonstrations; promotion of eCookbooks explaining the cost savings of electric cooking over LPG and equivalent time costs of wood cooking; investigation into in-country manufacture of electric cookers, supply chains, after-sales services, and service and repair centres; and exploration of financial mechanisms for increasing the affordability of electric cooking

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Appendices

1. Simli and TRIID studies
2. ECO study
3. Techno-economic modelling

Appendix 1

Simli and TRIID studies

A1.1 Cooking diaries form

The following tables constitute the cooking diaries used for the TRIID study, with the meal table repeated for the afternoon and evening meals.

Morning Meal

Date: ………….. ….. Start Time…….……. …… End Time ……

How many people meal prepared for? Total: ……. ….. Adult……… Children (below 16 yrs) …. ..

Food Items	Quantity	Water Quantity	Start Time	End Time	Stove Types	Energy measurement before cooking	Energy measurement after cooking	Cooking Utensils	Lid uses	Food condition	Saving for later	Who cooked?
Rice												
Dal/Pulses												
Corn beans												
Vegetables												

Chapati												
Green leaves												
Milk												
Dheedo												
Mushroom												
Eggs												
Meat												
Fish												
Beans												
Pickles												

Stove Types: **1**) Rice cooker **2**) LPG gas stove **3**) Kerosene stove **4**) Biogas stove **5**) ICS **6**) Traditional wood stove **7**) Induction hobs **8**) Others

Cooking Utensils: **1**) Kadhai **2**) Kasaudi **3**) Kettle **4**) Pan **5**) Pressure cooker **6**) Deure/Tapke **7**) Others

Lid uses: **1**) Yes **2**) No

Food condition: **1**) Fresh **2**) Stale food heated 3) Partially cooked

Saving for later: **1**) No saving **2**) Remains left **3**) Preparing next meal in advance

Who cooked morning meal? **1**) Father **2**) Mother **3**) Son **4**) Daughter **5**) Daughter in law **6**) Others

Activities before cooking meal …………… **Activities after cooking meal** …………..

Water Heating Events

Household Name: ………………………… Date ……………………… Survey Form Number………

	Water Quantity	Number of people	Purpose	Start Time	End Time	Stove Type	Energy-before cooking	Energy-after cooking	Cooking Utensil	Lid uses	Future Use (Thermos Flask)	Boiling Status	Who heated water?
1													
2													
3													
4													

Purpose **1**) Tea **2**) Drinking **3**) Animal Food 4) Others

Stove Types: **1**) Rice cooker **2**) LPG gas stove **3**) Kerosene stove **4**) Biogas stove **5**) ICS **6**) Traditional wood stove **7**) Induction hobs **8**) Others

Cooking Utensils: **1**) Kadhai **2**) Kasaudi **3**) Kettle **4**) Pan **5**) Pressure cooker **6**) Deure/Tapke **7**) Others

Lid uses: **1**) Yes **2**) No

Future Use **1**) Yes **2**) No **3)** Re-heated

Boiling status **1**) Very hot **2**) Boiling **3)** Warm

Who boils water? **1**) Father **2**) Mother **3**) Son **4**) Daughter **5**) Daughter in law **6**) Others

Daily Cooking Diary Summary Form

	Morning Meal	Afternoon Meal	Evening Meal
I/We brought food items (lists)			
I/We ate a meal at relative/family house			
I/We did not eat any meal			
List of food items cooked/heated			
Note (If any)			

A1.2 Registration survey

Table A1.1 is the registration survey used in the TRIID study.

Table A1.1: Registration survey used in TRIID study.

Household Information		
Q1	Village	
Q2	Community	
Q3	Contact person	1. Gender: 2. Contact no:
Q4	Family size	1. Total family members: 2. Adult: 3. Children (under 16):
Q5	Education	1. Literate 2. Illiterate
Q6	Education level	1. Primary 2. Secondary 3. Higher
Q7	Occupation	
Cooking Habits		
Q1	Who cooks	1. Male/Female/Both 2. Parents/Children
Q2	Average number of people at each meal	
Q3	Regular dishes	1. Breakfast 2. Lunch 3. Dinner
Q4	Which stove is used to prepare main food?	1. Traditional open stove 2. Improve cooking stove 3. LPG 4. Kerosene
Q5	What are the most common cooking dishes?	
Q6	Do you buy food items from market?	1. Yes 2. No If **Yes** then how often and which food items

Q7	Flame heat used for cooking	1. High 2. Low 3. Adjustable
Q8	Where is the kitchen located	1. Indoor 2. Outdoor 3. Open air 4. Multipurpose area
Q9	Are you aware about the harmful effect of smoke?	1. Yes 2. No
Fuel		
Q1	Which fuel is used to cook food?	1. Firewood 2. LPG 3. Biogas 4. Electricity 5. Kerosene 6. Others
Q2	Average quantity of wood required	1. Per meal (kg) 2. Per day (kg)
Q3	Main source of wood	1. Personal land 2. Community forest 3. Rivers 4. Others
Q4	Distance of wood collection site from household	
Q5	Collection time (hh:mm)	
Q6	Cost of cooking fuel in the market	1. Wood per Kg 2. LPG per cylinder 3. Electricity per unit 4. Kerosene per liter
Q7	Is firewood easily available?	1. Yes 2. No If **No**, then give reason ………
Q8	Did you buy firewood from the market?	1. Yes 2. No If **Yes**, then how often in a week/month
Q9	Do you use plastic to burn a fire?	1. Yes 2. No
Q10	What is your average monthly electricity bill?	

Cooking utensils

No.	Types of Utensils	Cooking Purpose	Quantity	Years (Purchase)
1	Kasaudi			

2	Karahi			
3	Tapke			
4	Dekchi			
5	Pressure cooker			
6	Fry pan			
7	Rice cooker			
8	Electric kettle			

Health		
Q1	Are family members suffered from following diseases?	1. Burns from wood stove 2. Cough 3. Respiratory problem 4. Eye or skin problem 5. Headache/dizziness 6. Flu 7. Others
Q2	Has family members visited healthcare centre due to above problem	1. Yes 2. No
Q3	Effect of smoke	1. Highly dense smoke 2. Dense smoke 3. Partially 4. Not at all
Attitudes towards change (Research)		
Q1	Have you considered cooking with electricity?	1. Yes 2. No
Q2	What equipment do you know is available?	
Q3	Have you ever heard about Induction cooker?	1. Yes 2. No
Q4	Have you ever cooked in Induction cooker?	1. Yes 2. No
Q5	What is the average electricity bill per month?	

Q6	Are you willing to participate in this electric cooking project?	1. Yes 2. No
	What do you expect from this Electric cooking project?	

A1.3 Exit surveys

Table A1.2 is the exit survey used in the Simli study.

Table A1.2: Exit survey used in the Simli study.

No.	Question	Rate from 1 to 5				
1	How much would you rate the electrical cooker in terms of user friendliness?	1	2	3	4	5
	Comments:	very hard				very easy
2	How much would you rate the cooking time performance of the electrical cooker?	1	2	3	4	5
	Comments:	Too slow				Too fast
3	How safe did you find the electrical cooker?	1	2	3	4	5
	Comments:	Not safe at all				Too safe
4	How much would you rate that the electrical cooker saves time than wood stoves?	1	2	3	4	5
	Comments:	no time				Saves time
5	How would you rate on the starting cost of the electrical cookers (12000 range including the utensils)?	1	2	3	4	5
	Comments:	Too expensive				Price is fine
6	How would you rate on the monthly running cost of the electrical cookers?	1	2	3	4	5
	Comments:	Too expensive				Price is fine
7	How much would you rate on the electricity service provided by the utility?	1	2	3	4	5
	Comments:	Worst				Great
8	Would you still use wood stove even though the electric cooker is more convenient?	YES			NO	
9	How much would you rate on the value of smoke free environment?	1	2	3	4	5
	Comments:	No value at all				Extremely valuable

10	What would be the most comfortable price range considering the value of electric cookers?	How much cost of electricity would you be willing to pay for using electric stoves per month?
	NPR - 1000 to 3000	NPR 300 - 600
	NPR - 3000 to 6000	NPR 600 - 900
	NPR - 6000 to 10,000	NPR 900 - 1200
	NPR - 10,000 to 15,000	NPR 1200-1500
11	Were you using the wood stove side by side with the electric cookers? If yes what are those items?	
12	During 14 days of survey how many times did the electricity went out and what did you do at that time?	
13	Other feedback:	

Table A1.3 is the exit survey used in the TRIID study.

Table A1.3: Exit survey used in the TRIID studies.

No.	Question		
1	Name		
2	Age		
3	Sex	1	Male
		2	Female
4	Relation to household head	1	Head
		2	Spouse
		3	Child
		4	Parent
		5	Grandchild
		6	Sibling
		7	Other
5	Are you the primary earner in the home?	1	Yes
		2	No
6	What cooking fuel or fuels do you use at this moment? **Comments:**	1	Wood
		2	LPG
		3	Electricity – induction stove
		4	Electricity – rice cooker
		5	Improved Cooking Stove
		6	Biogas
7	How often do you use each of these fuels/cookers, and for which foods? **Comments:**		

8	Why do you choose to use these fuels/cookers? **Comments:**	1	It's easily available and completely free
		2	It is a clean fuel
		3	It lights easily
		4	I am used to it
		5	I can afford it
		6	It is the only one I can get access easily
9	Kitchen location (Where is the kitchen located?)	1	Inside house
		2	Outside/Varanda
		3	Separate house
10	Do you ever use more than one stove At The Same Time? **Comments:**		Yes
			No
11	When using stoves at the same time, which stove types do you usually use together and why? Please give details **Comments:**	1	To cook quicker/saves time
		2	The food need different cooking techniques
		3	Different sized pots need different stoves
		4	Prefer the taste of food on a certain stove
		5	One of the fuels is hard to get so I try to limit the amount of time I use it for
12	What are the best things about cooking with electricity (induction stove and rice cooker)? Please give details **Comments:**	1	Fuel saving
		2	Cooks fast
		3	Smokeless kitchen
		4	Clean kitchen
		5	Saves money
		6	Better taste of food
		7	More comfort
		8	Others:
13	What are the worst things about cooking with electricity? Please give details **Comments:**		
14	During the 14 days of electric cooking survey, did you change your cooking behaviour? If yes, how and why? For example, are there foods you have cooked more because they are good to cook on the induction stove? Or are there foods that are harder to cook with electricity? **Comments:**		

15	During the 14 days of electric cooking survey did you cook more often or less often? Did you cook more dishes or fewer dishes per meal? Please give details **Comments:**		
16	How did you feel about only having one pressure cooker that can be used on the induction stove? How did this change your behaviour (if it did?) For example, did you have more rice/vegetables meals that don't require the pressure cooker to be used twice (for rice and daal)? **Comments:**		
17	What do you like most about cooking with firewood and/or LPG? **Comments:**		
18	What is most important to you? Rank the following in order of importance: Speed of cooking, taste of food, cost of cooking, ease of cooking, smokeless kitchen	1	Speed of cooking
		2	Taste of food
		3	Cost of cooking
		4	Ease of cooking
		5	Smokeless kitchen
19	Would you like to use Electric stove for future/coming up days? **Comments:**		Yes
			No
20	How much do you think you will use it, how often? Please give details		
21	Would you like to help tell people in your community about the importance of cleaner & efficient cooking? **Comments:**		Yes
			No
22	Before this research project- did you know about any clean cooking fuels/stoves? **Comments:**		Yes
			No
23	Do you think electric cooking is affordable? If yes, why? If no, why? Is it cheaper or more expensive than firewood/LPG? Why? **Comments:**		
24	If the electric stove was provided as co-finance system, would you be willing to pay more each month to cover its cost over a number of years e.g. 3 years? Please explain why **Comments:**		
25	What would be the most conformable price	1	NPR 1000 to 3000
		2	NPR 3000 to 6000

	range considering the value of electric cookers?	3	NPR 6000 to 10,000
		4	NPR 10,000 to 15,000
26	How much cost of electricity would you be willing to pay for using electric stoves each month? Please explain why **Comments:**	1	NPR 200-400
		2	NPR 400-600
		3	NPR 600-800
		4	NPR 800-1000
		5	NP 1000-1200
27	During 14 days of survey how many times did the electricity went out and what did you do at that time? And how often has the power been going out since the survey? What do you do when it does? **Comments:**		
28	Have you been using wood stove for room heating after intervention of electric stove? **Comments:**		
29	What do you do with leftovers from meals, generally? Eat them cold? Reheat them for a later meal? Give them to animals? **Comments:**		
30	Would you ever cook using only electricity and no other fuels – please explain why? **Comments:**		
31	How was the training on the induction stoves? How could it have been better? For example, would it have helped to have more training on some certain foods? **Comments:**		
Please tell me if you agree or disagree with each of the following statements			
32	Traditional cooking stove (wood stoves) are bad for my health and that of my family	1	Strongly Disagree
		2	Agree
		3	Neutral
		4	Disagree
		5	Strongly Agree
33	Electric stoves are safe to use	1	Strongly Disagree
		2	Agree
		3	Neutral
		4	Disagree
		5	Strongly Agree
34	Electric stoves are a clean way to cook	1	Strongly Disagree
		2	Agree
		3	Neutral
		4	Disagree
		5	Strongly Agree

35	Electric stoves are user friendly to cook (easy to cook with)	1	Strongly Disagree
		2	Agree
		3	Neutral
		4	Disagree
		5	Strongly Agree
36	Electric stoves can cook food quickly	1	Strongly Disagree
		2	Agree
		3	Neutral
		4	Disagree
		5	Strongly Agree
37	Electric stoves can perform very well on cooking different dishes (eg. Rice, dal, veg. chapatti, noodles etc)	1	Strongly Disagree
		2	Agree
		3	Neutral
		4	Disagree
		5	Strongly Agree
38	Do you think that cooking with Electric stove is good for your family?	1	Strongly Disagree
		2	Agree
		3	Neutral
		4	Disagree
		5	Strongly Agree
39	It is easy to control the heat on the induction stove	1	Strongly Disagree
		2	Agree
		3	Neutral
		4	Disagree
		5	Strongly Agree
40	Sometimes, the electric stove burnt the food	1	Strongly Disagree
		2	Agree
		3	Neutral
		4	Disagree
		5	Strongly Agree
41	Food cooked on the electric stove tasted better than usual	1	Strongly Disagree
		2	Agree
		3	Neutral
		4	Disagree
		5	Strongly Agree
42	I missed the smoky flavor of food cooked on wood stoves	1	Strongly Disagree
		2	Agree
		3	Neutral
		4	Disagree
		5	Strongly Agree
43	Electricity service provided by the utility company is reliable and effective	1	Strongly Disagree
		2	Agree
		3	Neutral
		4	Disagree
		5	Strongly Agree
	Any other Comments, Suggestion and Feedback		

Appendix 2

ECO study

A2.1 Cooking diaries survey

The cooking diaries used in the ECO study, created in the KoboToolbox platform, are presented in this section, starting on the following page.

8/28/22, 9:44 PM Cooking diaries survey

Cooking diaries survey

Household information

1. Household Identifier:

____

2. Date:

yyyy-mm-dd

Please take a photo of the notepad page associated with this cooking event

Click here to upload file. (< 5MB)

About the meal

Reason for heating event / which mealtime is this form for?

- ☐ Breakfast
- ☐ Lunch
- ☐ Dinner
- ☐ Snack
- ☐ Food for baby
- ☐ Water heating
- ☐ Other

Please specify:

____

Did you cook the meal at home?

- ○ Yes
- ○ No

Why didn't you cook at home for this meal?

- ☐ Went to relative's house
- ☐ Did not eat this meal
- ☐ Other

Please specify:

____

https://kf.kobotoolbox.org/#/forms/ahDibDo9M34YGXxcen8XDX/landing 1/24

Was this the first cooking/water heating event of the day?

- Yes
- No

How much wood did you start the day with (kg)?

How much wood did you end the day with (kg)?

Overall, how much wood was used for cooking/water heating on this day? (If extra wood was added during the day, take this into account in the calculation)

What was the energy meter reading at the start of the day (kWh)?

Fuel

3. What fuel was used?

- Electricity
- Firewood
- LPG
- Kerosene
- Charcoal
- Other

Please specify:

Before/ after cooking

4. What time did you start with any cooking activities? (lighting a fire, chopping vegetables)

hh:mm

How much kerosene was there before cooking (Litre)?

How much charcoal was there before cooking (kg)?

How much other fuel was there before cooking (kg)?

How much kerosene was there after cooking (Litre)?

How much charcoal was there after cooking (kg)?

How much other fuel was there after cooking (kg)?

How long did it take to start the CHARCOAL fire? (mins)

How long did it take to start the WOOD fire? (mins)

Was any Charcoal saved for later?

- Yes
- No

Was any Firewood saved for later?

- Yes
- No

About the meal

Who did the cooking and/or water heating?

- Mother
- Father
- Daughter
- Daughter in law
- Son
- Other

Please specify:

6. Name of the cook:

7. Gender of the cook:

- Male
- Female

About the meal

How many people were catered for?

9. Adults:

10. Children:

About the meal

11. Did any food not require cooking?

- Yes
- No

Please specify:

Dish and Water heating Details

12. How many dishes were cooked?

- 0
- 1
- 2
- 3
- 4
- 5

13. How many times was water heated?

- ◯ 0
- ◯ 1
- ◯ 2

Dish 1

» Which dishes did you prepare?

1a) Which dish was prepared?

- ◯ Rice
- ◯ Dal/Pulses
- ◯ Vegetables
- ◯ Roti
- ◯ Saag
- ◯ Pickles
- ◯ Corn Beans
- ◯ Milk
- ◯ Dheedo
- ◯ Mushroom
- ◯ Eggs
- ◯ Meat
- ◯ Fish
- ◯ Beans
- ◯ Beaten rice
- ◯ Potatoes
- ◯ Eggs
- ◯ Dalmot
- ◯ Noodles
- ◯ Pancake
- ◯ Other

Please specify:

» Devices

1b) What was used?

- ◯ Rice cooker
- ◯ Electric pressure cooker
- ◯ Microwave
- ◯ Induction cooker
- ◯ LPG stove
- ◯ Kerosene stove
- ◯ Improved cookstove (ICS)
- ◯ Traditional mud stove
- ◯ Other

Please specify:

____

» Utensils

1c) What was used?

- ☐ Kadhai
- ☐ Kasaudi
- ☐ Kettle
- ☐ Frying pan
- ☐ Pressure cooker
- ☐ Deure/Tapke
- ☐ Other

Please specify:

____

» Lid?

1e) Was a lid used?

- ◯ Yes
- ◯ No
- ◯ Sometimes

» Fresh?

1f) Fresh or reheated?

- ◯ Fresh
- ◯ Reheated
- ◯ Partially precooked

» Saving for later?

1g) Saving for later?

- None
- Leftovers
- Precooking
- Preparing meal in advance

» Duration

What time did you start cooking dish 1?

hh:mm

What was the meter reading before cooking?

What time did you finish cooking dish 1?

hh:mm

What was the meter reading after cooking?

Dish 2

» Which dishes did you prepare?

2a) Which dish was prepared?

- Rice
- Dal/Pulses
- Vegetables
- Roti
- Saag
- Pickles
- Corn Beans
- Milk
- Dheedo
- Mushroom
- Eggs
- Meat
- Fish
- Beans
- Beaten rice
- Potatoes
- Eggs
- Dalmot
- Noodles
- Pancake
- Other

Please specify:

» Devices

2b) What was used?

- Rice cooker
- Electric pressure cooker
- Microwave
- Induction cooker
- LPG stove
- Kerosene stove
- Improved cookstove (ICS)
- Traditional mud stove
- Other

Please specify:

» Utensils

2c) What was used?

- Kadhai
- Kasaudi
- Kettle
- Frying pan
- Pressure cooker
- Deure/Tapke
- Other

Please specify:

» Lid?

2e) Was a lid used?

- Yes
- No
- Sometimes

» Fresh?

2f) Fresh or reheated?

- Fresh
- Reheated
- Partially precooked

» Saving for later?

2g) Saving for later?

- None
- Leftovers
- Precooking
- Preparing meal in advance

» Duration

What time did you start cooking dish 2?

hh:mm

What was the meter reading before cooking?

What time did you finish cooking dish 2?

hh:mm

What was the meter reading after cooking?

Dish 3

» Which dishes did you prepare?

3a) Which dish was prepared?

- ◯ Rice
- ◯ Dal/Pulses
- ◯ Vegetables
- ◯ Roti
- ◯ Saag
- ◯ Pickles
- ◯ Corn Beans
- ◯ Milk
- ◯ Dheedo
- ◯ Mushroom
- ◯ Eggs
- ◯ Meat
- ◯ Fish
- ◯ Beans
- ◯ Beaten rice
- ◯ Potatoes
- ◯ Eggs
- ◯ Dalmot
- ◯ Noodles
- ◯ Pancake
- ◯ Other

Please specify:

____

» Devices

3b) What was used?

- ◯ Rice cooker
- ◯ Electric pressure cooker
- ◯ Microwave
- ◯ Induction cooker
- ◯ LPG stove
- ◯ Kerosene stove
- ◯ Improved cookstove (ICS)
- ◯ Traditional mud stove
- ◯ Other

Please specify:

» Utensils

3c) What was used?

- ☐ Kadhai
- ☐ Kasaudi
- ☐ Kettle
- ☐ Frying pan
- ☐ Pressure cooker
- ☐ Deure/Tapke
- ☐ Other

Please specify:

» Lid?

3e) Was a lid used?

- ○ Yes
- ○ No
- ○ Sometimes

» Fresh?

3f) Fresh or reheated?

- ○ Fresh
- ○ Reheated
- ○ Partially precooked

» Saving for later?

3g) Saving for later?

- ○ None
- ○ Leftovers
- ○ Precooking
- ○ Preparing meal in advance

» Duration

What time did you start cooking dish 3?

hh:mm

What was the meter reading before cooking?

What time did you finish cooking dish 3?

hh:mm

What was the meter reading after cooking?

Dish 4

» Which dishes did you prepare?

4a) Which dish was prepared?

- ◯ Rice
- ◯ Dal/Pulses
- ◯ Vegetables
- ◯ Roti
- ◯ Saag
- ◯ Pickles
- ◯ Corn Beans
- ◯ Milk
- ◯ Dheedo
- ◯ Mushroom
- ◯ Eggs
- ◯ Meat
- ◯ Fish
- ◯ Beans
- ◯ Beaten rice
- ◯ Potatoes
- ◯ Eggs
- ◯ Dalmot
- ◯ Noodles
- ◯ Pancake
- ◯ Other

Please specify:

____

» Devices

4b) What was used?

- ◯ Rice cooker
- ◯ Electric pressure cooker
- ◯ Microwave
- ◯ Induction cooker
- ◯ LPG stove
- ◯ Kerosene stove
- ◯ Improved cookstove (ICS)
- ◯ Traditional mud stove
- ◯ Other

Please specify:

» Utensils

4c) What was used?

- [ ] Kadhai
- [ ] Kasaudi
- [ ] Kettle
- [ ] Frying pan
- [ ] Pressure cooker
- [ ] Deure/Tapke
- [ ] Other

Please specify:

» Lid?

4e) Was a lid used?

- ( ) Yes
- ( ) No
- ( ) Sometimes

» Fresh?

4f) Fresh or reheated?

- ( ) Fresh
- ( ) Reheated
- ( ) Partially precooked

» Saving for later?

4g) Saving for later?

- ( ) None
- ( ) Leftovers
- ( ) Precooking
- ( ) Preparing meal in advance

» Duration

What time did you start cooking dish 4?

hh:mm

What was the meter reading before cooking?

What time did you finish cooking dish 4?

hh:mm

What was the meter reading after cooking?

Dish 5

» Which dishes did you prepare?

5a) Which dish was prepared?

- Rice
- Dal/Pulses
- Vegetables
- Roti
- Saag
- Pickles
- Corn Beans
- Milk
- Dheedo
- Mushroom
- Eggs
- Meat
- Fish
- Beans
- Beaten rice
- Potatoes
- Eggs
- Dalmot
- Noodles
- Pancake
- Other

Please specify:

» Devices

5b) What was used?

- Rice cooker
- Electric pressure cooker
- Microwave
- Induction cooker
- LPG stove
- Kerosene stove
- Improved cookstove (ICS)
- Traditional mud stove
- Other

Please specify:

» Utensils

5c) What was used?

- [ ] Kadhai
- [ ] Kasaudi
- [ ] Kettle
- [ ] Frying pan
- [ ] Pressure cooker
- [ ] Deure/Tapke
- [ ] Other

Please specify:

» Lid?

5e) Was a lid used?

- ◯ Yes
- ◯ No
- ◯ Sometimes

» Fresh?

5f) Fresh or reheated?

- ◯ Fresh
- ◯ Reheated
- ◯ Partially precooked

» Saving for later?

5g) Saving for later?

- ◯ None
- ◯ Leftovers
- ◯ Precooking
- ◯ Preparing meal in advance

» Duration

What time did you start cooking dish 5?

hh:mm

What was the meter reading before cooking?

What time did you finish cooking dish 5?

hh:mm

What was the meter reading after cooking?

Water 1

» Why was the water heated?

6a) Why was the water heated?

- Drinking/purifying
- Bathing
- Tea/coffee
- Milk
- Other

Please specify:

» Devices

6b) What was used?

- ◯ Rice cooker
- ◯ Electric pressure cooker
- ◯ Microwave
- ◯ Induction cooker
- ◯ LPG stove
- ◯ Kerosene stove
- ◯ Improved cookstove (ICS)
- ◯ Traditional mud stove
- ◯ Electric kettle
- ◯ Other

Please specify:

» Utensils

6c) What was used?

- ☐ Kadhai
- ☐ Kasaudi
- ☐ Kettle
- ☐ Frying pan
- ☐ Pressure cooker
- ☐ Deure/Tapke
- ☐ Other

Please specify:

» Lid?

6d) Was a lid used?

- ◯ Yes
- ◯ No
- ◯ Sometimes

» Heated from?

6e) How cold was the water/milk before heating?

- ◯ Fresh
- ◯ Still warm

» Heated to?

6f) How hot was the water/milk AFTER heating?

- ◯ Very hot
- ◯ Warm

» Saving for later?

6g) Saving for later (thermos)?

- ◯ None
- ◯ Some
- ◯ All

» Duration

What time did you start heating the water 1?

hh:mm ____________________

What was the meter reading before cooking?

____

What time did you finish heating the water 1?

hh:mm ____________________

What was the meter reading after cooking?

____

Water 2

» Why was the water heated?

7a) Why was the water heated?

- ◯ Drinking/purifying
- ◯ Bathing
- ◯ Tea/coffee
- ◯ Milk
- ◯ Other

Please specify:

____

» Devices

7b) What was used?

- ◯ Rice cooker
- ◯ Electric pressure cooker
- ◯ Microwave
- ◯ Induction cooker
- ◯ LPG stove
- ◯ Kerosene stove
- ◯ Improved cookstove (ICS)
- ◯ Traditional mud stove
- ◯ Electric kettle
- ◯ Other

Please specify:

» Utensils

7c) What was used?

- ☐ Kadhai
- ☐ Kasaudi
- ☐ Kettle
- ☐ Frying pan
- ☐ Pressure cooker
- ☐ Deure/Tapke
- ☐ Other

Please specify:

» Lid?

7d) Was a lid used?

- ◯ Yes
- ◯ No
- ◯ Sometimes

» Heated from?

7e) How cold was the water/milk before heating?

- ◯ Fresh
- ◯ Still warm

» Heated to?

7f) How hot was the water/milk AFTER heating?

- ◯ Very hot
- ◯ Warm

» Saving for later?

7g) Saving for later (thermos)?

- ◯ None
- ◯ Some
- ◯ All

» Duration

What time did you start heating the water 2?

hh:mm

What was the meter reading before cooking?

What time did you finish heating the water 2?

hh:mm

What was the meter reading after cooking?

What time did you finish all the cooking activities for the meal?

hh:mm

Any other comments? E.g. "there was no power" or "roti difficult to cook in EPC"

Any problems with this form or data?

A2.2 Notepad form

Table A2.1 is an example of the notepad form filled out by participants of the ECO cooking diary study, used by enumerators the following day to enter data into the KoboToolbox platform.

Table A2.1: Notepad form used in the ECO study, with example of data recorded.

Date	Meal / Water heating purpose	Meal start time	Meal end time	Dish name	Dish start time	Dish end time	Before cooking measurement (wood or electricity)	After cooking measurement	Comments
04/01	Breakfast	06:00	07:00	Rice Dal Vegetables	06:05 06:30 06:45	06:30 06:45 06:57	2 kg	0.5 kg	
	Tea	10:00	10:10	Tea	10:00	10:10	1 kg	0 kg	
	Lunch + tea	14:00	14:30	Noodles Tea	14:00 14:20	14:15 14:25	2.5 kg	1 kg	
	Etc… (dinner…)								

A2.3 Registration survey

The registration survey used in the ECO study, created in the KoboToolbox platform, is presented in this section, starting on the following page.

Registration survey

Survey Data

Date

yyyy-mm-dd

Name of enumerator

Information about the participant

Have the project details and your role in it been explained to you? Do you consent to participate? And do you consent for your data to be anonymised, used for research purposes and shared with the University of Bristol, and within and outside of the University, and published as part of research findings?

- ◯ Yes
- ◯ No

Household identifier (if HH identifiers have been given already)

Gender

- ◯ Male
- ◯ Female

Age

Phone number:

Literacy

- ◯ Literate
- ◯ Illiterate

What is the highest level of school you have attended?

- ◯ None
- ◯ Incomplete primary
- ◯ Completed primary
- ◯ Incomplete secondary
- ◯ Completed secondary
- ◯ Higher than secondary

Occupation of the household

Information about the household

» Group

Community

How many adults live in the household?

Out of total people how many are children?

How many people cook in your household?

» Cook details

» Cooking habits

» » Group

What is the average number of people each meal is cooked for?

Which of the meals are usually cooked at home each day?

- ☐ Breakfast
- ☐ Lunch
- ☐ Dinner

What are the most common dishes cooked?

Do you cook two foods on one stove at the same time? If so, why? And which foods?

Do you use two different stoves at the same time? If so, why? And which foods?

» » Group

Do you buy food items from market?

- ○ Yes
- ○ No

How often do you buy food items from market, and which foods?

What do you do with leftovers from meals, generally? Tick all that apply

- ☐ Eat them cold (do not reheat)
- ☐ Reheat them for a later meal
- ☐ Give them to animals
- ☐ Throw them away
- ☐ There are usually no leftovers

What flame heat do you use for wood stove cooking?

- ○ High
- ○ Low
- ○ Adjustable

Information about the dwelling

» Group

Where is the kitchen?

- ○ Indoor
- ○ Outdoor
- ○ Other

Please specify:

Where do you cook?

- ◯ Indoor
- ◯ Outdoor
- ◯ Both
- ◯ Other

Please specify:

____

Do you have a separate stove for animal food preparation?

- ◯ Yes
- ◯ No, we use the same stove as for cooking meals

Where is the stove for animal food located?

- ◯ Indoor
- ◯ Outdoor
- ◯ Other

Please specify:

____

Do you use your wood stove for room heating to keep warm?

- ◯ Yes
- ◯ No

For how many months in the year do you use your wood stove for keeping warm? E.g. for three months in winter

____

What cooking appliances do you have in your house? Check all that apply.

- ☐ Traditional wood stove
- ☐ Improved cookstove (ICS)
- ☐ LPG stove
- ☐ Electric kettle
- ☐ Rice cooker
- ☐ Biogas stove
- ☐ Kerosene stove
- ☐ Basic biomass cookstove (charcoal)
- ☐ Electric hotplate (portable)
- ☐ Electric pressure cooker
- ☐ Microwave
- ☐ Other

Please specify:

Number of appliances selected: 0

Appliance

What fuels are you using for cooking now?

- ☐ Firewood
- ☐ LPG
- ☐ Biogas
- ☐ Electricity
- ☐ Kerosene
- ☐ Charcoal

Do you buy or collect firewood?

- ○ Buy
- ○ Collect
- ○ Both buy and collect

How much wood is required per day, approximately? (in kg)

Firewood

» Buying firewood

How often do you buy firewood?

What quantity do you buy?

How much does that quantity cost? (NPR)

» Collecting firewood

How often do you collect firewood?

Where do you go to collect firewood?

What is the distance of your wood collection site from your household?

How long does each trip to collect take?

How much wood (approximately) do you collect each time?

How difficult is it to collect firewood? (1-Easy, 5 is Hard)

1 5

Buying charcoal

How often do you buy charcoal?

What quantity do you buy?

How much does that quantity cost? (NPR)

How hard is it to access charcoal?

1 5

Buying LPG

When did you start using the LPG stove?

How much did you pay for the LPG stove?

What size LPG cylinder do you use?

How often do you replace/refill the LPG cylinder?

How much does it cost to replace/refill the LPG cylinder?

How hard is it to replace/refill the LPG cylinder? (1-Easy, 5-Hard)

1 5

Buying kerosene

How often do you buy kerosene?

How much does that quantity cost you?

What quantity do you buy?

How hard is it to access kerosene? (1-Easy, 5-Hard)

1 5

Electricity

How long have you been cooking with electricity?

What do you spend on cooking with electricity per month?

Perceived difficulty of using fuels

How difficult is it to cook with firewood? (1-Easy, 5-Hard)

1 5

How difficult is it to cook with LPG? (1-Easy, 5-Hard)

1 5

How difficult is it to cook with biogas? (1-Easy, 5-Hard)

1 5

How difficult is it to cook with electricity? (1-Easy, 5-Hard)

1 5

How difficult is it to cook with kerosene? (1-Easy, 5-Hard)

1 5

How difficult is it to cook with charcoal? (1-Easy, 5-Hard)

1 5

Health

Are family members suffering from any of the following problems/diseases?

- ☐ Burns from wood stove
- ☐ Cough
- ☐ Respiratory problem
- ☐ Eye or skin problem
- ☐ Headache/dizziness
- ☐ Flu
- ☐ Other

Please specify:

Have they visited the healthcare centre due to any of the above problems?

- ○ Yes
- ○ No

Are you aware about the harmful effect of smoke?

- ○ Yes
- ○ No

Level of smoke

- ○ Very dense smoke
- ○ Moderate smoke
- ○ Mild smoke
- ○ None

Do you use plastic to start a fire for cooking?

- ○ Yes
- ○ No

Attitudes towards change

Have you considered cooking with electricity?

- ○ Yes
- ○ No

What electric cooking equipment do you know is available?

Have you heard of / about electric pressure cookers (EPC)?

- ○ Yes
- ○ No

Have you ever cooked using an EPC?

- ◯ Yes
- ◯ No

What do you expect from this electric cooking project?

Household electricity usage

What is your average monthly electricity bill? (NPR)

How often is the electricity supply bad? Is it bad at particular times? E.g. no electricity when you want it, not enough electricity for some appliances, dim lights, etc.

What do you use electricity for? (Tick all that apply)

- ☐ Indoor lights
- ☐ Outdoor lights
- ☐ Mobile phone
- ☐ Radio
- ☐ Television
- ☐ Rice cooker
- ☐ Electric kettle
- ☐ Iron
- ☐ Portable lights
- ☐ Refrigerator
- ☐ Computer/laptop
- ☐ Internet (WiFi router)
- ☐ Fan
- ☐ Electric heater
- ☐ Power tools
- ☐ Hairdryer
- ☐ Induction cooker
- ☐ Other

Please specify:

Number of appliances selected: 0

Device

Household electricity usage continued

» Group

What is electricity used for in the village? (Tick all that apply)

- ☐ Indoor lights
- ☐ Outdoor lights
- ☐ Mobile phone
- ☐ Radio
- ☐ Television
- ☐ Rice cooker
- ☐ Electric kettle
- ☐ Iron
- ☐ Portable lights
- ☐ Refrigerator
- ☐ Computer/laptop
- ☐ Internet (WiFi router)
- ☐ Fan
- ☐ Electric heater
- ☐ Power tools
- ☐ Hairdryer
- ☐ Induction cooker
- ☐ Other

Please specify:

____

» Group

How many mobile phones are owned in your household?

____

When do household members charge their phones? E.g. overnight, in the evening, in the afternooon, etc

____

Have you bought any new electrical devices recently? If so, which ones? E.g. rice cooker, electric kettle, electric heater, etc

____

What do you think of the new household meter tariff system? Did you support it?

____

How will the new tariff system affect your electricity consumption?

- ◯ It will increase
- ◯ It will decrease
- ◯ It will stay the same

A2.4 Exit survey

The exit survey used in the ECO study, created in the KoboToolbox platform, is presented in this section, starting on the following page.

Exit survey

Survey Data

Date

yyyy-mm-dd

Name of enumerator

Information about the participant

Household identifier

Gender

- Male
- Female

Approximate household income (per year) (NPR)

Information about the dwelling

Do you have a separate stove for animal food preparation?

- Yes
- No, we use the same stove as for cooking meals

Where is the stove for animal food located?

- Indoor
- Outdoor
- Other

Please specify:

Have you considered creating a new stove outside for animal food preparation?

- Yes
- No

Have you been using your wood stove to stay warm (sitting near the fire for warmth)?

- ◯ Yes
- ◯ No

For how many months in the year do you use your wood stove for keeping warm? E.g. for three months in winter

____

Cooking

» Electricity supply

How often is the electricity supply bad? Is it bad at particular times? E.g. no electricity when you want it, not enough electricity for some appliances, dim lights, etc.

____

What do you do when the electricity supply fails?

- ◯ Cook using wood or LPG stove instead
- ◯ Wait until the electricity supply returns and then cook using the EPC
- ◯ Other

Please specify:

____

Since the transition phase (recent 14 days of survey) how often has the electricity supply failed?

- ◯ Multiple times per day
- ◯ Once per day
- ◯ Every week
- ◯ Less than once a week
- ◯ Rarely

» EPC usage

Who does most of the cooking with the EPC?

- ◯ Mother
- ◯ Father
- ◯ Daughter
- ◯ Daughter in law
- ◯ Son
- ◯ Other

Please specify:

____

How many dishes do you cook in the EPC per day?

____

How difficult is it to cook Rice in the EPC? (1-Easy, 5-Hard)

1 5

How difficult is it to cook Dal in the EPC? (1-Easy, 5-Hard)

1 5

How difficult is it to cook Vegetables in the EPC? (1-Easy, 5-Hard)

1 5

How difficult is it to cook Roti in the EPC? (1-Easy, 5-Hard)

1 5

How difficult is it to cook Meat in the EPC? (1-Easy, 5-Hard)

1 5

How difficult is it to cook Saag in the EPC? (1-Easy, 5-Hard)

1 5

How difficult is it to cook Potatoes in the EPC? (1-Easy, 5-Hard)

1 5

How difficult is it to cook Noodles in the EPC? (1-Easy, 5-Hard)

1 5

How difficult is it to cook Dheedo in the EPC? (1-Easy, 5-Hard)

1 5

How difficult is it to heat Water or Milk in the EPC? (1-Easy, 5-Hard)

1 5

Since using the EPC have you changed your cooking behaviour? If yes, how and why? For example, do you cook more or less of some foods because of their compatibility with the EPC?

Now that you have the EPC do you cook more or less often than normal?

- More meals
- Fewer meals
- The same

Now that you have the EPC do you cook more dishes per meal, or fewer?

- ◯ More dishes per meal
- ◯ Fewer dishes per meal
- ◯ The same

Do you use the EPC and another stove at the same time?

- ◯ Yes
- ◯ No

What are your reasons for using two stoves at the same time?

- ☐ To save time (cook faster)
- ☐ Different foods need different cooking techniques
- ☐ Different sized pots need different stoves
- ☐ Prefer the taste of food on certain stoves
- ☐ One of the fuels is hard to obtain so I try to limit the amount of time I use it for

What do you think about cooking consecutive dishes in the EPC?

- ☐ It is worth the extra time because of the benefits
- ☐ We cook consecutively normally so it is not a problem
- ☐ It is inconvenient because it takes time and you have to clean the inner pot between dishes
- ☐ Any more comments? Please specify next:

Please specify:

How do you keep food cooked in the EPC warm?

Which foods tasted better in the EPC than on wood/LPG stoves?

- ☐ Rice
- ☐ Dal
- ☐ Vegetables
- ☐ Roti
- ☐ Meat
- ☐ Saag
- ☐ Potatoes
- ☐ Noodles
- ☐ Dheedo
- ☐ Milk

Which foods tasted worse in the EPC than on wood/LPG stoves?

- [ ] Rice
- [ ] Dal
- [ ] Vegetables
- [ ] Roti
- [ ] Meat
- [ ] Saag
- [ ] Potatoes
- [ ] Noodles
- [ ] Dheedo
- [ ] Milk

Did you miss the smoky flavour of any foods?

- ○ Yes
- ○ No

Which foods did you miss the smoky flavour of?

- [ ] Rice
- [ ] Dal
- [ ] Vegetables
- [ ] Roti
- [ ] Meat
- [ ] Saag
- [ ] Potatoes
- [ ] Noodles
- [ ] Dheedo
- [ ] Milk

What are the best things about cooking with the EPC?

- [ ] Saves fuel
- [ ] Cooks quickly
- [ ] Smokeless
- [ ] Clean kitchen
- [ ] Saves money
- [ ] Food tastes better
- [ ] Easier to use
- [ ] Other

Please specify:

What are the worst things about cooking with the EPC?

How could cooking with the EPC be improved?

How useful would 1 or 2 extra inner pots be? (1-Not useful, 5-Very useful)

1 5

What is most important to you? Rank the following in order of importance: Speed of cooking, taste of food, cost of cooking, ease of cooking, smokeless kitchen

1st choice

- ◯ Speed of cooking
- ◯ Taste of food
- ◯ Cost of cooking
- ◯ Ease of cooking
- ◯ Smokeless kitchen

2nd choice

- ◯ Speed of cooking
- ◯ Taste of food
- ◯ Cost of cooking
- ◯ Ease of cooking
- ◯ Smokeless kitchen

3rd choice

- ◯ Speed of cooking
- ◯ Taste of food
- ◯ Cost of cooking
- ◯ Ease of cooking
- ◯ Smokeless kitchen

4th choice

- ◯ Speed of cooking
- ◯ Taste of food
- ◯ Cost of cooking
- ◯ Ease of cooking
- ◯ Smokeless kitchen

5th choice

- ◯ Speed of cooking
- ◯ Taste of food
- ◯ Cost of cooking
- ◯ Ease of cooking
- ◯ Smokeless kitchen

Will you continue to use the EPC?

- ◯ Yes
- ◯ No

Why not?

____

How often will you use the EPC?

- ◯ 3+ times per day
- ◯ 1-2 times per day
- ◯ 3-4 times per week
- ◯ Less than once per week
- ◯ Rarely

» Economics

How much did you spend on electricity this month? (NPR)

____

Do you think electric cooking is affordable?

- ◯ Yes
- ◯ No

If the EPC was provided as co-finance system, would you be willing to pay more each month to cover its cost over a number of years e.g. 3 years?

- ◯ Yes
- ◯ No

Please explain why:

____

You have agreed to pay for 40% of the cost of the EPC. If you were not part of this project, what would a reasonable price range for the EPC? (NPR)

- ◯ 1000-3000
- ◯ 3000-6000
- ◯ 6000-10,000
- ◯ 10,000-15,000

How much cost of electricity would you be willing to pay for using EPCs each month? (In addition to the cost of electricity for other devices and appliances)

- 200-400
- 400-600
- 600-800
- 800-1000
- 1000-1200

Perceived difficulty of using fuels

How difficult is it to cook with firewood? (1-Easy, 5-Hard)

1 5

How difficult is it to cook with LPG? (1-Easy, 5-Hard)

1 5

How difficult is it to cook with biogas? (1-Easy, 5-Hard)

1 5

How difficult is it to cook with electricity? (1-Easy, 5-Hard)

1 5

How difficult is it to cook with kerosene? (1-Easy, 5-Hard)

1 5

How difficult is it to cook with charcoal? (1-Easy, 5-Hard)

1 5

How much do you agree or disagree with the following statements?

Traditional wood stoves are bad for my health and that of my family (1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree).

1 5

EPCs are safe to use (1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree).

1 5

EPCs are a clean way to cook (1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree).

1 5

EPCs are user friendly (easy to cook with)

1 5

It is easy to control the heat with the EPC (1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree).

1 5

EPCs can cook food quickly (1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree).

1 5

I was able to multi-task (do other things) whilst the EPC was cooking (1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree).

1 5

EPCs can perform very well on cooking different dishes (eg. Rice, Dal, Vegetables, Roti, Noodles, etc) (1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree).

1 5

Do you think that cooking with the EPC is good for your family? (1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree).

1 5

8/28/22, 9:44 PM Exit survey

Sometimes, the EPC burnt the food (1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree).

1 5

Food cooked in EPC tasted better than usual (1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree).

1 5

I missed the smoky flavor of food cooked on wood stoves (1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree).

1 5

The electricity supply provided by the MHP is reliable and effective (1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree).

1 5

https://kf.kobotoolbox.org/#/forms/aRhQyw3xbLKXYEQLUaZQHK/landing 14/15

Health

How has the health of family members changed since starting to use the EPC

- [ ] Improved
- [ ] Stayed the same
- [ ] Got worse
- [ ] Other

Please specify:

____

What is the level of smoke in the kitchen now?

- ◯ Very dense smoke
- ◯ Moderate smoke
- ◯ Mild smoke
- ◯ None

Attitudes towards the project

What do you think of this project so far?

____

How could the project be improved?

____

A2.5 A2EI logger data and load profiles explanation

The following is an explanation of the A2EI logger data processing and cooking event identification process, provided by A2EI.

All code is written in Python with Pandas. The cooking events are created by applying several event conditions for maximum resemblance to the actual cooking events. In essence, a cooking event is any change to the energy counter within 11 minutes.

Below is an overview of the conditions that are used for defining a cooking event:

1. Treatment of empty cells
    1. Fill current value (A) from row above
    2. Fill energy counter value (kWh) from row above

Explanation: The smart meters in this project are only sending data when a value changes, e.g. from 4 A to 4.1 A. Hence, the current value and energy counter value are filled out to match the value of the previous row.

2. Calculate instantaneous power (kW): current * voltage / 1000

Explanation: The power of the EPC is calculated by multiplying the current and voltage. This is more exact than the power value on the smart meter display, which is calculated as an average of the recording interval [read: 5 minutes].

3. Apply conditions for event start and end
    1. Indicate when EPC is turned on/off
    2. Calculate event end time
    3. Calculate event start time

Explanation: Several conditions are applied on the data to indicate if the EPC is turned on or off. This includes looking at the minimum energy consumption of an event (0.04 kWh), checking any irregularities in the time recording intervals and assigning changes in the energy counter to either an ongoing cooking event or a start or an end of a cooking event.

4. Disqualify events that are not qualifying as EPC events according to the threshold values

Explanation: If an event is longer than the maximum event duration (400 minutes) or has a maximum current below the rated current of the EPC (3.0 A), then these are removed from the list of cooking events. In case a cooking event is lacking a current value i.e. is so short [read: 5 to 10 minutes] that it only has empty cells as current values, then this event is not removed.

5. Merge events that are very close to each other into one

Explanation: Check if events start within 10 minutes to each other to produce longer and fewer events. These events are merged, because the events have typically been separated because of the fact that an appliance is maintaining the heat for 5 to 10 minutes without consuming any electricity.

6. Get event energy and event time

Explanation: Extract the energy consumption and event time of each session to produce the event list file

7. Calculate cooking events from data gaps

Explanation: Assign the energy and time between two subsequent recordings that are longer than 15 minutes and have a change in the energy counter value. The data gap is either allocated to the start section or end section of an existing event or it makes up a completely new cooking event if the energy gap is larger than the average event. Completely new events are marked with a 1 in the column called event_calc [read: calculated event].

Based on A2EI's database, the average cooking event duration of an EPC is 35 minutes and is using 0.3 kWh. This equates an average power of 0.51 kW [0.3 kWh/35 minutes/60 seconds].

As an example, if the length of the data gap is 1240 minutes and 3.2 kWh, it equates 10 events according to the average event energy and 35 events according to the average event duration. The lowest result is picked from the two calculations, i.e. 10 events. The cooking time is then calculated through the total energy divided by the average power, i.e. 3.2/0.51*60 = 373.33 minutes and as the entire data gap duration 1240 minutes, also here is the lowest value used, i.e. 373.33 minutes. The cooking time per event is thus 37.3 minutes [373.33 minutes/10].

Appendix 3

Techno-economic modelling

A3.1 MHP secretary and PEUs questionnaire

The following questionnaire was used to collect data for the techno-economic modelling described in Chapter 5.

General questions:

Q1	How many households are now connected?
Q2	Have there been any changes to the financial operation of the plant in the last year? E.g. different connection fee, tariff adjustment, maintenance spending, different salaries…
Q3	**Tariffs and household meters:** a) Household meters have been installed. Are any households still without meters? b) What will the new tariff system be for households, and how will (or was) this be decided? Who is part of the decision? Are community members represented in the decision process? How much are people in agreement with the proposed tariff? c) When will the new tariff system be introduced? d) How successful do you think the new tariff system will be, and why? e) Will electricity consumption reduce when consumers are paying for their usage? If so, how will the tariff be set to ensure enough revenue is generated?

	f) Will the tariff be set according to calculations? **(If we can complete our model with information on electricity usage in the community, we can use it to assess different tariffs to see how much revenue is generated, and show what the tariff needs to be)**
Q4	**Consumer paying habits:** a) Approximately, what percentage of consumers pay regularly for their electricity, at the moment? b) What are the reasons people don't pay regularly? (E.g. they are very poor, or they helped in MHP construction, etc) c) Do these consumers pay sometimes, when they are able to, or never? Can you describe the different groups of non-paying consumers, their reasons for not paying, and how often they pay? d) Will these consumers be required to pay when the new system is introduced? How can this be ensured?
Q5	Approximately, how much money is collected per month?
Q6	How many operators are there, and what is their salary? How happy are they with their job and salary?
Q7	Are there any other salaries which are paid from the MHP revenue? If yes, how much are they?
Q8	**MHP health, maintenance:** How has the MHP system been during the last year? What incidents have occurred? And what repairs and maintenance have been required?

	How much was spent on repairs and maintenance during the last year?	
Q9	Is there money budgeted for routine maintenance and purchasing spares?	
Q10	When there have been technical problems, has there been enough money to pay for repairs?	
Q11	How has the electrical demand changed during the last year? If it has changed, e.g. increased, why has this happened?	
Q12	What non-residential facilities/businesses/productive end uses are connected to the hydropower?	Hospital/health clinic
		Post office
		School
		Community centre
		Local government offices
		Flour mill/grain milling
		Bakery
		Furniture making
		Grocery shop
		Barber shop
		Tea shop
		Telecoms tower
		Other (please specify)
Q14	What is the payment structure for productive end uses and what do they pay?	
Q15	What productive end uses are powered by the MHP plant?	
Q16	Is the end uses' consumption metered and recorded? How much revenue is generated from end uses per month, if known? How much energy, if known?	
Q17	The community services such as **public lighting, the healthpost, schools, MHP office, local government office** – who pays for the electricity consumption of these?	

	If they do pay, do they pay a flat rate? If so, what is it? If not, what is the system?
Q18	Are there any social and political issues that have been caused by the MHP plant? If so, what are they?

Electricity demand questions:

Q19	What is electricity used for in households in the village? (Tick all that apply)	Lighting
		Mobile phone charging
		Radio
		Television
		Rice cooker
		Electric kettle
		Iron
		Portable lights
		Fridge
		Computer
		Fan
		Electric heater
		Power tools
		Hairdryer
		Induction cooker
		Other, please specify anywhere in the boxes
Q20	In terms of households, how has the electricity demand changed over the last year? Have people been buying new devices? E.g. electric kettles, rice cookers? Other devices?	
Q21	The typical peak demand seems to be around 70-75 kW, morning and evening. What is the typical demand in the night, and in the afternoon? (Last year overnight and afternoon demand were both around 30-40 kW) What causes the overnight demand? Phone charging? Lights? Rice mills? Stone crusher? Etc	

	What devices/end uses make up the afternoon load (also 40 kW)? This is more obvious as it must include some lighting, some rice cookers and electric cookers, etc, and what else?
Q22	How does the load vary throughout the year? E.g. does it change with the seasons? And with agriculture?
Q23	Mobile phones – on average how many people have them per household? E.g. for a household of five people, how many have mobile phones? Generally, when do people charge their phones (overnight, in the day, etc?)
Q24	TVs and antenna boxes (for cable TV) – are these separate devices? Do people have the antenna boxes? Or do people have TVs without a cable box?
Q25	Some people own power tools, for making furniture. For how many people is furniture making their business? How often do they use their tools?...

Industrial end uses

Q26	**See table below.** Are the industrial end uses (e.g. rice mills) **below** scheduled so that they are not all used at the same time? Or, is it not controlled? Are they all just operated whenever needed?

	If the rice mills are operated similarly and whenever needed, **just fill in the rows for the first 3 phase mill and the first single phase mill, leaving the rest.** **Please fill in the appropriate rows as fully as possible.**

Appliance	Nominal power, P [kW]	How long it is ON during each use? (minute)	Total use per day (hours)	Window of use: Start W1	End W1	Start W2	End W2	Comments: **E.g. usage restricted to afternoon, 2pm – 5pm**
Example: **Rice mill**	5	10 minutes	2 hours	07:00	10:00	19:00	23:00	Agreement not to use during peak times…
3 phase Rice mill no.1	?							
3 phase Rice mill no.2								
Single phase Rice mill no.1	Is single phase mill lower power?							
Single phase Rice mill no.2								
Single phase Rice mill no.3								
Single phase Rice mill no.4								
Single phase Rice mill no.5								
Stone crusher								
Irrigation pump ???								
Telecoms								

tower ???								

Q27	How many poultry farms are there? How many bulbs does it use, and what power? Are there any other appliances used in the poultry farm(s)? **Please fill in the table below as fully as possible.**

Type	Appliance	Nominal power, P [kW]	How long ON during each use?	Total use per day (hours)	Window of use: Start W1	End W1	Start W2	End W2	Comments:
Poultry farm	Bulbs								
Poultry farm	**Anything else?**								

Comments:

Community end uses

Information on community and commercial end uses is also very useful. All appliances and numbers are guesses, please make suggestions and changes and comments.

Type	Number	Appliance	Number of each appliance	Comments
Lighting		Public lighting (streetlights)	10 ?	
Healthpost	1	Indoor Bulb	5 ?	
		Outdoor Bulb	3 ?	
		Phone chargers	5 ?	
		Computer ?	1 ?	
		Electric kettle ?	1 ?	

		Refrigerator ?	1? 2?	
		Electric Heater ?	1 ?	
Office	2	Indoor Bulb	6 ?	
		Outdoor Bulb	1 ?	
		Desk Bulb ?	5 ?	
		Phone chargers ?	3 ?	
		Computer	2 ?	
		Printer	1 ?	
		Internet router	1 ?	
		Electric kettle ?	1 ?	
		Electric Heater ?	1 ?	
Primary and higher level schools	10 primary schools, 3 middle (up to class 8) schools, 2 higher = 15	Indoor Bulb	8 ?	
		Outdoor Bulb	6 ?	
		Phone chargers	6 ?	
		Electric Heater ?	2 ?	
		Computer ?	1 ?	
Campus school	2	Indoor Bulb	12 ?	
		Outdoor Bulb	6 ?	
		Phone chargers	10 ?	
		Radio	2 ?	
		TV	2 ?	
		Computer	5 ?	
		Printer	2 ?	
		Internet router	3 ?	
		Electric kettle ?	2 ?	

		Refrigerator ?	1? 2?	
		Electric Heater ?	2 ?	

Comments:

Business end uses

Type	Number	Appliance	Number of each appliance	Comments
Hotel		Indoor Bulb		
		Outdoor Bulb		
		Phone chargers		
		Radio		
		TV		
		Rice cooker ?		
		Electric kettle ?		
Shop (e.g. selling food or household items)		Indoor Bulb		
		Outdoor Bulb		
		Phone chargers ?		
		Radio		
		TV		

Comments:

A3.2 Household devices survey

The household devices survey, used in the creation of the techno-economic model described in Chapter 5, is presented in this section, starting on the following page.

Household devices survey

Survey Data

Date

yyyy-mm-dd

Household identifier

Have the reasons for this survey been explained to you? Do you consent to participate? And do you consent for your data to be anonymised, used for research purposes and shared with the University of Bristol, and within and outside of the University, and published as part of research findings?

- ◯ Yes
- ◯ No

Group

Indoor lights:

How many do you use regularly?

How often do you use it/them (turn on)?

- ◯ Every day
- ◯ Three times per week
- ◯ Once per week
- ◯ Once per fortnight
- ◯ Once per month
- ◯ Other
- ◯ We do not own this

Please specify:

How many hours do you use it/them (on days when used)? Enter decimal if not integer (e.g. 0.5 for 30 minutes). Enter zero if not owned

What times of the day do you usually use it/them (on days when used)? Select all that apply

- ☐ Morning
- ☐ Lunchtime
- ☐ Afternoon
- ☐ Evening
- ☐ Overnight
- ☐ Anytime

Please add any useful comments (e.g. we use the electric kettle in the morning only, or we use the rice cooker only on special occasions, or we keep the outdoor lights on all night)

____

Group

Outdoor lights:

____

How many do you use regularly? Enter zero if not owned

____

How often do you use it/them (turn on)?

- ○ Every day
- ○ Three times per week
- ○ Once per week
- ○ Once per fortnight
- ○ Once per month
- ○ Other
- ○ We do not own this

Please specify:

____

How many hours do you use it/them (on days when used)? Enter decimal if not integer (e.g. 0.5 for 30 minutes). Enter zero if not owned

____

What times of the day do you usually use it/them (on days when used)? Select all that apply

- ☐ Morning
- ☐ Lunchtime
- ☐ Afternoon
- ☐ Evening
- ☐ Overnight
- ☐ Anytime

Please add any useful comments (e.g. we use the electric kettle in the morning only, or we use the rice cooker only on special occasions, or we keep the outdoor lights on all night)

Group

Mobile phones (Note - here we are interested in charging, not usage):

How often do you charge them?

- ◯ Every day
- ◯ Three times per week
- ◯ Once per week
- ◯ Once per fortnight
- ◯ Once per month
- ◯ Other
- ◯ We do not own this

Please specify:

How many hours do you charge them (on days when you do charge them)? Enter decimal if not integer (e.g. 0.5 for 30 minutes). Enter zero if not owned

What times of the day do you usually charge them (on days when you do charge them)? Select all that apply

- ☐ Morning
- ☐ Lunchtime
- ☐ Afternoon
- ☐ Evening
- ☐ Overnight
- ☐ Anytime

Please add any useful comments (e.g. we use the electric kettle in the morning only, or we use the rice cooker only on special occasions, or we keep the outdoor lights on all night)

Group

Radio (Note: Is it battery powered? If powered by rechargeable batteries, we are interested in charging, not usage):

How often do you use it/them (turn on) (or charge if battery-powered)?

- ◯ Every day
- ◯ Three times per week
- ◯ Once per week
- ◯ Once per fortnight
- ◯ Once per month
- ◯ Other
- ◯ We do not own this

Please specify:

How many hours do you use it/them (or charge if battery-powered) (on days when used)? Enter decimal if not integer (e.g. 0.5 for 30 minutes). Enter zero if not owned

What times of the day do you usually use it/them (or charge if battery-powered) (on days when used)? Select all that apply

- ☐ Morning
- ☐ Lunchtime
- ☐ Afternoon
- ☐ Evening
- ☐ Overnight
- ☐ Anytime

Please add any useful comments (e.g. the radio is battery-powered with rechargeable batteries)

Group

Television:

How often do you use it/them (turn on)?

- ◯ Every day
- ◯ Three times per week
- ◯ Once per week
- ◯ Once per fortnight
- ◯ Once per month
- ◯ Other
- ◯ We do not own this

Please specify:

____

How many hours do you use it/them (on days when used)? Enter decimal if not integer (e.g. 0.5 for 30 minutes). Enter zero if not owned

____

What times of the day do you usually use it/them (on days when used)? Select all that apply

- ☐ Morning
- ☐ Lunchtime
- ☐ Afternoon
- ☐ Evening
- ☐ Overnight
- ☐ Anytime

Please add any useful comments (e.g. we use the electric kettle in the morning only, or we use the rice cooker only on special occasions, or we keep the outdoor lights on all night)

____

Group

Rice cooker:

____

How often do you use it/them (turn on)?

- ◯ Every day
- ◯ Three times per week
- ◯ Once per week
- ◯ Once per fortnight
- ◯ Once per month
- ◯ Other
- ◯ We do not own this

Please specify:

____

How many hours do you use it/them (on days when used)? Enter zero if not owned

____

What times of the day do you usually use it/them (on days when used)? Select all that apply

- ☐ Morning
- ☐ Lunchtime
- ☐ Afternoon
- ☐ Evening
- ☐ Overnight
- ☐ Anytime

Please add any useful comments (e.g. we use the electric kettle in the morning only, or we use the rice cooker only on special occasions, or we keep the outdoor lights on all night)

____

Group

Electric kettle:

____

How often do you use it/them (turn on)?

- ◯ Every day
- ◯ Three times per week
- ◯ Once per week
- ◯ Once per fortnight
- ◯ Once per month
- ◯ Other
- ◯ We do not own this

Please specify:

____

How many hours do you use it/them (on days when used)? Enter decimal if not integer (e.g. 0.5 for 30 minutes). Enter zero if not owned

____

What times of the day do you usually use it/them (on days when used)? Select all that apply

- [ ] Morning
- [ ] Lunchtime
- [ ] Afternoon
- [ ] Evening
- [ ] Overnight
- [ ] Anytime

Please add any useful comments (e.g. we use the electric kettle in the morning only, or we use the rice cooker only on special occasions, or we keep the outdoor lights on all night)

Group

Portable lights (Note - if powered by rechargeable batteries, here we are interested in charging, not usage):

How often do you charge it/them?

- ◯ Every day
- ◯ Three times per week
- ◯ Once per week
- ◯ Once per fortnight
- ◯ Once per month
- ◯ Other
- ◯ We do not own this

Please specify:

How many hours do you charge it/them (on days when you charge it/them)? Enter decimal if not integer (e.g. 0.5 for 30 minutes). Enter zero if not owned

What times of the day do you usually charge them (on days when you do charge them)? Select all that apply

- [ ] Morning
- [ ] Lunchtime
- [ ] Afternoon
- [ ] Evening
- [ ] Overnight
- [ ] Anytime

Please add any useful comments (e.g. we use the electric kettle in the morning only, or we use the rice cooker only on special occasions, or we keep the outdoor lights on all night)

Group

Refrigerator:

How often do you use it/them (turn on)?

- ◯ Every day
- ◯ Three times per week
- ◯ Once per week
- ◯ Once per fortnight
- ◯ Once per month
- ◯ Other
- ◯ We do not own this

Please specify:

How many hours do you use it/them (on days when used)? Enter decimal if not integer (e.g. 0.5 for 30 minutes). Enter zero if not owned

What times of the day do you usually use it/them (on days when used)? Select all that apply

- ☐ Morning
- ☐ Lunchtime
- ☐ Afternoon
- ☐ Evening
- ☐ Overnight
- ☐ Anytime

Please add any useful comments (e.g. we use the electric kettle in the morning only, or we use the rice cooker only on special occasions, or we keep the outdoor lights on all night)

Group

Computer/laptop (Note - here we are interested in charging, not usage):

How often do you charge it/them?

- ◯ Every day
- ◯ Three times per week
- ◯ Once per week
- ◯ Once per fortnight
- ◯ Once per month
- ◯ Other
- ◯ We do not own this

Please specify:

How many hours do you charge it/them (on days when you charge it/them)? Enter decimal if not integer (e.g. 0.5 for 30 minutes). Enter zero if not owned

What times of the day do you usually charge it/them (on days when you do charge it/them)? Select all that apply

- ☐ Morning
- ☐ Lunchtime
- ☐ Afternoon
- ☐ Evening
- ☐ Overnight
- ☐ Anytime

Please add any useful comments (e.g. we use the electric kettle in the morning only, or we use the rice cooker only on special occasions, or we keep the outdoor lights on all night)

Group

Internet (Router):

How often do you use it/them (turn on)?

- ◯ Every day
- ◯ Three times per week
- ◯ Once per week
- ◯ Once per fortnight
- ◯ Once per month
- ◯ Other
- ◯ We do not own this

Please specify:

How many hours do you use it/them (on days when used)? Enter decimal if not integer (e.g. 0.5 for 30 minutes). Enter zero if not owned

What times of the day do you usually use it/them (on days when used)? Select all that apply

- Morning
- Lunchtime
- Afternoon
- Evening
- Overnight
- Anytime

Please add any useful comments (e.g. we use the electric kettle in the morning only, or we use the rice cooker only on special occasions, or we keep the outdoor lights on all night)

Group

Fan (battery-powered? If so, record charging, not usage):

How often do you use it/them (turn on) (or charge if battery-powered)?

- Every day
- Three times per week
- Once per week
- Once per fortnight
- Once per month
- Other
- We do not own this

Please specify:

How many hours do you use it/them (or charge if battery-powered) (on days when used)? Enter decimal if not integer (e.g. 0.5 for 30 minutes). Enter zero if not owned

What times of the day do you usually use it/them (or charge if battery-powered) (on days when used)? Select all that apply

- [ ] Morning
- [ ] Lunchtime
- [ ] Afternoon
- [ ] Evening
- [ ] Overnight
- [ ] Anytime

Please add any useful comments (e.g. we use the electric kettle in the morning only, or we use the rice cooker only on special occasions, or we keep the outdoor lights on all night)

Group

Electric heater:

How often do you use it/them (turn on)?

- ◯ Every day
- ◯ Three times per week
- ◯ Once per week
- ◯ Once per fortnight
- ◯ Once per month
- ◯ Other
- ◯ We do not own this

Please specify:

How many hours do you use it/them (on days when used)? Enter decimal if not integer (e.g. 0.5 for 30 minutes). Enter zero if not owned

What times of the day do you usually use it/them (on days when used)? Select all that apply

- [ ] Morning
- [ ] Lunchtime
- [ ] Afternoon
- [ ] Evening
- [ ] Overnight
- [ ] Anytime

Please add any useful comments (e.g. we use the electric kettle in the morning only, or we use the rice cooker only on special occasions, or we keep the outdoor lights on all night)

____

Group

Power tools (battery-powered?):

____

How often do you use it/them (turn on)?

- ○ Every day
- ○ Three times per week
- ○ Once per week
- ○ Once per fortnight
- ○ Once per month
- ○ Other
- ○ We do not own this

Please specify:

____

How many hours do you use it/them (on days when used)? Enter decimal if not integer (e.g. 0.5 for 30 minutes). Enter zero if not owned

____

What times of the day do you usually use it/them (on days when used)? Select all that apply

- ☐ Morning
- ☐ Lunchtime
- ☐ Afternoon
- ☐ Evening
- ☐ Overnight
- ☐ Anytime

Please add any useful comments (e.g. we use the electric kettle in the morning only, or we use the rice cooker only on special occasions, or we keep the outdoor lights on all night)

____

A3.3 Description of RAMP algorithm

The following is a description of the general RAMP algorithm, accessible in the Github repository in [211]. An input file consists in a list of user type (i.e. Hospital, Low Income Household, School, etc.). There is a certain number of users from each of the user types (minimum is one). To each user type is associated a list of typical appliances. Almost all the usage parameters (specific power consumption, usage windows during a 24h period) are defined at the appliance level. A theoretical load profile is computed with the following steps:

1. identify an expected peak time frame to allow differentiating between off- and on-peak switch-on events of appliances

2. for each type of appliance of each user of each user type, check if the appliance type is used based on a weekly frequency of use. If not, ignore the appliance type. Otherwise, compute:

    i. the randomised appliance type's total time of use

    ii. the randomised vector of time frames in which the appliance type is allowed to be switched on

    Subsequently, iterate over the following steps until the sum of the durations of all the switch-on events equals the randomised total time of use defined in step 2.i.:

    iii. a random switch-on time frame within the allowed time frames defined in step 2.ii

    iv. compute the randomised power required by the appliance type for the switch-on time frame defined in step 2.iii

    v. compute the actual power absorbed by the appliances of the type under consideration during the switch-on event considering a random numerosity of appliances

    Repeat then step 2. N times to get a stochastic variation of the appliances' usage

3. Average the N profiles in the total load profile.

Appendix 4

Control of battery storage systems in MHP mini-grids

A4.1 Introduction

[145]In a battery energy storage system or BESS, the battery is connected to a grid network through an inverter [217]. Control of inverters in mini-grids is often achieved through droop control, by which inverters are made to behave like synchronous generators and share the load active and reactive power demand without communication links [218]–[224]. Distributed BESS under frequency control alone, where each inverter acts to restore the grid frequency to a setpoint, may compete with each other and the ELC. In droop control, the inverter output frequency and voltage are adjusted in order to supply more or less active and reactive power according to the load demand. For networks with mostly inductive transmission lines active power, P, is related to frequency, f, and reactive power, Q, is related to voltage, V, while for mostly resistive lines active power is linked to voltage and reactive power to frequency. The control equations for conventional droop control for networks with inductive lines are Equations (8.1) and (8.2) [8]. Figure 8.1 depicts the corresponding droop curves, showing how a change in measured grid P or Q causes the inverter to adjust its output f or V in order to contribute the required P or Q [8].

$$f = f_0 - k_p(P - P_0) \quad (8.1)$$

$$V = V_0 - k_q(Q - Q_0) \quad (8.2)$$

where k_p and k_q are the droop coefficients and f_0, P_0, V_0 and Q_0 are the nominal or setpoint values.

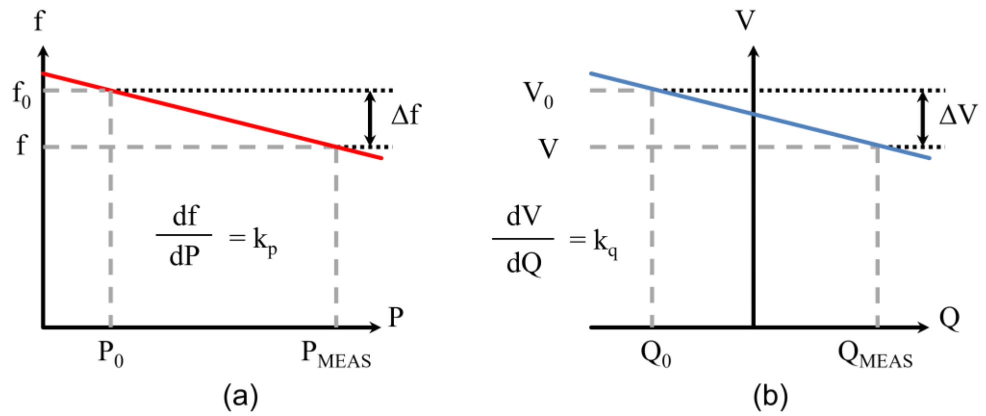

Figure 8.1: Example conventional droop characteristics for inductive lines. (a) Active power vs. frequency, Equation 8.1. (b) Reactive power vs. output voltage, Equation 8.2. P_{MEAS} and Q_{MEAS} are the measured powers. Reproduced with permission from [8]**.**

Droop control can be extended to include virtual impedance to decouple the power regulation as line impedance is often neither purely inductive nor resistive [219]–[221]. Secondary control can be incorporated to restore frequency and voltage to target values by adjustment of power references [192], [225], [226].

Droop control has been employed for BESS control for both grid-connected and standalone applications [217], [227]. However, droop control in these examples creates BESS which are grid-forming units. This is suitable when it is desirable to achieve equal power sharing amongst distributed generators including BESS. However, in these situations there is no ELC and no requirement for one generator to be run at a near constant speed. In MHPs, the generator forms the grid, and, with an increased load, requires support rather than power sharing. BESS in MHPs would ideally cover all excess demand above the rated generator power, while the generator itself continues operating at this constant output. Furthermore, BESS would be required to work alongside the ELC while the demand is beneath the generation, charging so as to store sufficient energy to deliver the excess load during peak times. Therefore, grid-supporting inverter control is more suitable for MHPs [196].

As the BESS would reach full capacity if charged for long enough, and in case of faults associated with them, the ELC would need to remain online and dumping any power not usefully charging BESS. Therefore, the MHP mini-grid context presents a different and mostly unexplored scenario for BESS integration. The BESS inverter needs to measure the frequency and voltage and provide or demand the necessary active and reactive power to support the network, counteracting changes in frequency and voltage, charging and discharging to meet high peak electricity demand. The frequency deviations will be the same for all elements of the mini-grid, whereas different voltage deviations will occur as a function of the grid impedance values [225].

For reverse droop control, which is much less commonly used than conventional droop, the inverter active and reactive power references are adjusted based on the measured local frequency and voltage [142], [143], [192], [218], [220], [225], [228]–[232]. Therefore, reverse droop controlled sources are suitable for operation alongside grid-forming units such as the synchronous generator in an MHP, as they can respond to changes in frequency and voltage by demanding or providing power [218]. Reverse droop control for distributed BESS in microgrids has been put forward [192], [232] but never explored for the special case of an MHP mini-grid i.e. where there is a single grid-forming generator which is best operated at reasonably constant power and an ELC which regulates frequency. BESS could be located centrally in the powerhouse or distributed strategically in the mini-grid, either just downstream of distribution transformers, or within HHs themselves.

This work explores how reverse droop control could be used for BESS to enable increased electric cooking and connection of PEUs to improve life in MHP communities, therefore addressing objective 5. The aim of the modelling was to validate a reverse droop control system, to provide proof of concept that it can enable the addition of BESS to MHP mini-grids, understand its operation, and compare BESS integration topologies in a simplified context.

A4.2 Model formulation

MATLAB/Simulink was used to model and understand an MHP mini-grid system featuring a 100 kVA synchronous generator (SG) with AVR, an ELC, one or more BESS in central and distributed topologies, and consumer loads arranged in a radial topology and connected through transformers and line impedances. Figure 8.2 presents a schematic of the model, with a centralised BESS and distributed BESS, for illustration, although each topology was considered separately. During the research, detailed models of the SG and ELC system, and BESS, were created, including the switching behaviour of the inner workings of the ELC and inverter. These models were combined and simplified to create a model of an MHP mini-grid based on the Simulink simplified synchronous machine (SSM), voltage sources and current sources, in order to reduce the complexity and computational requirements of the models while maintaining their functionality and representativeness. The inverter model was adapted from [224], altering its control scheme from conventional to reverse droop and expanding its functionality.

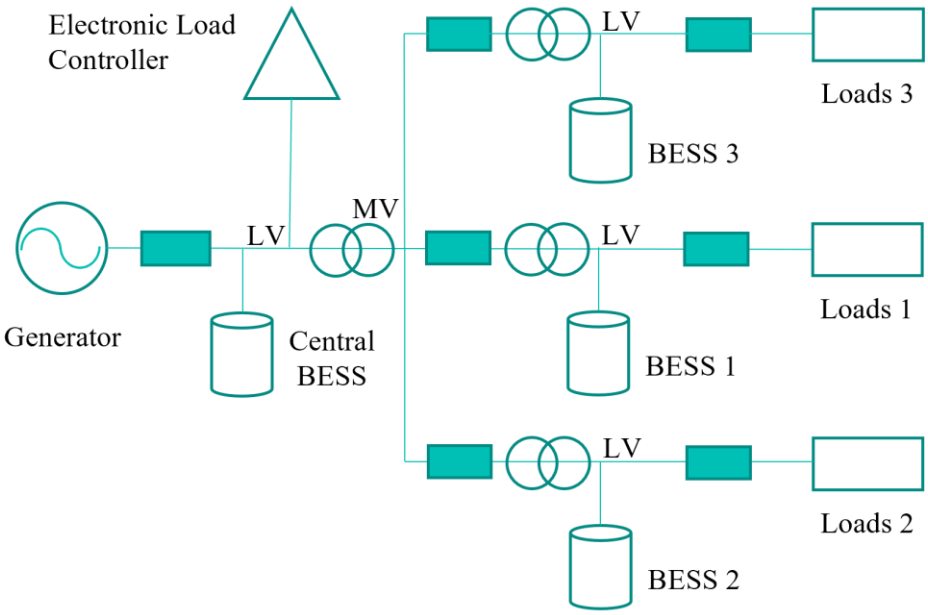

Figure 8.2: Diagram of the modelled mini-grid system, showing both the central BESS and distributed BESS (numbered 1-3), although each topology was considered separately.

Parameter values were chosen based on site data, literature and experimentation. Line impedances were chosen to represent a mini-grid of radial topology, with a step-up transformer near the powerhouse, three branches of transmission lines each 1-2 km in length, and consumer loads a short distance from a step-down transformer at the end of each branch. The high voltage distribution lines in the case study site are at 11 kV, while the low voltage mini-grid components are at 400 V. In the models, a BESS is located in or near the powerhouse for the centralised storage topology, whereas two or three BESS are located on the consumer side of the step-down transformers on each branch in the distributed storage topology.

Simulations were performed with constant load steps over ten seconds, loosely representing the morning or evening electricity demand of an MHP community with a large number of HHs cooking with electricity, thus elevating the load over the generated power in peak times. The simplified components and reduced timescales mean that system dynamics are not realistic and are instead specified to depict system behaviour clearly. The following sub-sections explain each model component.

A4.2.1 Synchronous Generator

The SG is represented by the Simplified Synchronous Machine (SSM) block with nominal power, frequency and voltage specified as 100 kVA, 50 Hz and 400 V respectively [233], [234]. The SG behaves according to the swing equation, well known in literature on power system stability and dynamics [235]–[237] (Equation (8.3).

$$J\frac{d\omega}{dt} = T_0 - T_{el} - D(\omega - \omega_0) \tag{8.3}$$

where J is the rotor inertia, T_0 the mechanical torque, T_{el} the electromagnetic torque, D a coefficient representing the damping torque of the damper windings, ω the rotational speed of the SG and ω_0 its nominal rotational speed. An increase in electricity demand equates to an increase in electrical torque demand, causing a reduction in rotational speed of the SG, and therefore a drop in frequency. The inertia and damping factor of the SSM affect its response settling time and frequency droop, respectively. These parameters were specified as 15 kg m^2 and 10 respectively, so that the system behaviour is clear, with settling times short enough that steady state is reached after each load step, and frequency droop set to show deviations from rated power, with values comparable to those in [144]. Constant mechanical input power of 100 kW was assumed for simplicity. Low values for SG internal resistance and inductance were specified at 0.01 Ω and 1 mH respectively to ensure approximately nominal output power. The AVR was represented by a DC1A Excitation System block which outputs the field voltage to be applied to the SG [234], [238]. It was assumed that the SG does not overload thermally or mechanically when outputting power above the nominal 100 kW.

A4.2.2 Battery energy storage systems

The BESS was modelled as an inverter, which was approximated as three controlled voltage sources driven by voltage signals derived from reverse droop control and current control loops, an approximation also adopted in [228], [239]. It was assumed a battery can demand/provide power through the inverter model according to the reverse droop control characteristics specified. Therefore, without the battery controller, battery power flow dynamics, inverter switching dynamics, or output filter, the model lacks dynamic accuracy and is instead intended to validate the control system concept and as a tool for exploring the resulting system behaviour.

An outer reverse droop control loop generates reference currents which are realised by an inner current control loop. The reverse droop control system is governed by Equations (8.4) and (8.5) with the measured frequency and voltage used to calculate active and reactive power references, which are tracked, converted to voltage references, and input to the voltage sources, as outlined in [192], [232]. Figure 8.3 presents the reverse droop curves used to control the inverters, according to the equations.

$$P = P_0 + k_p(f - f_0) \tag{8.4}$$

$$Q = Q_0 + k_q(V - V_0) \tag{8.5}$$

where P and Q are the references calculated according to the measured f and V, and f_0, P_0, V_0 and Q_0 are the nominal or setpoint values of frequency, active power, line voltage and reactive power. The reverse droop coefficients, k_p and k_q, which have negative values, are the gradients of the curves in Figure 8.3.

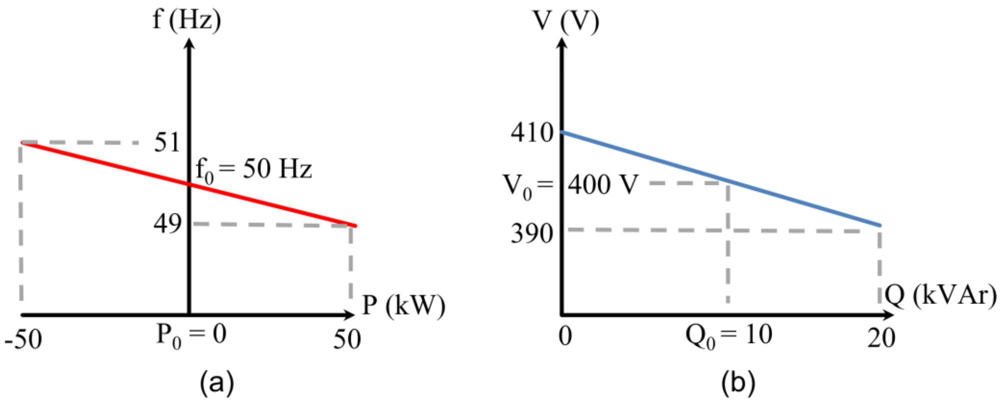

Figure 8.3: Reverse droop curves. (a) Active power vs. frequency, Equation . (b) Reactive power vs. output voltage, Equation .

The frequency-active power, f-P, droop parameters were specified so that, when the frequency drops to 49.8 Hz, the BESS inverter provides 10 kW, shown as positive P in the figure, whereas when the frequency increases to 50.2 Hz, it demands 10 kW, shown as negative power. Therefore, the BESS neither demands nor provides any active power at the nominal frequency f_0, 50 Hz, so P_0 is zero, while its power demand or provision increases as the frequency deviates from nominal. The voltage-reactive power, V-Q droop coefficient, k_q, was chosen as 1000, for simplicity, so that for every 10 V below the nominal line voltage V_0, 400 V, the BESS outputs an extra 10 kVAr, in addition to the nominal Q_0, 10 kVAr, provided at V_0. The droop equations could be adjusted to enable different responses for charging and discharging, or based on the SoC or capacity of the battery [217], [227].

Figure 8.4 depicts the overall control system, which is based on [192], [232]. Firstly, a phase locked loop (PLL) is employed to obtain an estimate of the mini-grid network angle and frequency at the point of inverter connection [234], [240]. The direct-quadrature-zero (*dq0*) transformation, combining the Clark and Park transformations, is used to obtain a two-axis representation of the voltage and current, with the zero component neglected assuming a balanced, symmetrical system [234], [241]. The q-axis component of the voltage is forced to zero by the PLL to obtain the network angle.

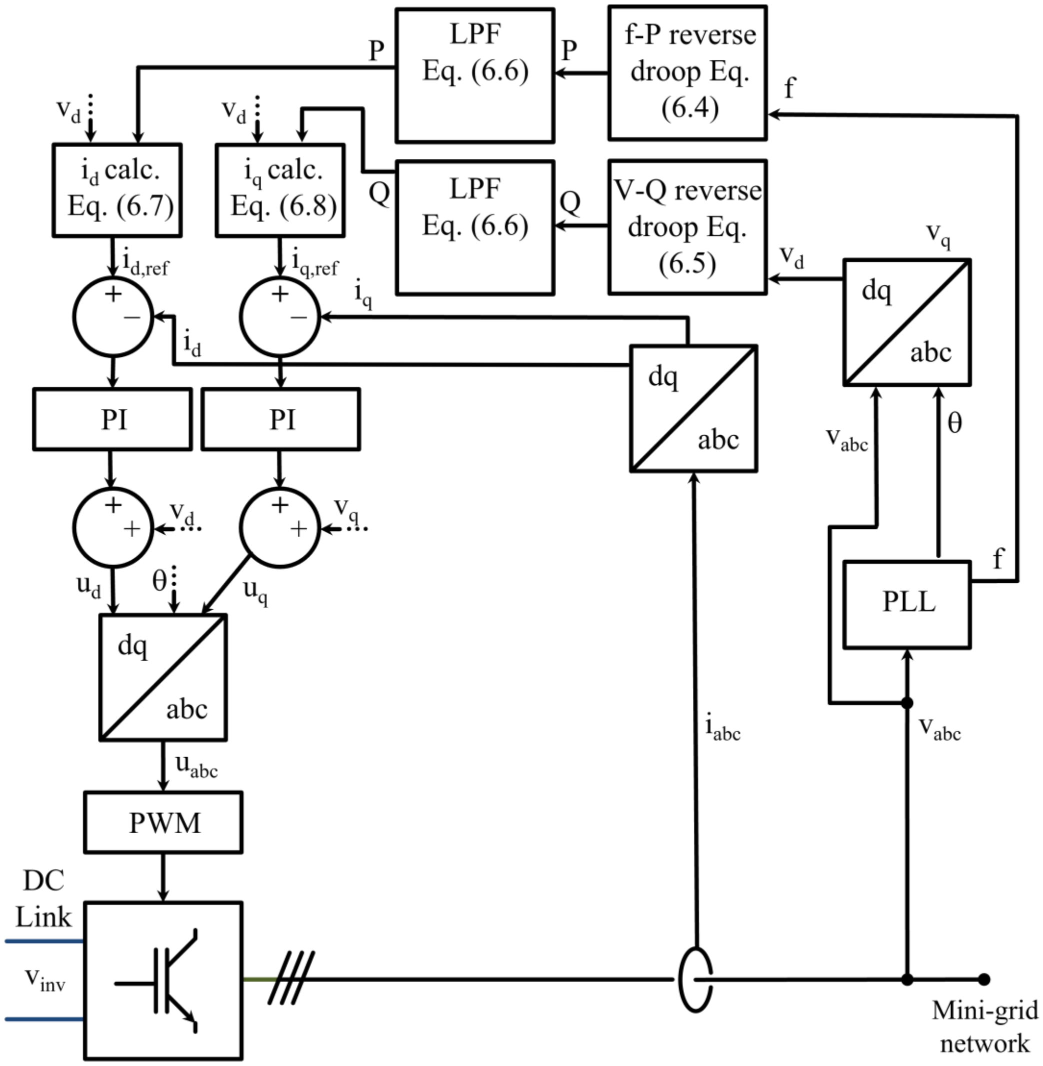

Figure 8.4: Proposed reverse droop control system.

The measured frequency and voltage are used in Equations (8.4) and (8.5) to calculate P and Q references which are then sent to low-pass filters (LPF) to stabilise the control loop and avoid noise and oscillations, and which emulate the inertial behaviour of a synchronous machine [143], [237]. As the control loops are implemented in parallel, the LPFs are required to slow down the reverse droop control loop which provides references to the inner current control loop [228]. Their parameters were chosen to ensure clarity of the system behaviour after load changes, implemented with the transfer function block according to Equation (8.6) [234], [242]:

$$H(s) = \frac{1}{0.1s + 1} \tag{8.6}$$

The PLL ensured that v_q was forced to zero, such that v_d becomes equal to the amplitude of the network voltage. Therefore, the P and Q references are converted to current references by division by v_d a constant factor of 3/2, in accordance with Equations (8.7) and (8.8) [192], [243]:

$$i_{d,ref} = \frac{P}{\frac{3}{2} v_d} \tag{8.7}$$

$$i_{q,ref} = \frac{Q}{\frac{3}{2} v_q} \tag{8.8}$$

The current references are then compared to the measured *dq* current components, fed through PI controllers, and finally used to reconstruct the voltage references for input to the voltage sources, by addition of the measured *dq* voltages and *dq* to abc transformation, leading to u_{abc}. The PI controllers ensure precise tracking of current references, with parameters chosen so that settling times and error are satisfactory for depicting the desired behaviour [234], [244]. In real systems pulse width modulation (PWM) would be employed on the control system output voltage signal to generate gate signals for the switching of the inverter, after which an LC filter would smooth the output waveforms [224]. In the model, the three phase voltage reference, u_{abc}, is instead sent to three controlled voltage sources voltage sources which emulate it.

A4.2.3 Electronic load controller

The ELC, rather than including detailed modelling of switches and other electronic components, was approximated as three controlled current sources, sinking an amount of power determined by frequency control including PI control. The frequency error relative to a setpoint, 50 Hz, is fed to a PI controller, then to an LPF, and finally multiplied by the rated generation phase currents for input to the current sources, to maintain the system at the frequency setpoint by dumping excess generation power. As for the BESS, the LPF represents the inertia of the ELC. Proportional and integral gains were chosen as 10 and 100 respectively to ensure adequate functionality while maintaining stability.

A4.2.4 Transmission lines

Transmission lines were modelled using Three Phase Series RLC Branch blocks [234], [245]. Small resistances following the SG and ELC represent a small distance to the centralised BESS and step-up transformer. RLC branches with resistance and inductance specified according to site data represent the transformers and high voltage lines of 1-2 km. Finally, small resistances represent the low voltage lines at the consumer end of the branches, following the distributed BESS. Transformers blocks were omitted to maintain simplicity and modelled by reduced line resistances to represent the high voltage lines and slightly increased line inductances.

A4.2.5 Electrical loads

The loads were approximated using the Three Phase Series RLC Load blocks, at 400 V and 50 Hz, which assume balanced loads [234], [246]. Active and reactive (inductive) power is specified in simple load steps, and with variation across the branches. The total nominal active power load varied from 60 kW to 105 kW to 140 kW. Loads were chosen in order to test BESS response to active power demand below and above rated generated power, with reactive power demand assumed to be inductive and varying with active power at an assumed constant power factor of 0.9, chosen according to site data. The active and reactive powers absorbed by the load are proportional to the square of the applied voltage, with a reduction in voltage causing a decrease in the demand.

A4.3 Results

MHP electrical system data analysis in Sections 3.5.5 and 4.4.3 showed that, even without the total load exceeding the generated power in Salyan, there were severe brownouts during peak times, partly due to faults with the ELC and AVR but also in part due to high loads. If an MHP were to be overloaded without grid reinforcement by BESS, the circuit protection would trip and system would collapse [146].

A4.3.1 Central BESS

A model with a centralised BESS was created, as illustrated in Figure 8.2. Figure 8.5 shows the mini-grid frequency, root-mean-square (RMS) line-to-line voltage at the SG, and active power flows of the SG, ELC, BESS and total load demand. It should be noted that, due to the voltage at the loads dropping increasingly as the loads increase, the total load demand varies from approximately 60 kW to 90 kW to 120 kW, rather than the nominal 60 kW to 105 kW to 140 kW**.** During 'hours' 4 and 5, when the load is above 100 kW, the SG provides just over 100 kW, due to its own frequency droop represented by its damping factor, while the BESS provides the deficient power to meet the load, around 15 kW as the frequency has dropped to around 49.7 Hz, shown as a negative power level in Figure 8.5. As clear from the plot, the BESS discharges more power than the deficient power due to losses in the transmission lines. The SG line-to-line voltage is maintained at nominal 400 V by the AVR, despite deviations after each load step.

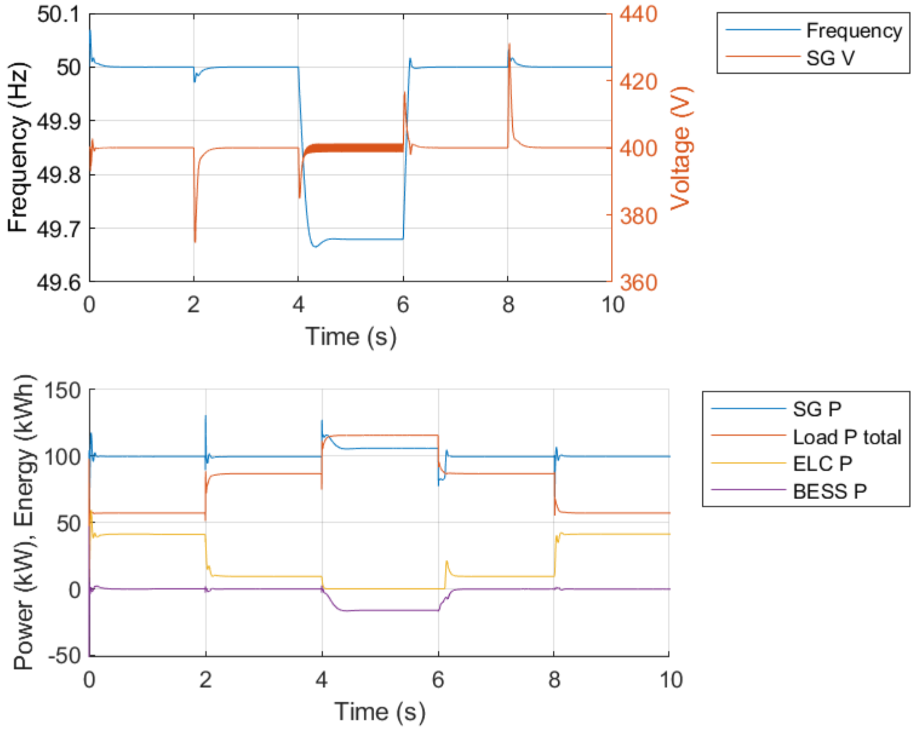

Figure 8.5: Frequency and power plots for model with one central BESS.

Therefore, during the discharge period, when the load exceeds 100 kW, the system works as intended. However, during hours 1 and 2 the ELC controls the system frequency to 50 Hz, as is the case in MHPs, which then prevents the BESS from demanding power and charging, as its f-P droop curve goes through zero at 50 Hz. Therefore, if the models included battery energy and SoC, and unless the BESS were fully charged to begin with, it would be unable to provide power during the discharge phase. An alteration to the BESS f-P droop characteristic was required to allow the BESS to charge so that it would have sufficient energy stored to discharge in hours 3 and 4. However, it was crucial that the ELC would maintain the system at a stable frequency. The reactive power demand is met by the SG and BESS, with the BESS providing a constant reactive power of 10 kVAr, according to its V-Q droop, because its co-location with the SG leads to its voltage remaining at nominal due to the control of the AVR. The V-Q droop could be altered so that the BESS contributes zero or any other level of reactive power.

One option to enable BESS charging is to shift the BESS f-P droop curve in Figure 8.3 down so that 49.8 Hz is the nominal frequency and the BESS demands 10 kW at 50 Hz. Then, as shown in Figure 8.6, the BESS charges during hours 1 and 2 as the ELC maintains the frequency at 50 Hz. In hour 2, the ELC stops sinking power but there is just enough spare generated power for the BESS to charge at the nominal 10 kW, and therefore the frequency remains at 50 Hz. However, during discharge, as shown in Figure 8.6, the SG provides more power than in Figure 8.5, while the BESS provides less, as its shifted fP droop leads to a lower discharge power for a given frequency. In fact, if the load were increased in hour 2 to just over 100 kW, at which point the frequency would fall just below 50 Hz, the BESS would continue to demand power, rather than switching to discharge mode to meet the excess load, until the load had increased to a higher level and the frequency had fallen beneath 49.8 Hz. Therefore, in this arrangement, the BESS provides less power than the previous and even works against the system for some loads. A further alteration was required.

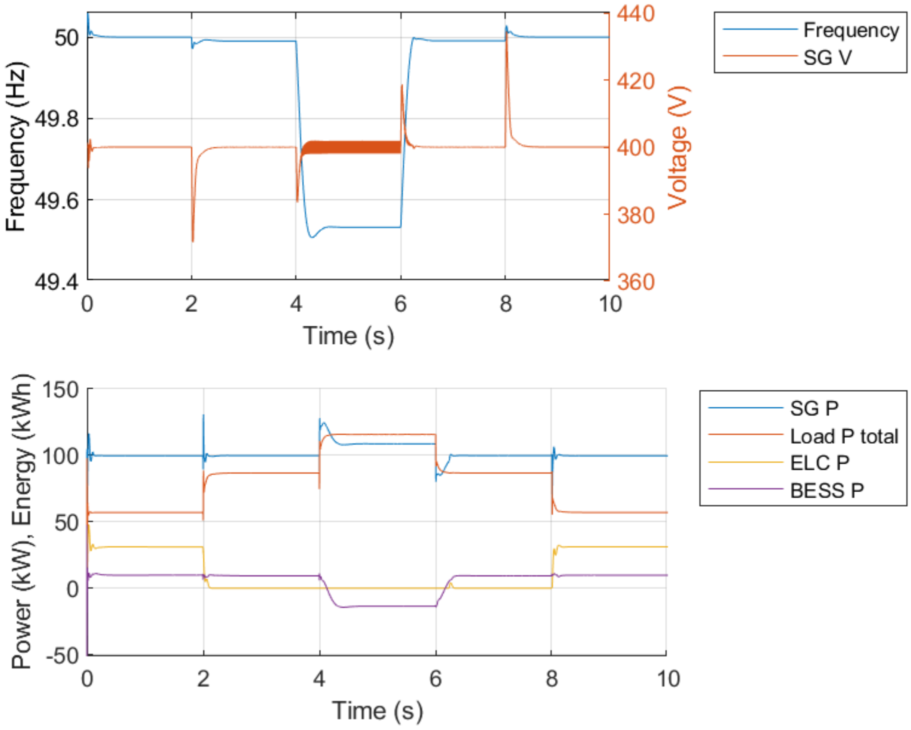

Figure 8.6: Frequency and power plots for model with one central BESS and the f-P droop curve shifted down to change the nominal frequency to 49.8 Hz.

Figure 8.7 presents a simulation of the system with the ELC setpoint adjusted to 50.2 Hz, rather than 50 Hz, and the BESS f-P droop curve unchanged from Figure 8.3. During the charging phase, the ELC dumps power in an effort to maintain the frequency at 50.2 Hz, the frequency at which the BESS demands 10 kW. In the discharging phase, the ELC is no longer in control so the BESS discharges to meet the load alongside the SG, providing the same power as in Figure 8.5, thus the ELC setpoint adjustment enables full BESS charging and discharging.

When the load increases in the second hour, the frequency decreases from 50.2 Hz because the spare power has reduced beneath 10 kW, so the ELC stops dumping power and is no longer in control, as seen in Figure 8.7. A new frequency is reached, below 50.2 Hz, enabling the BESS to charge with the remaining spare power. This happens because the ELC is holding the frequency at 50.2 Hz as long as there is sufficient spare power, so the SG produces slightly less than 100 kW, around 96 kW, according to its frequency droop. This could be seen as a disadvantage of this arrangement. However, as long as there is more than around 10 kW spare power in the system, the ELC holds the frequency at 50.2 Hz, and so the BESS charges with the desired 10 kW. Only when the ELC can no longer maintain the frequency at 50.2 Hz, because of the increased load, does the BESS charging power reduce below 10 kW.

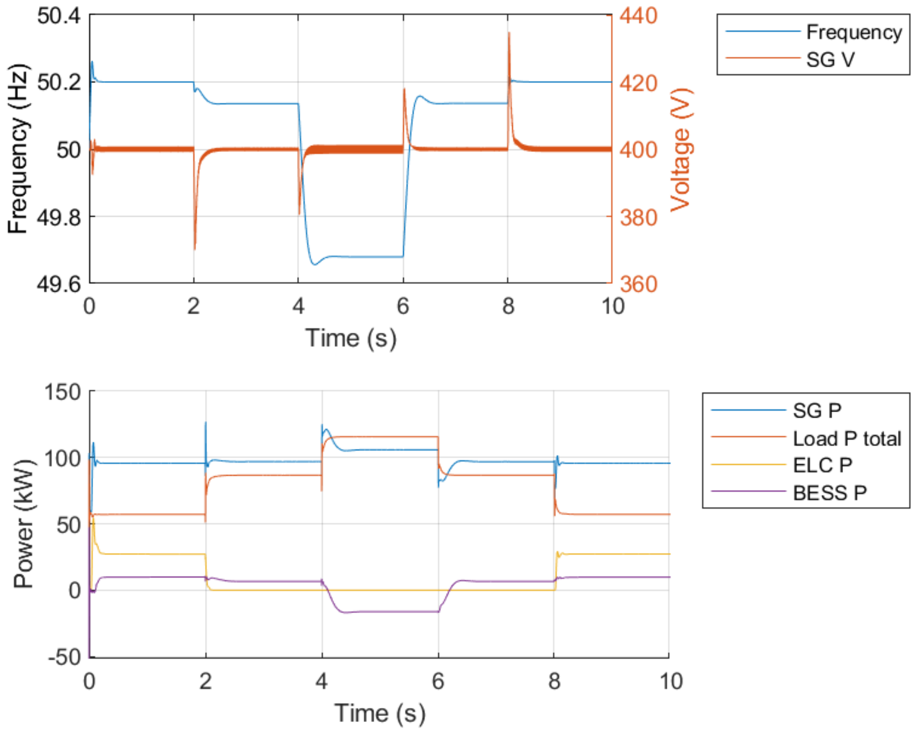

Figure 8.7: Frequency and power plots for model with one central BESS and the ELC setpoint adjusted to 50.2 Hz.

It is often the case that MHPs are run beneath nominal power to reduce the risk of wear and tear [136]. The SG frequency droop is chosen for illustration here. If implementing this system, the ELC setpoint could be chosen with knowledge of the SG droop, so that the SG provides a desired level of power during the charging phase, at a desired frequency which enables good separation of the ELC and BESS while being well within the upper limit for consumer loads. Secondary control, where the BESS demands or provides extra power in addition to its f-P droop according to an added frequency control term, to control the frequency to a setpoint, could be explored to enable the SG to produce nominal power. However, there would be competition between the BESS secondary control and the ELC.

The operation of the ELC 50.2 Hz setpoint system, whose behaviour is presented in Figure 8.7, was investigated in detail to understand the relationships between the SG, ELC and reverse droop-controlled BESS. At the first load step, on the hour 2 mark, the increased load causes a reduction in frequency, as shown in Figure 8.7. The ELC stops dumping power, as it cannot control the system once the frequency falls below 50.2 Hz, its frequency setpoint. The SG increases its output power slightly, as the frequency falls. The BESS measures the falling frequency and adjusts its active power reference according to its f-P droop, reducing the demanded charge power, which then reduces the effective load demand on the SG. At this point, the frequency stops falling, before an equilibrium frequency is reached, where the SG and BESS provide and demand a certain power level, according to their droop characteristics.

When the load is increased at the hour 4 mark, a similar process occurs, except that the frequency drops beneath 50 Hz as the load increases beyond 100 kW. This time, the SG increases its output power significantly, responding immediately to the increased load. The BESS sees the falling frequency and, as it falls, switches to discharging mode, and starts to provide more and more power. The BESS power provision acts to support the SG and restore the frequency slightly, enabling the SG to reduce its output power, until once again an equilibrium frequency is reached, and the BESS provides most of the excess load power. The resulting system frequency, around 49.7 Hz, is well within the MHP limits of 50 Hz ± 5%, the lower limit of which is 47.5 Hz. Once again, the SG droop was chosen for illustration and could, in reality, lead to smaller deviations from nominal power output. Furthermore, the BESS f-P droop coefficient could be adjusted so that it provides more power for a given frequency deviation. Secondary control could be used to ensure that the BESS takes on the entirety of the excess load, and without the complication of interaction with the ELC present in the charging phase, by introducing a frequency control loop to increase the BESS discharge power until the frequency is restored to 50 Hz.

The simulation highlights the nature of reverse droop control and its suitability for supporting the SG in an MHP mini-grid. While the SG responds immediately to load changes due instant changes in its electrical torque demand, speed and therefore frequency, the BESS responds gradually to frequency changes, after the SG, restoring the frequency to a desirable level by providing most of the excess power requirement to the load. Therefore, rather than measuring and sharing the load power with the SG, as in conventional droop control, the BESS can be tuned to allow the SG to remain at or close to its nominal frequency and power output. The inertia of the SG dictates its speed of response and settling time, while the LPF of the BESS has a similar effect, although the BESS will always respond after the SG because it responds to frequency changes.

At the hour 6 mark, when the load reduces to its previous level, the SG output power drops due to the reduced demand power, while the BESS is still discharging to the load, causing the frequency to increase suddenly and quickly, due to the excess power in the system. The BESS responds to the increasing frequency by reducing its power output, allowing the SG to increase its power output back towards nominal in order to supply the load. Eventually, the BESS switches to charging mode and starts to demand power, halting the rise in frequency, and an equilibrium frequency just below 50.2 Hz is reached, with the system returning to the state of hour 4. This behaviour illustrates the response of the BESS to load changes, measuring the frequency and changing its active power output or demand accordingly, and responding after the SG, whose control leads to immediate responses. In reality, such large and sudden load steps would not occur. Nonetheless, as mentioned, inertias and droop characteristics could be tuned to ensure desired response times and dynamics.

Figure 8.8 shows that the AVR ensures that the SG and BESS remain at nominal voltage, or, in the case of the BESS, just below, as a small line resistance represents a short distance to the BESS from the powerhouse. Figure 8.9 shows that, therefore, the reactive power demand is met by the SG mostly, with a constant contribution of 10 kVAr from the BESS, its nominal reactive power output at nominal voltage, according to its V-Q droop, as presented in Figure 8.3. Figure 8.8 shows that the voltages at each load vary according to demanded active and reactive power sent through each branch, dropping to around 371 V, 355 V and 339 V respectively, beneath the minimum voltage limit of 5% below nominal, 380 V, illustrating the severe voltage sags that would result from high loads that in total exceed the generated power with the current infrastructure of MHP mini-grids.

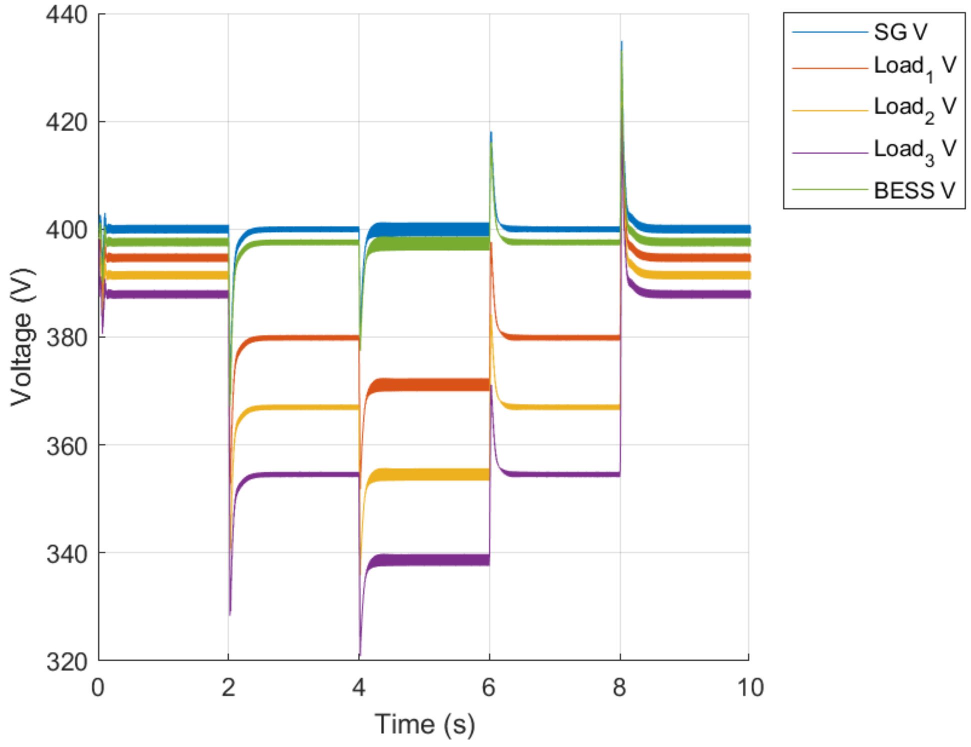

Figure 8.8: Voltages for model with one central BESS.

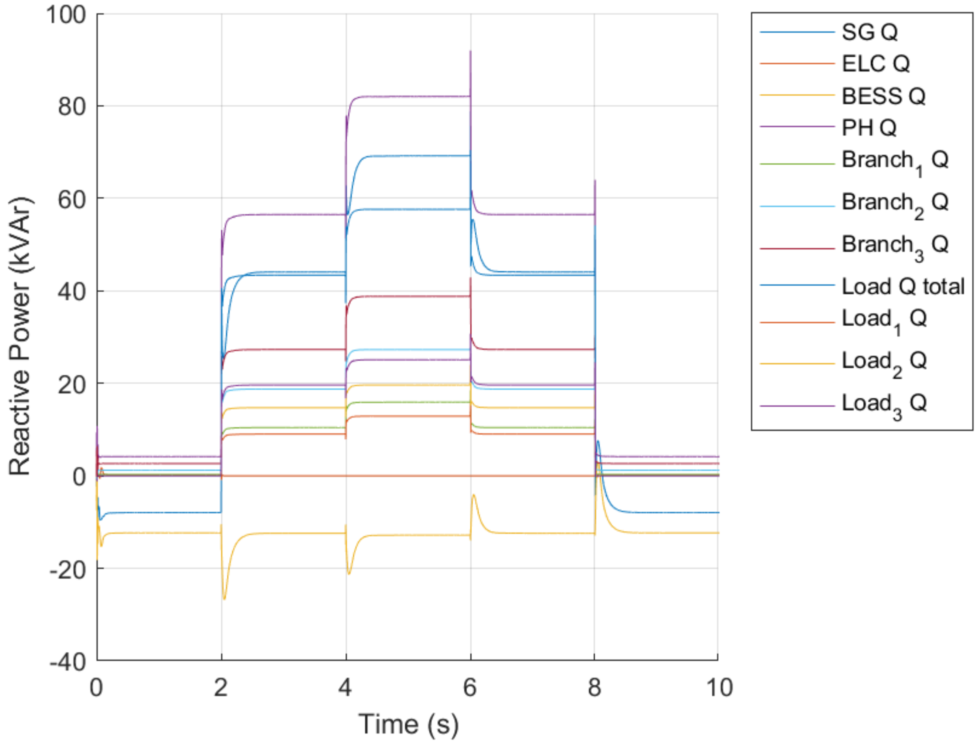

Figure 8.9: Reactive power flows for model with one central BESS, including total reactive power at the powerhouse (PH).

Although the control scheme has been shown to enable BESS integration, charging and provision of power for high loads, the co-location of the BESS with the SG in the powerhouse means that the active power in the initial transmission lines has now increased above 100 kW during the discharge phase. The SG and BESS work together to cover the total load, which reaches almost 120 kW, leading to the powerhouse active power flow reaching over 120 kW in hours 4 and 5, as shown in Figure 8.10. A system featuring distributed BESS would be unlikely to have the same problem.

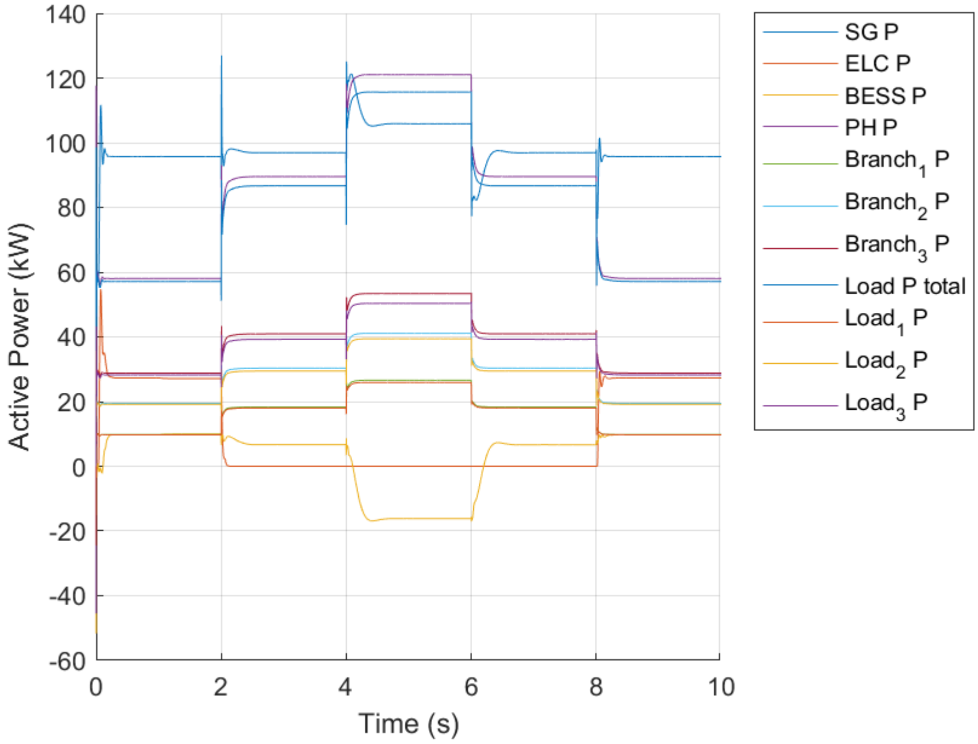

Figure 8.10: Active power flows for model with one central BESS, including total active power at the powerhouse (PH).

A4.3.2 Distributed BESS

An alternative topology with distributed BESS was explored. As the mini-grid frequency is universal in the system, the reverse droop control scheme can be applied to distributed BESS, allowing their placement at strategic locations in the mini-grid without the requirement for communication between them. A model was created with three BESS located on the consumer end of each branch, downstream of where each step-down transformer would be. Figure 8.11 presents the behaviour of the system in this arrangement. Firstly, it is noted that, as the voltage at the loads is higher than previously due to each BESS supporting the system through reactive power generation, as will be explained, the total load demand varies from approximately 60 kW to 100 kW to 130 kW, rather than the nominal 60 kW to 105 kW to 140 kW, increased from the centralised BESS model. However, the control scheme means that the systems behave similarly.

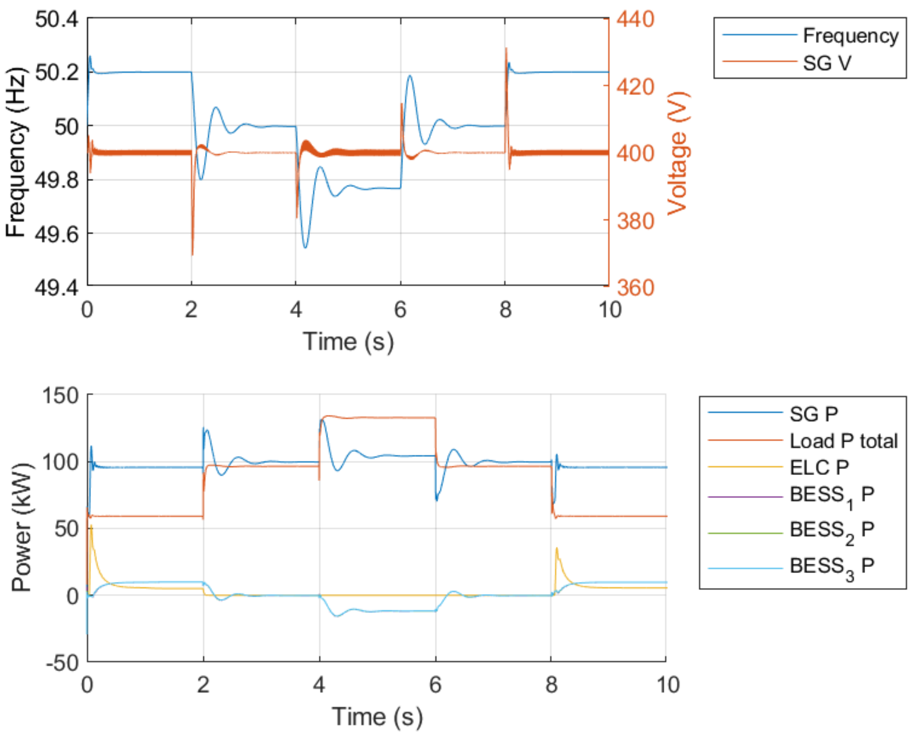

Figure 8.11: Frequency and power plots for model with three distributed BESS, with the power profiles of the BESS overlapping due to identical responses.

As shown in Figure 8.11, in the first two hours, the ELC maintains the frequency at 50.2 Hz, as before, enabling each BESS to charge at 10 kW. The BESS profiles in Figure 8.11 are superimposed as the common frequency produces identical active power responses. In this case, therefore, there is less spare power than when only one BESS was charging, so the ELC dumps less power. In hours 2-4, the system settles on a frequency of approximately 50 Hz, due to the load demand of approximately 100 kW, so neither do the BESS charge nor the ELC dump power. In the discharge phase, hours 4 and 5, the frequency drops to just under 49.8 Hz, and each BESS provides an equal share of the excess load. Therefore, the lowest frequency is higher than that of the centralised BESS system, even though the total load demand is higher, because the three BESS can share the load deficit, and have the same reverse droop characteristics as previously.

At the hour 8 mark, the immediacy of ELC response compared to that of the BESS causes a spike in ELC active power demand, before each BESS starts to respond to the increased frequency by demanding 10 kW, thus reducing the spare power for the ELC to dump. Compared with Figure 8.7, there is a larger frequency change at hour 8, which causes the

ELC response overshoot. Furthermore, the inertial terms of the BESS LPFs in the system of Figure 8.11 were doubled to produce a more stable response, slightly slowing down the BESS response to changes. The system behaves as predicted and desired, with each BESS charging and discharging to support the mini-grid. Once again, alterations to droop characteristics and inertias could be made to achieve desired responses.

As mentioned, in this distributed BESS topology, the load voltages are higher due to the V-Q droop control of the BESS. As the BESS are located towards the consumer loads, they experience the same voltage drops as the loads, as the load active and reactive power demands increase. In a similar way to the BESS responding to frequency changes by adjusting its active power demand or output, each BESS measures the local voltage and adjusts its reactive power output accordingly and in a restorative fashion for the voltage, in such a way that equilibrium voltage levels are reached. Therefore, the lowest voltage levels at the loads were increased from the centralised model to 389, 379 and 368, as shown in Figure 8.12, due to increasing BESS reactive power outputs, shown in Figure 8.13. In this topology, therefore, the BESS are able to increase the power quality of the network, due to their location, whereas a centralised BESS cannot contribute to power quality as its voltage is maintained at the nominal level.

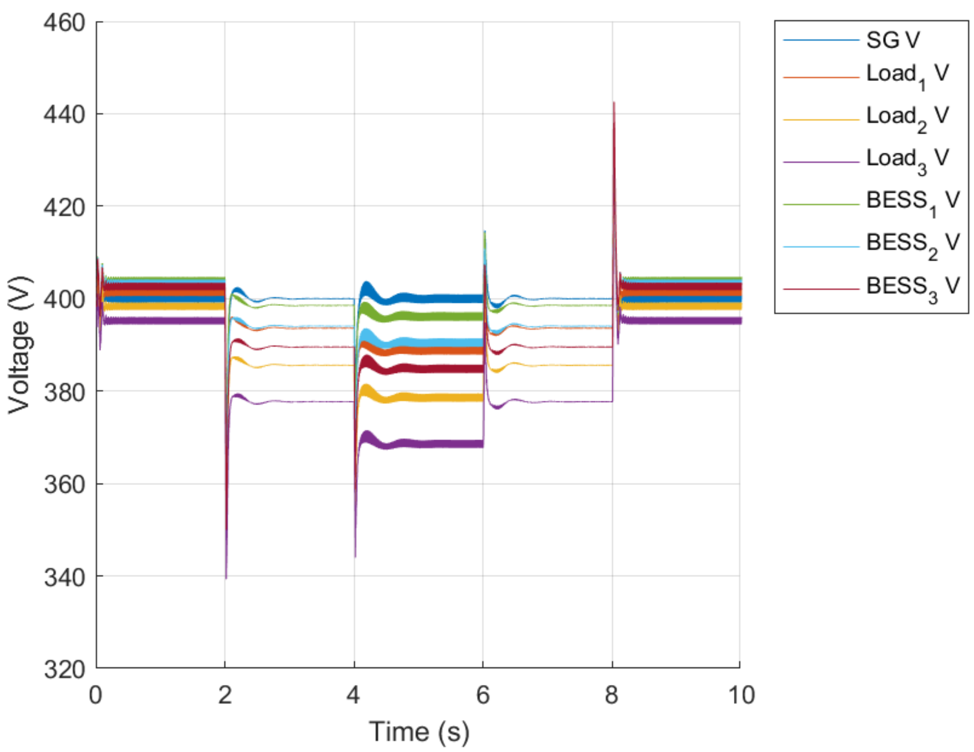

Figure 8.12: Voltages for model with three distributed BESS.

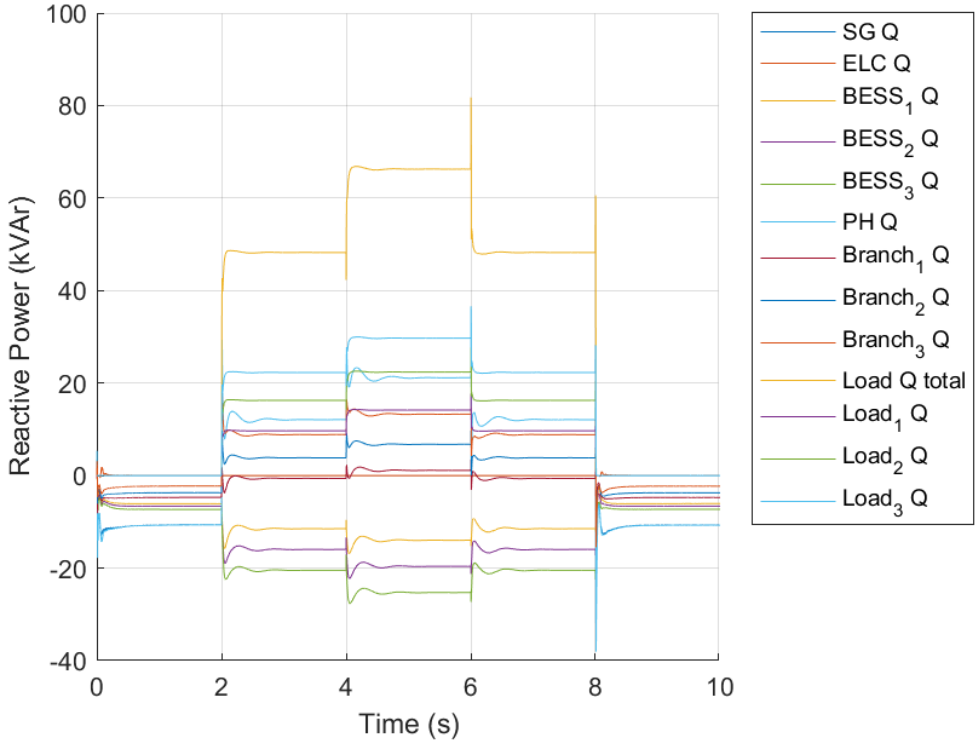

Figure 8.13: Reactive power flows for model with three distributed BESS, including total reactive power at the powerhouse (PH).

As shown in Figure 8.13, the SG and three BESS cover the load reactive power demand together. BESS 3, in whose branch the load active and reactive power demand is highest, therefore experiences the greatest voltage drop and so provides the highest reactive power contribution. The SG sends reactive power to each load proportionally and according to the reactive power demand not met by the relevant BESS. Each BESS provides a different amount of reactive power to their respective loads due to the aforementioned voltage differences.

In MHP communities, HHs and other end uses are dispersed across the landscape so transmission lines are of varying lengths, and loads are connected at the consumer end to numerous branches that split off from the main lines. Therefore, the impedances of lines and branches vary and so voltages vary across the mini-grid, both spatially and temporally according to the load demand, meaning that BESS would provide different reactive power contributions, and V-Q droop characteristics would require careful design to best improve power quality.

As before, the V-Q droop characteristics of the BESS could be adjusted as desired, removing or changing the nominal reactive power contribution as well as the droop coefficient. In this case, the BESS in branch 1 maintains the lowest voltage above the minimum limit of 380 V, whereas the BESS in branch 2 is very close to doing so for its load, and the V-Q droop coefficient of BESS 3 would need to be significantly increased to generate sufficient reactive power for the voltage at load 3 to be restored above this limit. As shown in Figure 8.12, the initial voltage at each BESS is actually above the nominal 400 V, due to the nominal reactive power contribution of the V-Q droop characteristic elevating to resulting voltage, as the initial total load P is low and total load Q is zero. These voltages are well below the upper voltage limit, which is around 420 V, although the load situation is unrealistic as in reality there would always be a reactive power demand, only omitted here to understand the system behaviour without it and for initial stability. As the voltage drops from each BESS to each load anyway, it may make sense, if implementing this system, to prop up the voltage at the BESS by outputting a large nominal reactive power contribution. However, the disadvantage is injecting additional current into the system by outputting reactive power, increasing the current carrying requirements of the mini-grid infrastructure.

Figure 8.14 also shows that with the distributed BESS topology the active power in the initial lines, from the powerhouse, is only equal to the SG power, as the BESS are located downstream and only output power to the loads at the end of their branches. Therefore, during the discharge phase, the power in the powerhouse, step-up transformer and transmission lines is reduced, while the power in the consumer lines remains equal to the load power in each branch, neglecting losses. In the charging phase, the power in the consumer lines includes both the branch load power and BESS charging power. As each BESS demands and provides the same power due to the common frequency, the SG sends power to each branch in proportion to the load on the branch. For example, in hours 4-6, the power sent to branch 3 is higher than that to the other branches, as there is a higher load to be served and with the same contribution from the BESS. Overall, the simulations provided insight into the operation of a reverse droop control system for centralised and distributed BESS.

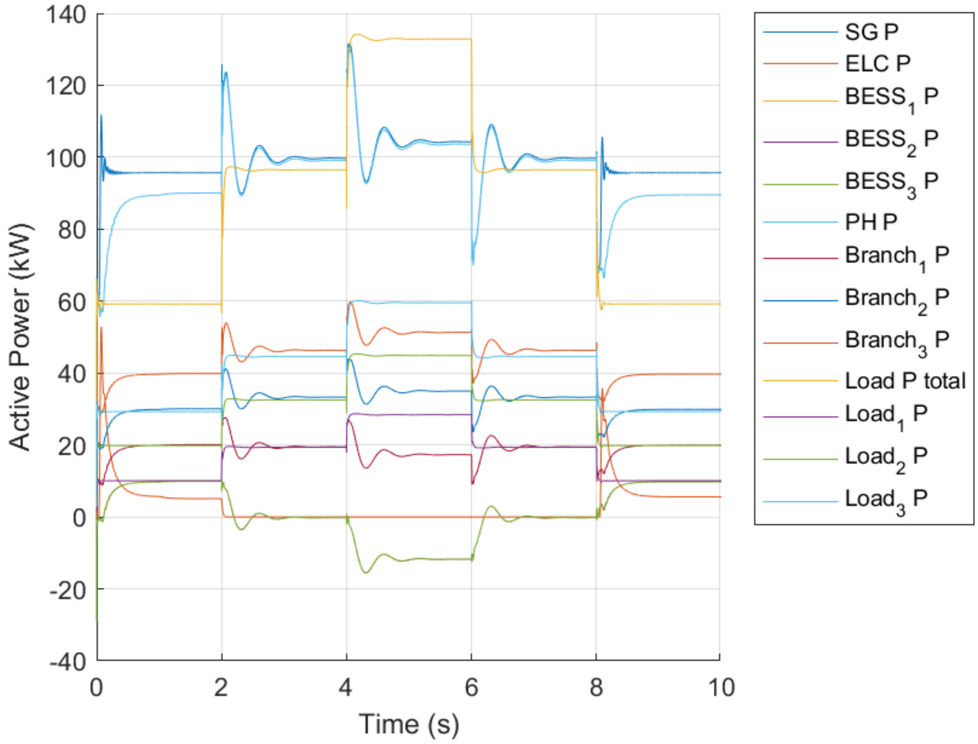

Figure 8.14: Active power flows for model with three distributed BESS, including total active power at the powerhouse (PH).

A4.4 Discussion

This chapter presented and explored a Simulink model of a MHP mini-grid with BESS integrated, in centralised and distributed topologies, using a reverse droop control system to enable the BESS to demand and provide active and reactive power as required by the network. Conventional droop control, which would enable load sharing between the generator and BESS, is less suitable for the MHP mini-grid context, for which it is desirable that the generator runs at a constant speed, generating constant power. However, with reverse droop control, an important question is how to ensure that the BESS provide most of the excess load, i.e. the demand above the nominal generated power, during the discharging phase. This can be done by adjusting the BESS droop characteristics, according to the droop characteristic of the generator, so that the BESS takes on most of the load step.

Generally, if the control system were implemented, the droop characteristics of the BESS inverters could be designed so that the network frequency and voltage are maintained within their acceptable limits of ± 5% deviation from nominal, which were identified in Section 2.4. For f-P droop, for both centralised and distributed topologies, this would involve ensuring that the load requirements of the BESS could be met at a reasonable frequency. For a centralised BESS, this would simply be the maximum deficient load, whereas, more detailed understanding of the load distribution through the network and downstream of the distributed BESS would be required for the latter topology. Secondary control could be used in the f-P droop specifications to restore the frequency to nominal during the discharging phase if it was not possible to keep the frequency within its desired limits by selection of droop parameters alone.

For V-Q droop, centralised BESS are unable to contribute to power quality in the mini-grid, as the powerhouse voltage is maintained at nominal by the AVR, instead only providing a nominal reactive power output. Distributed BESS could contribute to power quality, with their V-Q droop characteristics designed according to the line impedances, local voltage and load, to prop up the voltage at the transformer and further downstream, at the consumer loads. However, this would require detailed modelling of the entire mini-grid and load distribution. Modelling based on real data on network layout, including line lengths, impedances, transformer locations, and using realistic load profiles, could be used to understand how much distributed BESS could contribute to power quality without inputting excessive additional current to the grid, and what infrastructure upgrades might be required, of cables and transformers, to increase their load capacities.

For the charging phase, for which the droop characteristic could be different compared to the discharging phase, the control could be designed so that the BESS are charged at a healthy rate, during off-peaks periods, making use of the spare energy but not charging unnecessarily quickly, which affects battery cycle life. The BESS should be able to recharge fully during each off-peak period, if they are sized to meet the deficient load of each mealtime. However, if the afternoon off-peak demand increases as more appliances and end uses are connected to the mini-grid, it may be necessary to size the BESS to cover both mealtime deficient loads, recharging fully overnight instead. The droop characteristics could be adjusted to enable this, with the automatic nature of droop control an advantage, as any spare power in the afternoon period could still be utilised. Generally, several BESS with different droop parameters, depending on their capacity and expected loads, could be specified.

The modelling explored different BESS configurations, focussing firstly on integrating a centralised BESS into the mini-grid and then investigating distributed BESS at strategic locations in the network. In addition to the advantage of enabling improved power quality through V-Q droop, distributed BESS reduce the load capability requirements of upstream mini-grid infrastructure, such as lines and transformers, as compared to the centralised topology, for which the maximum total load must be supported by the initial lines from the powerhouse. Therefore, depending on the level of electric cooking penetration, further infrastructure upgrades would be required for centralised BESS than distributed, which would also be more expensive to repeat with load evolution over time. However, it would be easier for MHP operators to monitor and maintain a centralised BESS, located at the powerhouse, while such an arrangement also requires fewer components than a distributed BESS topology.

Battery-supported HH electric cooking systems would reduce mini-grid infrastructure upgrade requirements further, although evidently the number of components required to cater for similar levels of electric cooking penetration would vastly increase, and the burden of system monitoring and maintenance would mostly likely fall to HH members, who would require training. Furthermore, as MHPs are often weak grids, power supply instability would reduce the reliability of a HH BESS.

The introduction of HH BESS to a community may involve HHs purchasing their systems gradually, which would reduce the feasibility of integrating them into an intelligent control system. Community agreements on manual off-peak charging windows could be trialled, or timers used to schedule charging, or automated charging based on SoC employed, each of which would lead to most BESS charging simultaneously during off-peak periods.

Alternatively, reverse droop control could be applied to HH BESS in the same way as for central and distributed BESS. However, if based on frequency, active power may be directed back through the network for HHs not cooking during peak times, potentially overloading the surrounding lines, although discharge power limits could mitigate this. Reverse droop control based on voltage could be applicable but voltage level variation between HHs would complicate such an arrangement. Reverse droop control could be confined to the charging phase so that, during off-peak periods, HH BESS are charged according to their droop characteristics, working alongside the ELC at a desired frequency setpoint. The switch-on of electric cookers could signal the batteries to discharge, providing the required power for cooking.

Increased intelligence, possibly requiring communication links, could be incorporated into control systems to increase the utilisation of MHP generation, using any spare power at peak times, as well as during off-peak periods. For instance, a system can be envisaged which enables some HH electric cooking to be served by MHP generation, while in others the HH BESS discharge to meet the cooking loads, with an algorithm monitoring the mini-grid status and prioritising HH BESS usage based on SoC. A similar effect could be achieved through the use of a UPS-style system with added functionality which enables a combination of both MHP generation and HH BESS power to provide for a single electric cooking load, thereby making use of all available grid power and reducing the discharge power requirements of HH BESS. However, intelligent control architecture and communication links may be required to share grid power amongst HHs optimally, set HH BESS discharge power levels, and dictate whether some cooking loads are met by battery power alone. Such a system could potentially incorporate reverse droop control principles, although this would require further research.

Considering potential faults with BESS during operation, if they occurred during peak times, it might be necessary for the plant to be shut down. Otherwise, the generator could continue to provide power to loads. For the distributed BESS topology, it may be the case that other BESS can send power back through the lines to the loads on the affected branch. There are also shutdowns in MHPs, either unintended blackouts when the system collapses, or scheduled downtime for maintenance, during which BESS would be unable to charge. Therefore, BESS could be sized to cover longer periods of operation, including potential downtime, though this would increase costs. Importantly, the BESS would be equipped with anti-islanding protection to ensure they stop demanding or providing power in the event of an outage.

The reverse droop control system is applicable to other mini-grid topologies, in addition to the modelled radial network, such as a linear topology, where load branches are connected to the main lines at increasing distances from the powerhouse. The control system would work similarly in this arrangement, providing the required active power according to universal frequency deviations, although the losses in the lines would be different, with distributed BESS in a linear topology experiencing increasingly reduced voltage levels, presenting a different prospect for V-Q droop design.

The Simulink models did not incorporate BESS parameters such as capacity, efficiency, SoC, and power limits, nor investigate how nominal charging power could be varied with SoC by adjustment of droop parameters, or how droop characteristics could be varied between the charging and discharging phases. Such factors could be incorporated into the models in Simulink or using other software. However, the understanding gained from the control system modelling can be taken forward to power flows modelling which could enable simple BESS sizing, using realistic cooking loads.

The simulations revealed rules on how the generated power is shared between the BESS, in the charging phase, and the loads, in the discharging phase, and how much each BESS contributes to the total deficient load in the distributed BESS topology. It was found that the generated power is shared between load branches, in proportion to the loads, while the BESS either provides the total deficient load, in the centralised topology, or distributed BESS share the deficient load, outputting the same power level as they experience the same frequency deviations. This type of modelling is taken forward and used in Chapter 6 to estimate BESS capacities for increased electric cooking.

The modelling in this chapter has a number of limitations. The models were simplified, with voltage and current sources used to represent the BESS plus inverters and ELC respectively, rather than incorporating realistic circuitry such as switches and filters and detailed electrical models of batteries. Therefore, without consideration of BESS and inverter efficiencies, the models slightly underestimate the battery power requirements. It was assumed that the BESS can be controlled to demand and provide power according to droop characteristics and respond within useful time windows. The dynamics of the system are illustrative rather than realistic, with simple load steps specified for clarity, and component inertias and damping factors tuned to the context rather than based on obtained data.

Site-specific data would be required to improve the applicability and adherence of the models to realistic mini-grid contexts, including modelling of network topology and component locations. Stability analysis of droop parameters was not included and would be required if implementing such a system, either using an improved Simulink based on real data, or other software [227]. However, the models validated the selected control methods and provided insight into the resulting system behaviour in different topologies.

A limitation of Simulink is its inability to cope with the computational requirements of complex models, with the reported, simplified, ten ‘second’ simulations requiring minutes to run. Therefore, a full electrical system model could be developed using alternative software, such as OpenDSS, if case study mini-grid data was available. Such data could enable specification of a detailed MHP mini-grid model, including realistic load profiles generated by the TEM outlined in Chapter 5 at specified locations in the network, the use of ECO study data on HH voltage levels, and incorporating all electrical components parameters such as line impedances, transformers, battery and ELC models, enabling realistic simulation of reverse droop-controlled BESS.

The model could be used to understand voltage drops for different topologies, for varying degrees of electric cooking penetration, to determine infrastructure upgrade requirements, and enable design of distributed BESS V-Q droop characteristics. Incorporation of realistic battery modelling would enable determination of battery capacity requirements. For HH BESS for supporting electric cooking, the model could be used to experiment with different control strategies to evaluate their effectiveness and complexity, enabling determination of suitable and realistic methods of integration into MHP mini-grids.

A4.5 Summary of work

This work investigated how reverse droop control could be used to integrate BESS into MHP mini-grids, enabling increased electric cooking by storing off-peak MHP generation for use during peak times, thereby effectively reducing peak loads, and addressing objective 5 on battery storage. The modelling provided a proof of concept for reverse droop control for BESS, based on the literature, in a new context of an MHP mini-grid, where the centralised or distributed BESS is/are required to work alongside the generator and ELC, charging with excess generated power and discharging when the total load surpasses the generated power to meet the extra load. Reverse droop was selected as the most suitable control method as it enables BESS to respond to changes in grid frequency and voltage, sinking or providing the required power, enabling the generated power to remain reasonably constant.

The simulations showed that the reverse droop control system works as intended. During the discharge phase, when the total load exceeds the generation, the system operation is straightforward, with the frequency dropping below nominal, enabling the BESS to discharge the required amount of power according to its droop curve, alongside the generated power. The key difference presented by the context is the ELC, which uses frequency control to dump excess generated power when the total load is less than the generation. The ELC frequency setpoint was increased above nominal so that, rather than dumping all of the spare power, the BESS charges with some of the spare power, according to its droop characteristic, while the ELC maintains the frequency at a desirable level. Therefore, the reverse droop control system enables full charging and discharging of the BESS.

The control system was shown to work for both centralised and distributed BESS topologies, and revealed important differences between them. Due to the distributed BESS being located at the consumer end, with the distribution transformers, the load carrying requirements of the initial lines around the powerhouse and the step-up transformer are reduced to around the nominal generated power, as, during the discharge phase, there is no centralised BESS outputting power at the powerhouse alongside the generator. The droop characteristics of the inverters can be altered according to the context and topology. The frequency-active power, f-P, droop could be designed so that the frequency is maintained within acceptable limits, with knowledge of the likely maximum load requirements of the BESS, although this would require more detailed modelling for the distributed topology, to understand the load distribution throughout the network. Secondary control could also be used to restore the frequency to nominal during the discharging phase.

In the distributed BESS topology, the voltage-reactive power, V-Q, droop enables the BESS to prop up the voltage at their locations in the network by outputting reactive power according to the local voltage drop, which is not possible in the centralised topology. Therefore, distributed BESS can improve power quality, although this is at the expense of injecting extra current into the mini-grid. Design of the V-Q droop characteristic is more complicated than the f-P droop, for distributed BESS, and would require a detailed mini-grid model as the network voltage varies according to location and with the load.

Theoretically, reverse droop control could also be applied to HH BESS for electric cooking, using frequency or voltage as the active power control variable, although this would lead to power being sent back through the network from HHs not cooking with electricity at a given time. Alternatively, reverse droop control could be applied during charging only and, when the cookers are switched on, the batteries could provide power to their cookers as required. More intelligent BESS charging/discharging control systems involving communication links could make full use of the available energy. However, if HHs purchase battery-supported electric cooking systems over time, it may be likely that they are not integrated into an intelligent control system, and instead charged and discharged as required by the HHs, possibly according to agreements and instructions from MHP management about charging during off-peak periods to reduce peak loads.