MECS-TRIID Draft Project Report (public/confidential version)

Assessing electric cooking potential in micro hydropower microgrids in Nepal

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Executive Summary

The transition to electric cooking in rural Nepali communities with micro hydropower (MHP) mini-grids was explored through cooking practices and MHP behaviour data collection and analysis, laboratory tests of battery powered cooking and modelling of MHP system power flows with and without storage. A cooking diary study was conducted which collected data from 15 households (HHs) in a rural village in Eastern Nepal called Salyan of Solukhhumbu district on the transition from wood and LPG cooking to electric - induction hobs and rice cookers. The study led to a refined cooking diary methodology for the Nepali context. Key outcomes included: datasets of Nepali cooking times and energies to dish level resolution for wood and electric cooking; cooking menu and schedule data pre- and post-intervention; data on fuel stacking; exit surveys; and a cost comparison between cooking fuels. Findings included that there was a simplification of cooking (narrower menu and fewer dishes per meal) in the electric cooking phase but that generally HHs accepted and adapted successfully to the new technology. 83% of dishes were cooked on induction hobs and rice cookers, with varying degrees of fuel stacking with firewood and LPG between the HHs. In the eight weeks following the intervention phase, usage of the electric stoves fell for some HHs due to wood stoves providing space heating in the winter months and reduced spare power during dry season.

MHP system data was collected before and after the introduction of electric cooking. Peak load times coincided with peak electric cooking windows. Although the nominal generation capacity is 100 kW, only about 80 kW was typically generated during the electric cooking phase due to it being dry season which meant that the mini-grid struggled to support 15 HHs cooking with 1 kW induction hobs and up to five rice cookers at the same time. The sharp rise in load currents during the evening peak time seems to be the major contributor for the significant voltage and frequency drop during the transition phase. The percentage drop in voltage and frequency is significantly less during the morning peak compared to evening peak. The system operated in a higher range of stability during the baseline period as the maximum daily load (57.35kW) was still 7% less than the average daily generation power. Mini-grid stability and generated power variability across the seasons presents a challenge for electric cooking.

Batteries could enable unused generated energy in the MHP to be stored and used for cooking, allowing increased uptake of electric cooking. To assess the feasibility of cooking Nepali dishes from lithium batteries, a battery eCook demonstrator was set-up in the PEEDA lab. Rice and dal were cooked successfully from the battery, proving feasibility, but limitations on equipment meant that detailed insights into the effect of high-power cooking on battery usable capacity and cycle life were not obtained.

MHP system data was used to model energy and power flows in the mini-grid in order to understand how battery storage could be integrated. The model provides a sizing tool for centralised storage - the battery capacity can be calculated so that the load is always met and the battery state of charge never falls below a certain level. Analysis showed that a maximum of around 500 HHs could cook with electricity from centralised or HH level battery storage if the spare energy in the mini-grid was used to its full potential. For centralised storage the system would require upgrading to meet the maximum load and for HH batteries an intelligent charging control system would be required.

A cost comparison of electric cooking with LPG and wood cooking revealed that in some cases households paid less to cook with electricity than with LPG and, if a labour charge is attached

to firewood collection, wood. Battery electric cooking requires significant investment for both centralised and household level storage, although a household battery cooking system to cover daily electric cooking, excluding cookers, could be paid for over 20 or 5 years in monthly instalments of $20.30 and $30.60 respectively.

A strong understanding of how electric cooking can be integrated into Nepali MHP mini-grids was obtained along with key indicators of mini-grid suitability which could enable a national macro-assessment of the potential of electric cooking in mini-grids. Further projects planned include field trials of battery electric cooking and electric pressure cookers.

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1. Introduction

1.1 There are over 3,300 rural communities in Nepal that have micro hydropower (MHP) systems providing them with electricity with an average power consumption of only 100 Watts per household. During the wet season, MHP plants offer relatively constant power output throughout the day and night (unlike variable solar photovoltaics or wind) making it an ideal candidate to explore electric cooking. A small-scale e-cooking pilot study in 2018 identified that this highly constrained supply struggled to support the increased load during peak times.

1.2 A multi-disciplinary consortium made up of local non-government organisations (PEEDA and KAPEG) and academic institutions (Bristol and Coventry) was brought together to address these challenges.

Aims of the project

1.3 The project aimed to address the challenge of enabling widespread adoption of electric cooking in Nepali MHP mini-grids through:

1.4 1) Refining qualitative methods to assess Nepali cooking practices using a localised version of the MECS e-cooking diary and a survey to understand community willingness to adopt new cooking technologies;

1.5 2) Collecting high quality quantitative data through existing meters and sensors of cooking energy requirements and MHP electrical system behaviour;

1.6 3) Establishing an electric cooking laboratory in Nepal to simulate and test storage scenarios on MHP mini-grids through battery storage and behaviour change solutions, and;

1.7 4) Translating these findings to inform policies and scale up of electric cooking through partnerships with international funding agency (UNDP) and government body (AEPC).

1.8 These project outcomes will be applicable to the wider Nepali national power grid and other grids and mini-grids in countries with similar cooking practices and grid infrastructure.

Objectives of the project

1.9 There are five key objectives in the project:

1.10 1) Refine the MECS cooking diaries methodology for a Nepali context.

1.11 2) Measure MHP system data pre- and post- e-cooking intervention.

1.12 3) Use the cooking diary and system data to develop wider scale implications of electric cooking in Nepali MHP microgrids

1.13 4) Develop a battery e-cook demonstrator system for the Nepali market

1.14 5) Develop modelling tools for design of a battery-supported cooking system for Nepali MHP microgrids

2. Methodology

2.1 Enabling widespread electric cooking in constrained MHP microgrids and larger hydropower networks requires collection of high-quality data, highlighting details on Nepali cooking practices and the MHP system behaviour when electric cooking is integrated in the system. From this, the applicability of low power electric cooking for MHP microgrids was assessed, and modelling tools developed for design of a battery system to enable the cooking load to be averaged throughout the day, freeing peak capacity for more electric cookers. Alongside the data gathering, laboratory testing of battery-based electric cooking was performed to understand the system technical challenges. This project aimed to investigate constrained MHP microgrid electric cooking, which can be broken down into three areas: **data collection**, **battery-based electric cooking investigation**, and **analysis and reporting**.

Outline of the concept

2.2 These concepts were based on previous trials of electric cooking in MHP microgrids carried out by the project partners

2.3 **Work Package 1: Data Gathering**

2.4 The methodology for cooking diary studies and MHP data collection was refined, trialled, and further refined according to the results, leading to a robust method for Nepali electric cooking studies. 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. MHP system data was collected for the entirety of the cooking diary study. Furthermore, pre- and post-study surveys were conducted to collect detailed feedback from participants. In addition to the induction hobs, which were well accepted in previous studies, rice cookers were also trialled as they provide low power opportunities to cook staple Nepali food of rice. From previous studies, participants found it difficult to cook flatbreads on the induction hobs, so more training was given to the participants on using the different cooking technologies.

2.5 MHP differs greatly from solar PV and wind power in that it produces constant power throughout the day and night. Furthermore, it is subject to seasonal variation due to dry seasons and monsoons which vary the water flow and therefore power generated. Therefore, MHP mini-grids are a different and unexplored prospect for electric cooking which require investigation for adoption to be realised. The project determined the requirements and the adaptations required for MHP mini-grids to support electric cooking. Using high quality data loggers and sensors ensured high data quality to allow investigation into the impact of electric cooking on the MHP mini-grid.

2.6 **Work Package 2: Battery-based Electric Cooking Investigation**

2.7 Energy storage can support additional electric cookers in the MHP mini-grid, when it is severely constrained at peak load. This project proposed tools for assessing how a battery electric cooking system could be designed for future projects, evaluating size, location and distribution of storage resources, as well as changes to the mini-grid infrastructure required to support this. This work utilised the data from WP1 to support the analysis.

2.8 Together with the design work, a household-based battery electric cooking system was laboratory tested using components available in the Nepali market where possible to assess its viability and understand the technical challenges of battery powered cooking in Nepal.

2.9 **Work Package 3: Analysis and Reporting**

2.10 The data generated in WP1 were used to develop a strong understanding of the Nepali cooking context, by analysing the data from the cooking diaries together with the MHP system data. Utilising both datasets, this enabled a strong understanding of how electric cooking can be integrated in constrained MHP mini-grids and identified the opportunities and challenges of using energy storage within MHP mini-grids to reduce the peak load demand due to cooking.

2.11 The datasets will be published online, along with analysis of the work through academic papers and technical reports, to ensure that this knowledge is widely disseminated.

Intellectual Property Rights

2.12 There are no intellectual property rights associated with this project.

Assumptions made

2.13 There are three main assumptions made in this work: firstly, that the selected participating households 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 are typical of standard cooking practices for Nepali households, with minimal changes due to the study; and finally that the cooking diary protocol captures the actual cooking practices, with participants recording all data required.

3. Implementation

Localised Nepali Cooking Diary

3.1 Cooking is deeply related to cultural experience and varies widely on the types of food prepared within a small community. In other sense it is unique to each community. Pre-intervention cooking diaries is necessary at the initial phase of the project to understand cooking behaviour of the selected community. This project has adapted the pre-intervention cooking diaries to understand how cooking is performed in Nepalese kitchen, which fuel and appliance they use, time and energy required, changes in their cooking behaviour and adaptation on new technology etc. The cooking diaries prepared by the eCook researchers were further customised based on the local context of cooking.

3.2 Cooking diary methodology is used as a reference to collect the baseline and the intervention phase data. The baseline survey and intervention phase data for this project is taken for a 2-week period assessing traditional wood stove and electric fuel usage to understand existing and post-installation behaviours and preferences. A modified version of the cooking diaries is developed in order to create relevancy for the meals generally cooked in Nepalese context.

Field Site Selection

3.3 Four micro hydro projects were shortlisted for the field investigation to finalize one micro hydro project as a research site. The short-listed sites were 100kW installed capacity, located in different geographical areas. Rawa Khola Micro hydropower of Khotang and Triveni Solukhola Micro Hydropower project of Salyan, Solukhumbu were visited with a checklist for qualification. While, the remaining 2 MHP sites located in Baglung were not able to visit due to the occurrence of floods and landslides.

Power-house data logging set-up

3.4 The power supply for electric cookers is from the 100kW MHP grid which electrifies 1025 households including the several single phase and three phase industrial loads. The penetration of 15 induction cookers in the power range of 1kW means significant load increase during the transition phase.

3.5 The data logger monitoring set-up was used to collect electrical measurement from the MHP's powerhouse during the baseline survey. All sensors and data loggers were assembled and configured at KAPEG before its deployment to the site. The table below presents details of the data collection dates and number of days..

Table 1: Table with the start and end dates of the baseline and transition period

Data Monitoring	**Start Date**	**End Date**	**Total days**
Baseline Survey	20th September 2019	9th October 2019	19
Transition Survey	21st November 2019	25th December 2019	35

MHP electrical data collection and analysis methodology

3.6 The MHP electrical data is collected through standard data loggers from Campbell scientific instruments. The key purpose of the MHP electrical data collection is to study and differentiate the impact of the new cooking appliance load increase in the MHP grid. Data loggers were installed in the powerhouse for collecting various electrical parameters such as Power, AC voltage and current, power factor of the three different phases to investigate the effect.

3.7 The data loggers were configured with 10 second sampling time with the logging interval of 1 minute. The loggers recorded 6 samples of instantaneous data and averaged it over a minute interval. The sampling and logging interval were chosen considering the transient spikes and also the loggers storage capacity. The MHP operator was trained to interface and operate the data logger and visual software platform in the computer system so that the technical team could monitor the instantaneous data and the status of data collection through remote communication.

3.8 The analysis of the MHP data involved using three different software platforms for data conditioning, filtering and visualization. Data are first observed in Microsoft excel for initial inspection, calculation and some filtering. Python and SAS visual analytics are used later mostly for visualization. In the later stages, the data recorded in the minute interval are resampled to 10 minute intervals for creating clear comparative plots.

Cooking diary study

3.9 The baseline phase and transition phases took place for two weeks at the end of September and November 2019 respectively. 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. In the transition phase, HHs were provided with induction hobs with nominal power of around 1 kW. Three HHs had bought rice cookers between the baseline and transition phases and two further HHs were provided with rice cookers, totalling five HHs.

3.10 Generally, HHs cooked 2-3 meals per day and heated water a similar number of times for tea, drinking water or animals. Meals were almost always cooked fresh (not reheated), although leftovers, often given to animals, were recorded for over 200 dishes in both phases. In each HH it was usually the mother or daughter in law who did the cooking.

3.11 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. After receiving feedback on the baseline phase which included that HHs found it difficult to keep weighing and recording wood and food and water quantities, the operational set-up was adapted. It was clear that HHs were able to record their own cooking diary data. A supervisory enumerator was employed, who would visit each HH every day, removing the need for further enumerators. Therefore, 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%.

3.12 The daily energy consumption per capita reduced from 5.7 kWh in the baseline phase for wood cooking to 0.42 kWh in the transition phase for electric cooking. Table 2 below shows the key energy outputs from the transition phase The median number of people was four, with a mean of 4.81 and standard deviation of 1.88. Table 2: Key energy outputs from the transition phase

Key output	Median (kWh)	Median (MJ)	Mean (kWh)	Range (kWh)	Standard deviation (kWh)
Daily energy	1.50	5.40	1.63	5.20	1.01
Daily energy (electricity)	1.90	6.84	2.06	4.60	1.01
Daily energy per capita (electricity)	0.42	1.51	0.43	0.74	0.15
Event energy (electricity)	0.30	1.08	0.45	2.20	0.41
Event energy per capita (electricity)	0.07	0.24	0.10	0.70	0.09
Meal energy (electricity)	0.70	2.52	0.72	2.20	0.40
Meal energy per capita (electricity)	0.15	0.54	0.16	0.70	0.09
Water/Tea energy (electricity)	0.10	0.36	0.17	0.70	0.12

Dish energy (electricity)	0.30	1.08	0.35	1.30	0.20
Dish energy per capita (electricity)	0.07	0.27	0.08	0.40	0.05

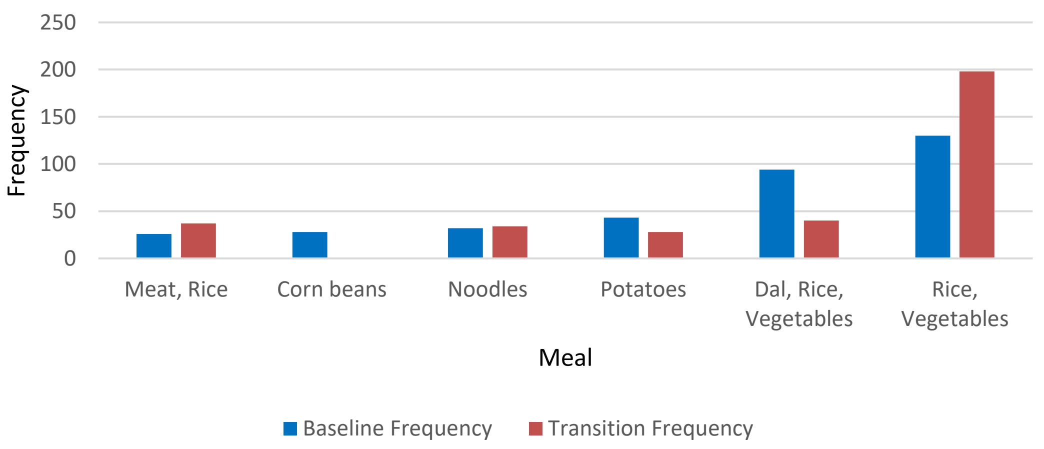
3.13 The median daily cooking time across the HHs reduced from 2:55 to 2:28 while the meal cooking times were similar. This is partly due to the baseline phase taking place during school holidays meaning that more afternoon family meals were had at home. HHs reported that they were often working during the afternoon in the transition phase.

3.14 In the baseline phase 95% of dishes were cooked on wood stoves and 2% with LPG. Fuel stacking was common in the transition phase but 77% and 6% of dishes were cooked on induction hobs and rice cookers respectively. There was significant fuel stacking by nine HHs, LPG and wood, for between 17% and 43% of their dishes.

3.15 Dish level energy data was collected in the transition phase, leading to a database of electric cooking energy consumptions for Nepali dishes -. Rice was cooked in the pressure cooker on the induction hob 261 times with a median energy per capita of 0.054 kWh, standard deviation 0.037 kWh, whereas it was cooked the rice cooker 92 times with a higher median, 0.076 kWh, and standard deviation 0.064 kWh, an interesting finding as rice cookers are thought to be highly efficient.

3.16 Figure 1 below shows how the cooking menu changed across the HHs between the phases. Generally, the most commonly cooked meals in the morning and evening are Rice, Vegetables and Dal, Rice, Vegetables, and Noodles or Potatoes or Corn Beans are regularly had for the afternoon meal. 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. Generally, there was a narrowing of the cooking menu in the transition phase, with a focus on the staple dishes and fewer dishes cooked per meal (the overall mean reduced from 2.39 to 2.06). For example, Chapati frequency reduced from 39 to 16. The simplification of cooking practices is likely due to HHs growing accustomed to the new stoves. Extra training was provided on cooking Chapati on the hobs due to anticipated difficulty and thicker Chapati pans compared to previous studies were sourced, enabling easier cooking.

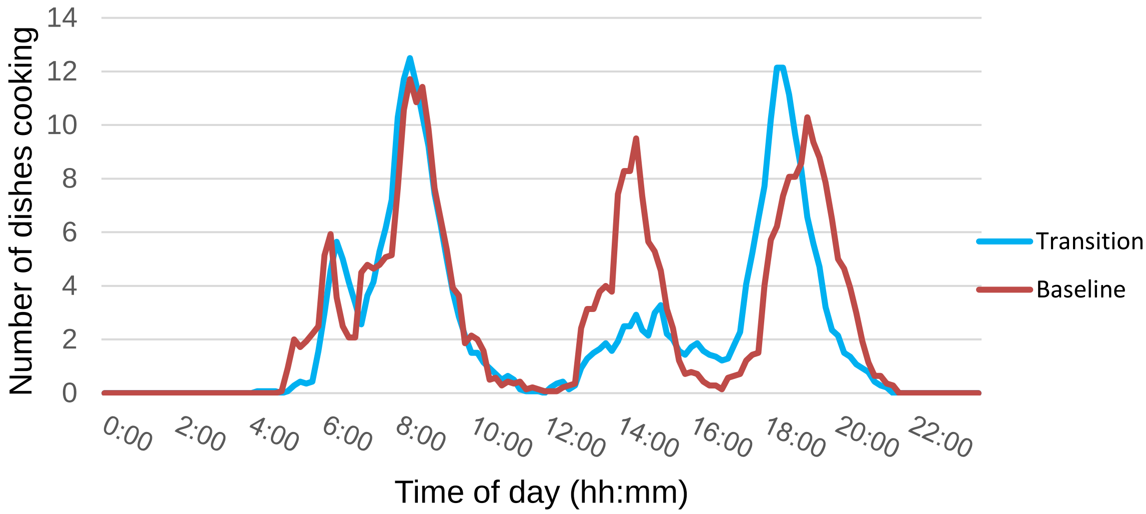
Figure 1: Frequency of common meals in each phase



3.17 In general, water heating events were faster on electric stoves, whereas other dishes such as meat, vegetables and rice - especially that cooked in the rice cooker - were slower. Despite some increased cooking times HHs generally reported feeling that the induction hobs and rice cookers saved time, partly due to not having to chop wood and light a fire. One HH reported feeling able to do other things during cooking.

3.18 Figure 2 below provides an insight into the cooking schedule, 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). It reveals when people cook, showing that two or three main meals are cooked each day, the morning, afternoon and evening meals, and the peak times for these meals. The early morning peak at around 6 am corresponds to water heating events for tea, milk, drinking water and water for animals. There is a slight shift to earlier cooking in the transition phase for the evening meal. The afternoon meal is prepared far less often in the transition phase due to school holidays. The morning and evening peaks are a similar width in each phase, implying similar cooking times in each phase.

Figure 2: Average number of dishes being cooked throughout the day in the transition phase



3.19 Figure 2 shows that concurrent cooking - participants cooking two dishes at the same time - was relatively rare in both phases even though many HHs have both an ICS and traditional wood stove, two places on their wood stove, LPG stoves and, in the transition phase, induction hobs and rice cookers. In the baseline phase only two HHs seemed to cook concurrently on their wood stoves more than a few times. In the transition phase, concurrent cooking was more common, especially among the HHs with rice cookers. Three HHs cooked concurrently between electricity, wood and/or LPG less than ten times. Four of the five HHs with rice cookers used it concurrently with the induction hobs and, to a lesser extent, with wood and LPG. 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.

3.20 Nepali cooking usually involves cooking rice and dal in pressure cookers. HHs often use two when cooking with firewood so that there is no need to empty and clean one and the first dish can stay warm in the first pressure cooker. The HHs were provided with one induction friendly pressure cooker for the transition phase. Some HHs asked about the possibility of obtaining another but did not follow up on their interest when the MHP secretary offered to make an order. During the exit survey one HH also asked if a vessel in which to keep food warm could be obtained. This shows that Nepali cooking benefits from multiple cookers (pressure cookers or rice cookers) in terms of convenience, keeping food warm and enabling concurrent cooking.

3.21 The cooking diary study presented a number of challenges. There were data issues such as missing data (especially final wood values and number of people), duplication of data, erroneous time data recording, energy meters only showing one decimal place, and some dishes/meals not recorded in both phases.

3.22 Future electric cooking studies could be improved by household data loggers to record cooking loads and energy readings to greater precision, digital cooking diary data collection and semi-automated analysis, an extra pressure cooker for induction cooking systems, trialling electric pressure cookers with two interchangeable interior pots, and conducting surveys both directly after the transition phase and some months later, perhaps digitally and remotely, enabling a direct feedback channel.

Exit surveys

3.23 An exit survey aims to capture the user experience of cooking on electricity and user's feedback for further studies. Verbal interviews were taken with each of the users along with specific questions to reflect the users experience for qualitative analysis. One of the main objectives of this research project is to approach towards clean electric cooking which may improve the performance, user-friendliness, safety and time-saving in order to provide impactful benefits to the selected participation.

3.24 Generally, the HHs were happy with the cookers and pleased to have been selected for the project. They cited advantages such as quick and easy cooking, smoke free kitchens, saving time not lighting a fire, being able to do other things while cooking and being able to clean the stoves easily. HHs were happy to no longer need to collect as much firewood, which is a strenuous task, especially for the elderly.

3.25 The main problem cited was low voltage, sometimes just after starting to cook, although during the transition phase this was generally only a problem on rare occasions. Six HHs reported this occurring with the most affected HH without power for three to four days. As it was the dry season, the generated power in the mini-grid dropped to around 80 kW, meaning that the power supply collapsed for some HHs when they tried to cook on the electric stove. HHs did not report difficulty cooking particular dishes although, as mentioned, there was a focus on cooking the staple dishes. Some HHs reported burning rice at first as they were adapting to the new stoves but that they quickly became accustomed to them.

3.26 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 55 days since the transition phase. 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. The median percentage of electric cooking was 44.5%, over 70% for six HHs and very low for others. Reasons for reduced electric cooking and increased fuel stacking included further reduced MHP generation power compared to the transition phase due to the season and some HHs relying on heat from wood stoves for warmth in winter. During the cold climate the MHP secretary and operators are disinclined to restore the generated power to a higher level by diverting more water to the MHP plant at the intake due to the coldness of the water, preferring to wait for warmer weather.

MHP data analysis during the baseline and transition period

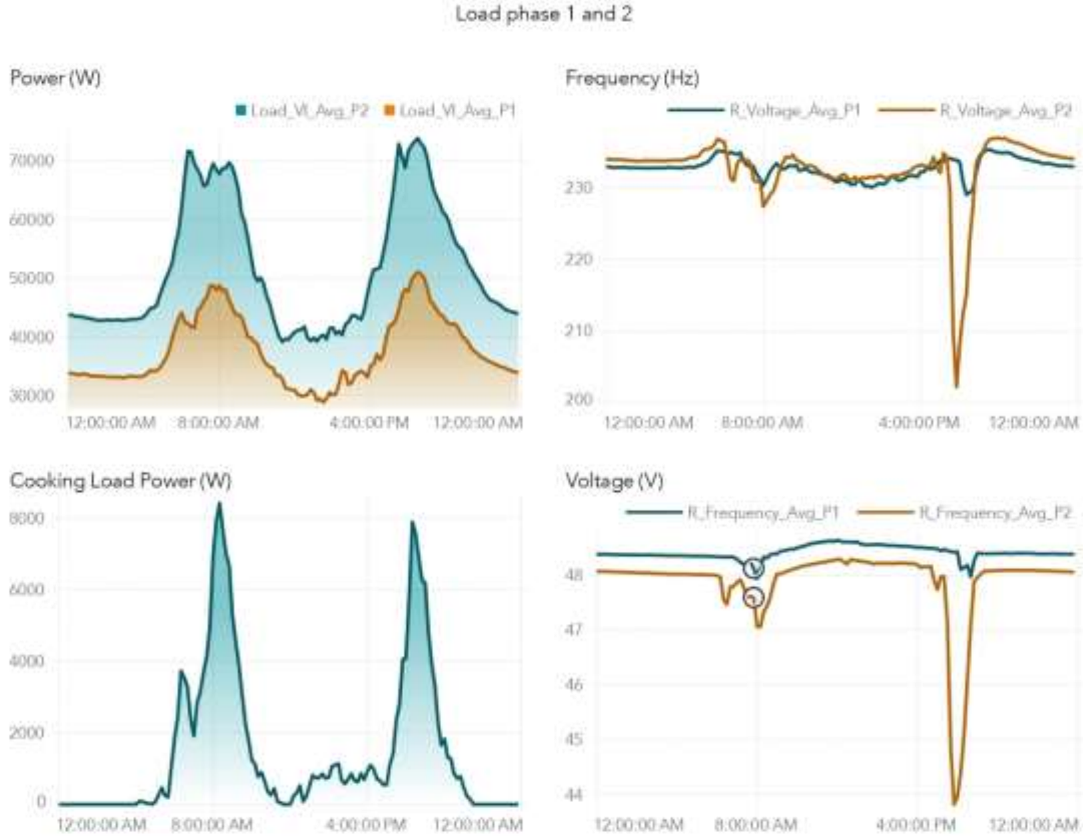
3.27 The MHP electrical data collected during the baseline survey were of a total 19 days from which 12 days of data were extracted for analysis. 7 days of data were filtered out due to the power outages and gradually decreasing generation. The power outages are mostly during the afternoon which is assumed to be mostly controlled outages. The gradually decreasing generation is the consequence of decreasing flow in the canal. Days with such events are termed as abnormal days and are filtered out to generate better average plots.

3.28 The data collected during the transition phase was stretched to 35 days out of which14 days of data matching the cooking dairy dates were extracted for analysis. 13 days of data were processed as only 1 of the days during the transition phase had a significantly long power outage, unlike the baseline phase where the power outage was comparatively more frequent but short.

3.29 The plots demonstrated and discussed in this section are 10minutes resampled mean plots of the filtered data generated mostly through SAS Visual Analytics. The average, maximum and minimum of the 10 minutes resampled data of each of the days from baseline and transition phase are calculated and plotted for comparative analysis.

Comparative analysis

Figure 3: Comparative plots of total load and generation power, voltage and frequency during the baseline and transition period. The magnitude and span of cooking load power during the transition phase is also illustrated.



3.30 Figure 3 shows the comparative load power plots between the baseline and transition period where the MHP was operated with different generation power. The Table 3 summarizes the operating condition of the MHP during the 2 phases.

Table 3: Descriptive analysis of various parameters from the baseline and transition period and its percentage change

Parameters	Baseline phase	Transition phase	Percentage change
MHP LOAD - TOTAL			
Total base load power	27.66kW	39.18kW	29%
Average Load Power	37.71kW	51.80kW	27%
Maximum Load Power	57.35kW	80.414kW	29%
Minimum Load Power	5.23kW	26.83kW	81%
MHP GENERATION			
Average Generation Power	61.87kW	78kW	21%
Maximum Generation Power	72.93kW	83.86kW	13%
Minimum Generation Power	20.90kW	36.45kW	43%
VOLTAGE AND FREQUENCY			
Average Voltage and Frequency	233V, 48Hz	233V, 48Hz	0%, 0%
Maximum Voltage and Frequency	236V, 49Hz	238V, 48Hz	1%, -2%

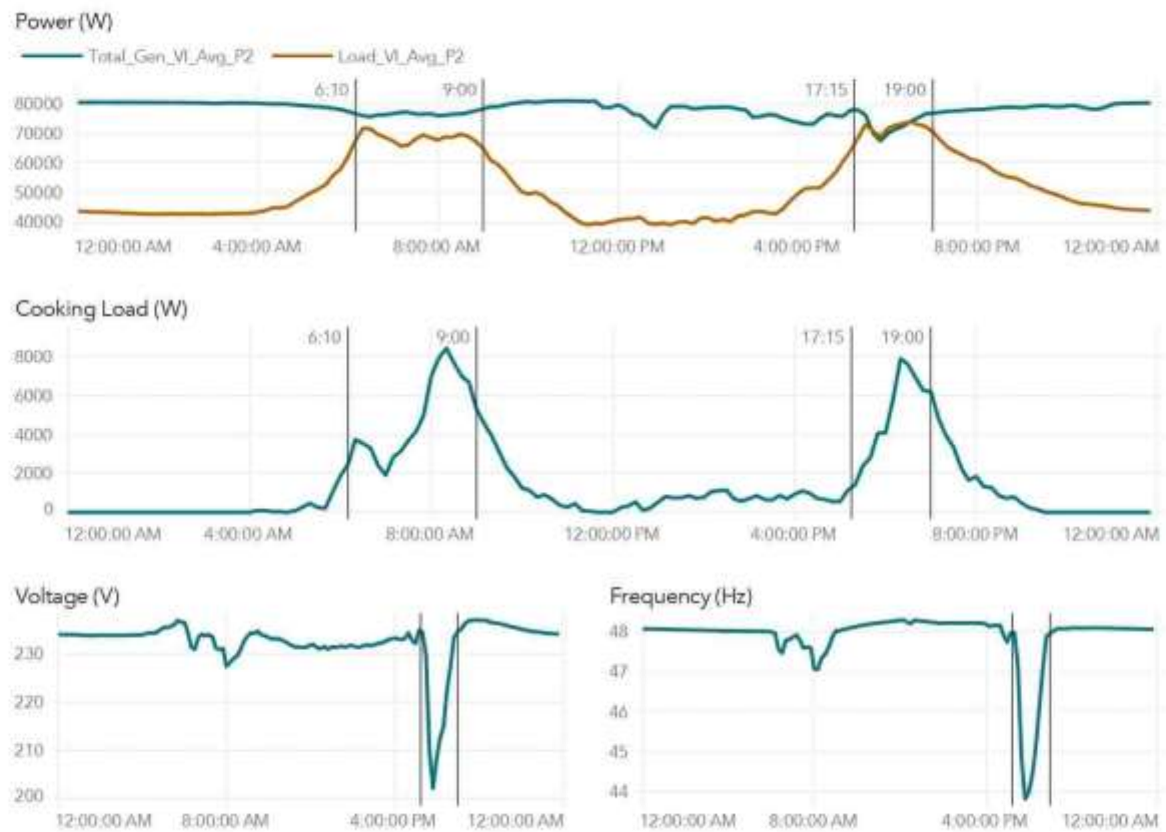
Minimum Voltage and Frequency	229V, 48Hz	203V, 44Hz	-13%, -9%

3.31 Estimating 90kW average generation all around the year, the MHP operated at 69% of the generation capacity during the baseline period while 87% during the transition period based on daily average values. Although, the MHP operated in its full capacity during the transition phase with the maximum available flow that could be diverted to the MHP canal way.

3.32 During the baseline period, the maximum daily load (57.35kW) is still 7% less than the average daily generation power. Because of this situation, the voltage and frequency change between the maximum and minimum values is only 3% and 2% respectively even during peak hours. The MHP system operated with good stability.

3.33 During the transition phase, the maximum daily load is 3% above the average daily generation power. The maximum daily load is the peak power during the evening time as can be seen from Figure 3 which is true for both baseline and transition period. Higher voltage and frequency drop are observed during the peak hours of the transition period as the demanded load was above the generation capacity. The voltage drops of 13% from the average value (233 V) are observed during the peak hours of transition period while the calculation shows only 2% drop during the baseline period. Figure 4 tries to see the correlation between the electric cooking load with total MHP load and its influence on system voltage and frequency.

Figure 4: Figure illustrating transition phase - average generation and load power, cooking load and impact on systems voltage and frequency



3.34 The synthetic load profiles are created by calculating an average power for each dish cooked in the day from its energy and cooking duration. The power values calculated are mostly reasonable (around 1 kW or less), but some are accurate (much more than 1 kW, e.g. 6 kW). The inaccuracies are either due to inaccurate cooking duration data recording (like saying rice was only cooked for a few minutes, giving rise to a high-power value, when maybe the start or end time recorded is wrong and it was cooked for 20 minutes), or inaccurate energy meter reading recording. However, the plots should give a reasonable approximation to the actual daily cooking load profiles, at least to the shape and peaks.

3.35 As in the first 2 plots in the Figure 4, there is no apparent similarity in the shape of the plot between the total MHP load and the cooking load. This indicates that the cooking load may not be influencing the total load compared to other MHP loads during the peak hours. On the other hand, the magnitude of the cooking load is similar during both hours of the daily cooking period. But the drop-in frequency and voltage during the morning peak time is significantly less than the evening peak time.

3.36 A key point to note is that the MHP load increased by 27% and the baseload power increased to 29% from the baseline to transition period. As the transition period was in winter and during the dry season, it is estimated that other heating loads could have been active as to a potential reason behind the increase in load power beside the cooking load. The primary reason behind the voltage and frequency drop during the evening peak time in the transition phase is due to the sharp rise in load currents as apparent from the data analysed from the powerhouse.

3.37 The start and end of the 2 daily peaks as observed in Figure 4 is based on frequency and voltage destabilization and its continuous drop. The morning peak is characterized by a plateau type peak while the evening peak is characterized by a sharp rise. The morning peak is 2.8 hrs long while the evening peak is relatively short spanning to 1.7hrs. Both peaks of the cooking load fall within the 2 peak hours. Therefore, a more detailed phase-wise analysis may generate the influence of cooking load on the daily individual phase loads.

Battery E-Cook Demonstrator

3.38 The system aimed to assess the performance of lithium ion batteries for cooking Nepali meals. A specification was created in order to enable component sourcing. 24 V was specified to match the voltage of widely available inverters in Nepal and India. 1-1.5 kWh of usable capacity was deemed necessary to cook 1-2 Nepali meals based on a previous electric cooking study in Simli, Rukum where the average meal energy was 0.7 kWh. A minimum of 1 kW continuous discharge power was specified as this is the power requirement of many induction hobs. A 25.6V 80Ah LiFePO4 battery and 24V 2.3kVA Inverter/Charger (UPS) were purchased to meet the specification, costing a total of $841.95. The UPS was adapted by the manufacturers to be able to charge lithium ion batteries.

3.39 It was not possible to source lithium ion batteries with high power discharge capability in Nepal due to unavailability. Lithium ion batteries in Nepal are generally used for low power applications such as lighting. Therefore, components were sourced from India. Energy meters were also purchased, and a CR 1000 data logger already purchased for the project was added to the system.

3.40 Tests included cooking rice and dal from the battery on an induction hob and comparing results to cooking from the mains. Results showed that Nepali dishes can be cooked from a lithium ion battery in comparable time to mains cooking and consuming a similar amount of energy. Rice and dal required 0.55 kWh and 0.35 kWh from the battery respectively.

3.41 Battery testing was limited by issues with the data logger and being unable to source a state of charge indicator and cycle count monitor. These would have allowed more detailed assessment on the effect of high power cooking on battery usable capacity and health. Future work includes sourcing such components and performing more in-depth tests. The purchased UPS was chosen as an inexpensive option. It used 60 W of internal power even in no load condition and the voltage dropped down to 200 V when the induction hob was set to 1 kW. Power was drawn from the battery all the time, reducing its usable capacity. A more efficient inverter would improve the system.

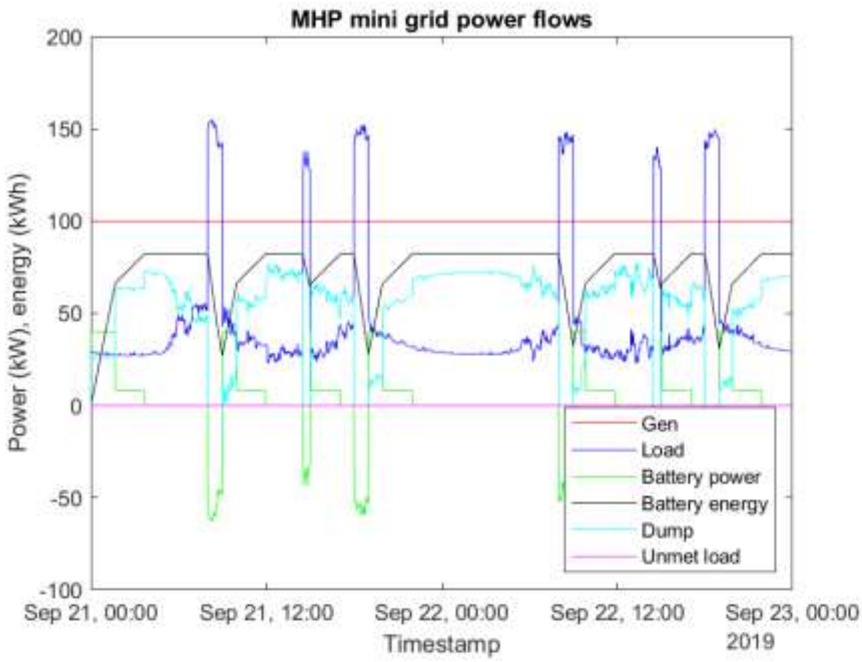
MHP Mini-grid Storage Modelling

3.42 A MATLAB model for analysis of power flows and energy in the field site MHP mini-grid was created in order to assess how energy storage could enable the uptake of electric cooking by large numbers of households. The baseline phase load data recorded by the data logger in the MHP powerhouse was used as normal load data and comprised 15 full days of data. One output of the model is a calculation of the minimum number of HHs that could cook directly from the mini-grid on each day, according to the spare power during peak times. For 1 kW electric stoves the mean across the days was 42, ranging from 36 to 49. As reported, in the transition phase just 15 HHs cooking with electricity destabilised the grid at times. The difference is due partly to the model assuming that the full 100 kW of generation power is available and can be used without destabilisation, when actually only around 80 kW was generated and when the load neared the generation the grid voltage dropped. Furthermore, the load increased generally between the phases.

3.43 An element of the model investigates how centralised storage in the powerhouse can reduce peak loads to the level of the generated power. Overall, the battery charges through a bidirectional converter 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. The load can be adjusted by adding extra electric cooking load according to a number of households cooking with electricity at certain times. Electric cooker power, power profile, cooking windows, number of households cooking and how their cooking is scheduled can all be varied in the model to assess different scenarios. Charging C rates were chosen to approximate constant current, constant voltage charging over four hours so as not to stress the battery. A discharging maximum C rate of 1C was chosen as high power discharge reduces available capacity and affects cycle life. C rates were kept constant so the system behaviour could be investigated but can be varied in the model.

3.44 The model can be used as a guide for sizing a central battery because it was found that the minimum capacity is that required to meet the maximum meal excess load - the highest extra energy above 100 kW (generation), which occurs during a mealtime - while maintaining the battery state of charge 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 a required minimum battery capacity to meet it and therefore all other meals, as long as there is sufficient time and power in between meals for the battery to recharge sufficiently. The battery capacity reached by the model could be increased by measures to account for decay and capacity loss at high discharge.

3.45 An example scenario modelled were created assuming that 100 households (of 1025 connected to the mini-grid in the village) started cooking with 1 kW induction hobs for three meals per day (including water heating events), each at the same times. The hob power was assumed to be constant at 1 kW for the duration of each meal - this is unlikely as HHs tend to reduce the power during cooking but is an approximation and can also be varied. The meal durations and times were chosen according to cooking habits identified in the cooking diaries. In this scenario, the required battery capacity to keep the battery state of charge above 20% was 82 kWh and the mini-grid infrastructure would require upgrading to be able to tolerate a maximum of 161 kW through the lines during peak cooking times - the peak of the total load. Figure 5 shows the power flows for two days of this modelled scenario.Figure 5: Mini-grid power flows for two days of modelled scenario – generation, load, battery power and energy, dumped power and unmet load. The unmet load was zero as the battery was sized to be able to meet the extra cooking load every day without being exhausted.



3.46 When the load is increased to include 300 or 400 HHs cooking with electricity the sizing rule broke down because the required battery capacity was so high that there was insufficient spare power to charge it at its nominal power, meaning that it could not reach full charge between every meal. As the maximum meal excess load was for an evening meal in the data used, the battery capacity had to be increased further until the minimum state of charge reached a desirable level. Another more realistic load scenario of two groups of HHs cooking in adjacent hours was also modelled and the findings were similar. In each scenario the mini-grid would require upgrading to carry the maximum load.

3.47 The potential of HH level batteries for electric cooking was also explored. The eCook Modelling Spreadsheet, kindly provided by Professor Matthew Leach was used to size a HH battery at 2.89 kWh based on the median HH daily cooking energy requirement for electric cooking, which was 1.8 kWh. Worst- and best-case scenarios for HH battery charging in the mini-grid were created.. The worst case calculated the number of batteries that could be charged at the same time at the end of the day when the base load was around 30 kW at 37 if constant current, constant voltage charging employed, and represents a charging strategy based on battery voltage only i.e. that charging begins when the voltage depletes to a certain level**.** The best case calculated the total spare energy in the mini-grid on each day excluding cooking windows, reduced it charging efficiency, cable losses, line losses and 5% so as not to destabilise the grid, and divided it by the battery charging energy required to replenish it from 20% state of charge to give the number of batteries. The mean across the days was 471, representing an intelligent control system that schedules HH battery charging and adjusts charging power according to the state of the mini-grid. A more realistic charging control system whereby batteries charge when depleted to a certain state of charge but only while the grid voltage is stable would enable an intermediate number of HHs to cook from HH batteries.

3.48 Running the central storage model at a 500 HHs load scenario showed that this is around the maximum number of HHs that could cook with electricity, because however high the battery capacity, the high load significantly depleted the battery during each meal and there was insufficient spare power for it to recharge in time to meet the load of the next meal without being depleted much further. Therefore, the models provide an indication of the limits of energy storage in MHP mini-grids. Infrastructure requires upgrading for centralised storage due to the increased power which is not the case for HH batteries unless they feed in to the mini-grid. However, centralised batteries could be managed by a trained MHP operator.

3.49 Further work includes refining the model to improve the battery model, including more accurate efficiencies, incorporating voltage and power factor rather than only investigating real power flows, assessing configurations with batteries located at distribution transformers, using updated base load data and accurate and/or stochastically varying electric cooking load profiles**,** and reducing the generated power available so as not to destabilise the mini-grid.

Gender Equity

3.50 Cooking is one of the key activities for women in Nepal, where more than 75% of households still use solid biomass like wood-fuel and animal dung. Without access to cleaner cookstoves and fuels, women endure incredible hardships and are exposed to deadly smoke that kills over 22,000 people annually in Nepal. In addition, mostly women walk for hours to collect wood from community forest or rivers and have to carry heavy loads, putting them at high risk of physical and sexual attack and physical injuries. Thus, one of the main objectives of this project is to aware about clean cooking practise and adaptation of clean cooking in MHP microgrids, where 80% of selected participation were women leading the daily cooking activities, received training on electric cooking and started to cooked food items in electric cookers that have helped them to save time without inhaling smoke thereby taking care of their health and their family members.

Hence, this project opens a new opportunity to acknowledge the critical role access to clean cooking in achieving gender equity in the selected community.

Key Project Outcomes

3.51 The project showed that electric cooking is possible in Nepali MHP mini-grids with constrained power sources and that it is compatible with Nepali cooking practices. It produced a refined cooking diary methodology for the Nepali context which captures dish level energy data. Key diary study outputs included datasets of Nepali cooking times and energies, cooking menu, schedule and fuel stacking data. HHs with rice cookers and some other HHs cooked concurrently between stoves, showing that this could be a desirable feature for a cooking system for the Nepali context. The cooking diary study showed that participants can record dish level energy data with high data coverage. Employing a supervisory enumerator and paying HHs a daily sum incentivised them to record data. The knowledge on Nepali cooking habits and practices will enable informed design of future electric cooking interventions and a smoother transition to electric cooking.

3.52 Fuel stacking occurred due to preference for original stoves, needing to finish a meal quickly for school or work, so that HHs could cook concurrently on two stoves, and due to low voltage. The generated power was limited to around 80 kW during the transition phase, significantly less than the 100 kW nominal capacity. In the eight weeks that followed, usage of the electric stoves fell for some HHs due to wood stoves providing space heating in the winter months and further reduced spare power during dry season.

3.53 During the transition period as the MHP was loaded with 15 induction cookers and 3 rice cooking loads, the MHP remained at appreciable stability during the morning peak time, while the evening peak suffered a relatively greater voltage and frequency fall down. The total electric load rose sharply at the evening peak time reaching the maximum generation capacity causing sharp fall in voltage close to 200V and 44Hz. It is difficult to entirely credit the voltage and frequency dip to the electric cooking load as the two peaks do not align together in the vertical axis, but the evening cooking load definitely added to the total electric load while operating at full generation capacity. The peak time of the MHP load did coincide with the peak cooking load time. Overall, the mini-grid struggled to support just 15 HHs cooking with electricity. The project provided a strong understanding of the behaviour of MHP mini-grids and how electric cooking can be integrated.

3.54 The use of batteries for cooking could enable more HHs to cook on a mini-grid. Battery laboratory tests confirmed that lithium ion batteries can support Nepali cooking but that inverter efficiency is an issue and further investigation of the effect of high power cooking on usable capacity and cycle life is required. MHP mini-grid system energy and power flows modelling provided tools to understand and size battery storage to enable increased uptake of electric cooking on a central and HH level. Analysis showed that a maximum of around 500 HHs could cook with electricity from centralised or HH level battery storage if the spare energy in the mini-grid was used to its full potential. For centralised storage the system would require upgrading to meet the maximum load and for HH batteries an intelligent charging control system would be required.

Limitations of the innovation/approach/design/system

3.55 There are a number of limitations of the proposed system and study. Induction cooking requires specialist cookware which adds to the cost of a cooking system. Providing one pressure cooker reduced the ability of participants to cook concurrently and keep food warm. Other efficient devices such as electric pressure cookers should be trialled, with multiple inner pots. The upfront cost of any system presents a barrier to uptake.

3.56 The limited spare power in the mini-grid caused voltage drops which led to fuel stacking. Batteries present a possible solution. The laboratory battery cooking tests were limited by the equipment - a state of charge indicator and cycle count monitor would enable more detailed insights into technical issues. The battery cooking system purchased was limited by the efficiency of the inverter and its power draw from the battery even with no cooking load. A more efficient inverter could improve the system.

3.57 Modelling of battery storage in the MHP mini-grid provides a useful battery sizing tool and indication of potential for HH level batteries but the model requires refining and further detailed analysis to present more realistic conclusions. Updated base load data and measured electric cooking load profile data would improve the model outputs.

3.58 The culture of using wood stove cooking for space heating means that fuel stacking is inevitable during the winter months in rural Nepali communities. Therefore, in terms of alleviating indoor air pollution, other space heating methods or moving wood stoves outside may be the only options.

3.59 The cooking diary study was subject to limitations such as data quality issues, energy meter readings to only one decimal place, and limited analysis time due to manual data processing. Comparing data between phases was problematic due to the change of season and school holidays during the baseline phase. Improvements in training on cooking with electric stoves were hard to assess due to the simplification of cooking practices recorded, with HHs rarely cooking Chapati (flatbread) in the transition phase. Future studies should develop an eCookBook to disseminate Nepali electric cooking techniques in detail and digitise data collection and processing.

4. Practical applications of the concept to the national cooking energy system (including costs)

4.1 3,300 rural communities in Nepal have MHP mini-grids. Key indicators of mini-grid suitability for electric cooking have been generated from this and previous projects, enabling a macro-assessment from limited information and data. Indicators include data on generation and load and variation over the year, load balance across phases and transformers, industrial loads, planned future loads, cooking fuels and supply, electricity tariff, and MHP team competency**.**

4.2 For this project a cost comparison between electric cooking and fuelwood/LPG was conducted. Costs for electricity, LPG cooking and fuelwood cooking were calculated for the two-week transition period from electrical energy consumption and the proposed electricity tariff, LPG cylinder cost and reported replacement frequency, and equivalent labour costs of fuelwood collection. The median electric cooking cost across the HHs was $1.69 for the two-week period, with a range of $0.79 to $4.15. For LPG, the median was $1.60, with a range of $0.72 to $5.34.

4.3 Fuelwood collection is generally done according to 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 500 NPR per person per day. An annual equivalent cost was calculated as $108.90, which is $4.18 over two weeks. 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 costs are similar to their previous costs and in some cases, lower.

4.4 The MHP mini-grid storage modelling tools could be used on other mini-grids using data on generation power, base load and electric cooking load profiles. The model shows how much extra power the mini-grid infrastructure would require upgrading for, and includes a method for assessing the potential of HH batteries for cooking. Household level battery storage could enable widespread uptake of electric cooking in mini-grids. According to the eCook Modelling Spreadsheet and accounting for the proposed electricity tariff in Salyan, a 2.89 kWh HH level battery system would have an initial investment cost of $1027 or monthly costs of $20.30 over 20 years or $30.60 over 5 years. The purchased system for laboratory tests costed $841.95 in total.

4.5 A central 152 kWh battery, which would enable approximately 200 HHs to cook with 1 kW electric stoves if their cooking was scheduled into two groups of 100 HHs cooking in adjacent hours, would cost $46,300 at $304.64/kWh in 2020 according to the eCook Modelling Spreadsheet. This capacity could be increased to account for the unavailability of around 10-20 kW of MHP generated power and battery capacity decay. Infrastructure strengthening and additional equipment would increase the cost further. Overall, battery supported cooking requires large investments for both HH level and centralised storage.

4.6 The two types of induction cooker were imported from India, costing $42.97 and $47.80, while the sets of cookware and rice cookers were purchased in Kathmandu for $61.62 and $24.25 respectively. The cookware makes up a large proportion of the expense for induction cooking. Electric pressure cookers present an alternative solution, with the one purchased for the PEEDA laboratory costing $59.64 from Kathmandu, but not requiring any additional cookware.

5. Next steps (e.g. beta or field testing and implementation; more development etc)

5.1 The knowledge generated in this work has provided a solid platform of methods and tools to both expand the use of electric cooking in MHP mini-grids and support communities through this transition. There are two major aspects of this work that are seen as next steps for the work in this area.

5.2 Having shown that batteries can be used for Nepali cooking and assessed their potential to reduce peak cooking loads can enable widespread uptake of electric cooking in mini-grids, further laboratory testing of battery cooking is planned. Once an in-depth understanding of battery cooking has been developed, a project trialling small-scale and large-scale battery electric cooking in a Nepali mini-grid is planned to understand how to integrate battery charging into the system and what technical issues arise in the field..

5.3 Alongside this, material and tools to enable dissemination and expansion of electric cooking services across Nepal need to be developed. This will include promotional material to support consumers in understanding the options to utilise electric cooking, including product types, recipes and techniques relevant to Nepali cuisine, and household benefits from transitioning to electric cooking. Investigations into institutional support needs, such as electric cooking service centres and supply chain management, will be necessary to provide a firm base for electric cooking to grow within both urban and rural Nepal. A tool to enable a macro assessment of MHP mini-grids is required, to identify MHP sites that are currently capable of supporting electric cooking, and pathways for MHP sites to be suitable to integrate electric cooking. Key indicators of suitability for electric cooking will be determined from the conducted electric cooking projects and used to create a dataset of Nepali mini-grids with assessment of suitability.

5.4 Alternative electric cooking devices also provide possibilities to improve cooking practices in Nepal. Electric pressure cookers (EPCs) present an alternative to the induction cooking system trialled and their potential to cater for Nepali cooking requires exploration, following on from the initial investigations within the PEEDA cooking laboratory. To this end, the team has applied for the MECS ECO Challenge Fund to understand how EPCs can be assimilated into Nepali cooking practices, conducting an EPC based intervention and developing a promotion campaign to provide information for the public and relevant organisations and stakeholders to support the promotion of electric cooking practices in Nepal.

5.5 Urban, grid-connected populations in Nepal are a key group to target with electric cooking projects. In smaller urban settlements, where clean-cooking options such as LPG are limited, expensive and with an unreliable supply chain, biomass is still used as the primary cooking fuel. Therefore, it is important to understand how electric cooking can be integrated into the cooking culture for these communities.

5.6 During the Clean Cooking Forum in Nairobi, the team met a Nepali cookstove entrepreneur who would like to develop indigenous stoves. Therefore, we are currently working with the entrepreneur to develop a project in this area.

Dissemination Plan

5.7 Nepal has a national campaign to promote and achieve clean cooking solutions for all by 2022, with the aims to contribute towards people's well-being and the promotion of energy efficient electric cooking. The findings of this project will be disseminated with the wide range of stakeholders including: Government agencies (AEPC, RERL, District Development Committees), private sector organisations (Importers of electric cooking devices), financial institutions (Development Banks), academic institutions (Kathmandu University, Tribhuvan University) as well as developments partners to ensure access of quality and efficient electric cooking products in the rural areas of Nepal.

5.8 With the co-ordination among government bodies and experts, further research work will be carried out to identify the technology, investment and policy gaps to implement the clean cooking program throughout the country. Working closely with the key stakeholders, we will use the outcomes to support the development of new policy and investment plans to enable a scale-up of electric cooking solutions across Nepal.

5.9 To this end, the project partners will continue to work closely with the national stakeholders to disseminate the outcomes of the research and provide input to future projects and policy to support the achievement of clean cooking across Nepal. During the project, PEEDA and KAPEG have contributed to national clean cooking programs in Nepal, reporting on the progress of the current research, and will present the final outcomes at future events.

5.10 An academic paper is planned to highlight the outcomes from this work, with the data published on the University of Bristol's Research Data Repository (data.bris.ac.uk)

6. Conclusion

6.1 The project generated detailed understanding, knowledge, datasets, tools and skills on the transition to electric cooking in Nepali MHP mini-grids which can be applied to other mini-grids as well as to grid-connected communities. The cooking diary study revealed what, when and how people in rural Nepali communities cook, generating datasets of cooking energy and time requirements of Nepali dishes.

6.2 The transition was negotiated successfully by all participants who generally reported being very pleased with the cookers and benefits of time savings and smoke free kitchens. Electric stove usage since the transition phase reduced for some households but this was mainly due to seasonal reduction in generation power and the use of wood stoves for space heating. The study shone light on other cultural factors such as using multiple pressure cookers or stoves to keep food warm.

6.3 The effect of electric cooking on the mini-grid was investigated. The MHP operated with 62kW average generation with proper stability during the baseline period which meant that 31% of the MHP still remained as spare capacity. During the transition period, when the MHP was loaded with 15 induction cookers and 3 rice cooking loads, there was very little spare power. The MHP remained at appreciable stability during the morning peak time, while the evening peak caused a relatively greater voltage and frequency fall down. The total electric load rose sharply at the evening peak time reaching the maximum generation capacity causing sharp fall in voltage close to 200V and 44Hz. The project showed that mini-grids with limited spare power can only support a small number of households cooking with electricity.

6.4 The potential of energy storage to enable greater uptake of electric cooking was explored, showing that further laboratory testing is required to gain an in-depth understanding of the technical issues of using batteries for high power cooking. Modelling tools provided a battery sizing tool for centralised storage in the MHP powerhouse and an understanding of the dynamics of a system incorporating storage. They showed that a maximum of around 500 households could use electric stoves on the mini-grid with a high capacity battery bank. Household level batteries for cooking could enable up to a similar number of households to cook with electricity depending on the intelligence of a charging control system.

6.5 Electric cooking was shown to be comparable in cost to LPG and wood cooking in the project community. Household battery cooking systems could be paid for over 20 or 5 years in monthly instalments of $20.30 and $30.60 respectively. A macro assessment of electric cooking feasibility in Nepali mini-grid communities is planned, as well as further laboratory battery and electric pressure cooker tests, and battery cooking and electric pressure cooker field trials.